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RESEARCH ARTICLE

# Grassland ecosystem services: a systematic review of research advances and future directions

**Yuanyuan Zhao · Zhifeng Liu · Jianguo Wu**

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**Abstract**

*Context* Grasslands provide a variety of ecosystem services (ESs) for humans. While much ES research has focused on forests and wetlands, synthesizing the currently somewhat sporadic studies of grassland ecosystem services (GESs) is much needed.

*Objectives* We aimed to review the scope, major methods, and key findings of GESs, and identify knowledge gaps and future directions.

*Methods* We conducted a systematic review of articles published during 1970–2018 (including 380 peer-reviewed articles from Web of Science and 32 book chapters from Google Scholar).

*Results* The number of GES studies has accelerated in recent decades, with China (31%) and the United States (18%) together accounting for almost half of them. A total of 33 GESs were mentioned in the searched articles, of which carbon sequestration, forage production, and water erosion control had the highest frequencies. Methods for evaluating GESs include field survey, field experiments, and statistical and process-based modeling. Grasslands are the primary source of meat and dairy products, account for about one-third of the total carbon of all terrestrial ecosystems, and provide numerous other ESs, such as night cooling, soil erosion control, and flood mitigation.

*Conclusions* This review presents the state-of-the-science of GESs, and identifies several future research directions. To move forward, we propose a framework

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Y. Zhao
Yanchi Research Station, School of Soil and Water Conservation, Beijing Forestry University,
Beijing 100083, China

Y. Zhao
Key Laboratory of State Forestry Administration on Soil and Water Conservation, Beijing Forestry University,
Beijing 100083, China

Z. Liu (✉) · J. Wu
Center for Human–Environment System Sustainability (CHESS), State Key Laboratory of Earth Surface Processes and Resource Ecology (ESPRE), Beijing Normal University, 19 Xinjiekouwai Street,
Beijing 100875, China
e-mail: Zhifeng.liu@bnu.edu.cn

Z. Liu
School of Natural Resources, Faculty of Geographical Science, Beijing Normal University, Beijing 100875,
China

J. Wu
School of Life Sciences and School of Sustainability, Arizona State University, Tempe, AZ 85287, USA

with a 3-M methodology: (1) “Multi-scales”—understanding GESs from various spatiotemporal scales; (2) “Multi-methods”—evaluating GESs with multiple statistical and modeling techniques using multiple data sources; and (3) “Multi-perspectives”—assessing GESs from ecological, social, and economic perspectives for sustainability.

**Keywords** Grassland ecosystem services · Systematic review · Provisioning services · Regulating services · Cultural services · Grassland sustainability

## Introduction

Grasslands are among the most widely distributed terrestrial biomes globally (White et al. 2000; Dixon et al. 2014). The term “grassland”, in a broad sense, includes all herbaceous vegetation types, including the Eurasian steppes, the North American prairies, the South American pampas, and the African veld and savannas, as well as some woody shrub-based deserts and tundra and various artificial grasslands and grazing land around the world (White et al. 2000). Following this definition, the global grassland area is 52.54 million km$^2$, accounting for 40.5% of the global land area without permanent ice cover (i.e., excluding Greenland and Antarctica; see Table 1) (White et al. 2000). Because the structure and function of shrub- and trees-dominated ecosystems are quite different from those of non-woody ecosystems, in this study we use “grassland” refers primarily to herbaceous plant communities.

The concept of ecosystem service (ES) provides a crucial bridge between biodiversity/ecosystem function and human well-being (MEA 2005), and ES research has seen two major bursts since the 1970s (Wu 2013). The first occurred in the late 1990s when ES began to spread widely as an interdisciplinary concept (Costanza et al. 1997; Daily 1997). During this period, the concept and methods for evaluating ESs attracted much attention from the academic community (de Groot et al. 2002; Sutton and Costanza 2002; Hein et al. 2006; Jenkins et al. 2010; Abulizi et al. 2017; Sannigrahi et al. 2018). Although the ES monetization approach (Costanza et al. 1997, 2014) has contributed to the rise of ES research with far-reaching implications for ES research, criticisms on the approach remain abundant (e.g., Silvertown 2015). The second burst was stimulated by the Millennium Ecosystem Assessment Report (MEA 2005) and has continued to the present. ES research during this period has made extensive progress in many aspects, including more unified definitions, improved ES classification systems, and diversification of research methods. Scientists have increasingly recognized that ES research is much more than ecosystem monetization or valuation, and that it is essential to understand the kinds, amounts, and flows of ESs as well as their tradeoffs and synergies (Wu 2013; Silvertown 2015).

Grassland ecosystem services (GESs) refer to all the benefits (including products, resources, and environment) provided by biodiversity and ecosystem structure and function of grasslands to meet the needs of human survival, life, and well-being (Sala and Paruelo 1997). In addition to foods, fibers, drugs, energy, and other products with direct economic value, grasslands also provide important non-physical services, e.g., climate regulation, erosion control, recreation and tourism, and inheritance of national culture, to human beings along with its biodiversity (Sala and Paruelo 1997; Havstad et al. 2007; Sala et al. 2017) (Fig. 1). Grassland landscape elements act directly or indirectly on ecosystem structure and dynamics, which in turn affects ecosystem products and services (Fig. 1). As climate change and human activities continue to intensify, the temporal and spatial patterns of grasslands and their productivity are constantly changing, directly affecting GESs (Lamarque et al. 2014; Byrd et al. 2015). As the more than 38% of the total global population reside in dryland regions (consisting mainly of grasslands and deserts), and as about 90% of the dryland people live in developing countries (MEA 2005), GES research has important implications for improving human well-being and promoting sustainable development around the world (MEA 2005; Havstad et al. 2007; Wu 2013).

Studies on GESs have received widespread attention and made progress in several aspects, such as the temporal and spatial characteristics of GESs (MEA 2005; Egoh et al. 2011), impacts of climate change and human activities on GESs (Han et al. 2008; Byrd et al. 2015; Li et al. 2019), tradeoffs/synergies of GESs (Pan et al. 2014), and relationships among biodiversity, ecosystem function, ESs, and human well-being (Egoh et al. 2009; Wang et al. 2017a). Several reviews on certain GESs exist, including bioenergy production

**Table 1** The area of global grasslands

| Grassland type | Whittaker and Likens (1975)[a] | | Atjay et al. (1979)[a] | | Olson et al. (1983) | | PAGE (White et al. 2000) | |
|---|---|---|---|---|---|---|---|---|
| | Million km$^2$ | Percent[b] | Million km$^2$ | Percent[b] | Million km$^2$ | Percent[b] | Million km$^2$ | Percent[b] |
| Savanna | 15.0 | 11.6 | 12.0 | 9.3 | × | × | 17.9 | 13.8 |
| Tropical woodland and savanna | × | × | × | × | 7.3 | 5.6 | × | × |
| Dry savanna and woodland | 8.5[c] | 6.6 | 3.5 | 2.7 | 13.2[d] | 10.2 | × | × |
| Shrublands[e] | × | × | 7.0 | 5.4 | × | × | 16.5 | 12.7 |
| Non-woody grassland and shrubland | × | × | × | × | 21.4 | 16.5 | 10.7 | 8.30 |
| Temperate grassland | 9.0 | 7.0 | 12.5 | 9.7 | × | × | × | × |
| Tundra | 8.0 | 6.2 | 9.5 | 7.3 | 13.6 | 10.5 | 7.4 | 5.7 |
| Total | 40.5 | 31.3 | 44.5 | 34.4 | 55.5 | 42.8 | 52.5 | 40.5 |

× signifies data are not available or have been combined with other categories

[a] Desert and semidesert scrub not included

[b] Total land area used for the world is 129,476,000 km$^2$ excluding Greenland and Antarctica

[c] Includes woodland and shrubland

[d] Includes dry forest and woodland

[e] Includes warm, hot, or cool shrublands

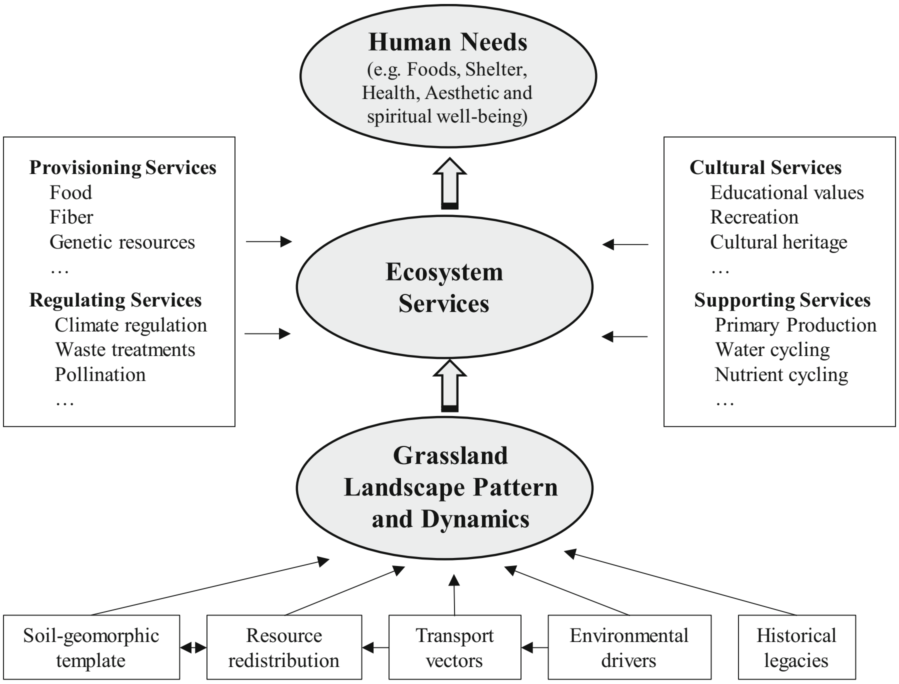

**Fig. 1** Main ecosystem services of grasslands and their interactions with the grassland landscape and human needs (Modified from Campbell et al. 1996, White et al. 2000 and Havstad et al. 2007)

(Ceotto 2008; Prochnow et al. 2009), food production (O'Mara 2012), water regulation (Sirimarco et al. 2017), and GESs in specific places (Honigova et al. 2012; Modernel et al. 2016; Ren et al. 2016; Holland et al. 2017; Pogue et al. 2018). Because of the wide distribution and high diversity of grasslands, however, existing studies are sporadic in space and in topical coverage as compared to ES research for forests and urban ecosystems. Comprehensive in-depth reviews of GESs would help coalesce the different research fronts and advance the science and applications of GESs (Havstad et al. 2007; Honigova et al. 2012; Sala et al. 2017). Thus, the objectives of this paper are to review the current scope, major quantitative methods, and key findings of GESs, to discuss existing shortcomings and challenges, and then present a conceptual framework of GES research to help move this field forward.

## Methods

This review was conducted based on a literature search and a systematic review including quantitative statistics and qualitative content analysis (Fig. 2). Our research protocol broadly followed the guidelines of Chapman et al. (2017). Systematic reviews have an advantage over traditional reviews and commentaries in that they cover studies by following an explicitly formulated procedure (Khan et al. 2003; Vukomanovic and Steelman 2019).

### Literature search

Because the benefits of nature were regarded as services in 1970s (Westman 1977), the Web of Science online databases (Web of Science Core Collection, Chinese Science Citation Database, KCI-Korean Journal Database, Russian Science Citation Index, and SciELO Citation Index), were searched for the period 1970–2018. The following syntax was used: TS = ((grassland* or steppe* or prairie* or pampas* or veld* or savanna* or rangeland*) and ((ecosystem* service*) or (provision* service*) or (regulat* service*) or (cultu* service*) or (support* service*) or (habitat* service*))) and la = English. A total of 4086 unique articles were returned from the databases.

For the acquisition of the relevant list, all articles were reviewed at title and abstract level with the following three criteria: (1) focus on GESs; (2) explicit analysis of the term "GESs"; or (3) alternatively, describe the goods or benefits that humans obtain from grassland ecosystems. We included not only articles focused solely on GESs, but also those on ESs of multiple ecosystems including grasslands. Both articles on GES evaluation and monetization were included in the list. During this process, 380 relevant studies were remained.

We also did additional searches in Google Scholar and identified 32 additional articles closely related to GESs, including some book chapters and ES evaluation tool guide. The final analysis was based on 412 articles, among which 367 were research articles and 45 were review papers or illustration reports on GES evaluation. For the selected articles, we recorded: study area, publication year, GES mentioned and examined, evaluation methods and major results.

### Literature review

We firstly analyzed the characteristics of the selected GES studies. A "word cloud" was produced using the titles, key words, and abstracts of selected articles. A general characterization of these studies was provided in terms of their geographical distribution, the number of publications over time, and GESs mentioned or examined in the selected studies.

Then, we reviewed the advances in GES research. The ES classification in the MEA (2005), which includes supporting services, provisioning services, regulating services, and cultural services, is the most widely used scheme. Because supporting services refer to ecosystem functions or processes that are based on biodiversity and ecosystem structure (such as soil formation, productivity, and nutrient cycling), which are not really "services" (Wu 2013), we focused mainly on provisioning, regulating, and cultural services of grasslands. The current scope, major quantitative methods, and key findings were summarized for the three types of GES. Finally, we identified research gaps and challenges, and proposed a conceptual framework to help advance research in GES.

## Characterization of GES studies

We first visualized the key words in the selected articles using word cloud analysis (Fig. 3). We found

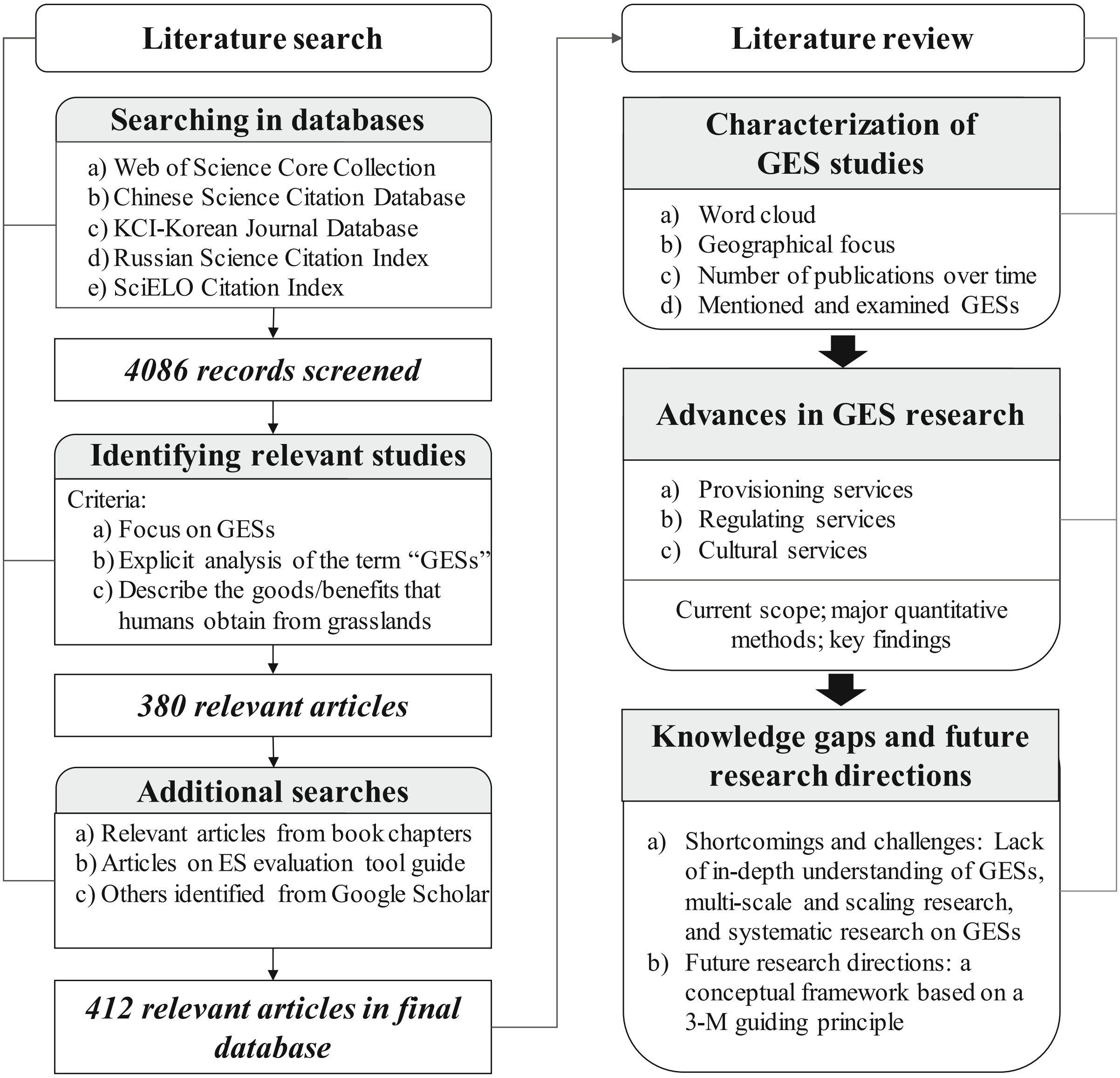

**Fig. 2** Flowchart showing the systematic literature search and literature review

that "ecosystem", "services" and "grassland" are among the most commonly used words in GES studies. Other important key words include "value", "production", "grazing", "carbon", "soil", "climate", and "conservation", which denote the main research topics of GESs.

Among the research articles, 68 studies were on the monetization assessment of GESs and others were about the biophysical quantities of benefits gained from grassland ecosystems. In terms of the spatial distribution of the GES studies, 22 studies were conducted at global or continental scales and the other 358 were conducted within different countries. The distribution was spatially clustered consistently with the grassland distribution (Fig. 4). Approximately one-third of the studies (106 research articles) were conducted in China, 18% (64 research articles) in the USA, and about 25% in European countries (UK: 21 articles, 6%; France: 20 articles, 6%; Italy, Switzerland, and Spain: 8, 7, and 5 articles, respectively, 6% in total). Other study regions include Africa (9%), South America (8%), and Oceania (5%). Studies

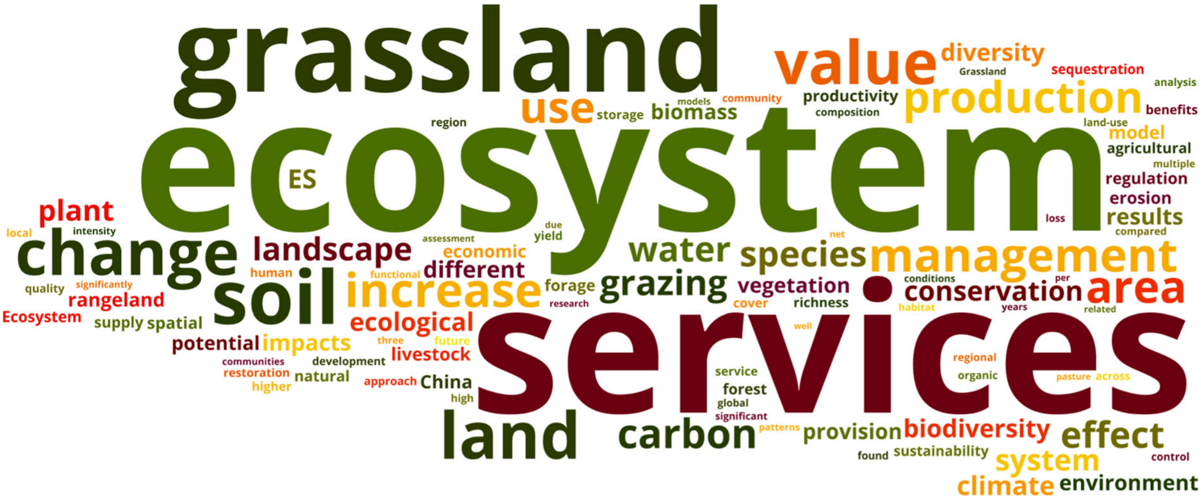

**Fig. 3** Word cloud generated based on words in the titles, keywords, and abstracts of all selected articles. The size of the word is indicative of the relative frequency of the occurrence of the word

focused mainly on the steppes in Eurasia, alpine grasslands in the Qinghai–Tibetan Plateau, tallgrass prairies in North America, pampas in South America, and savannas in Africa and South America.

GESs related to provisioning, regulating, and cultural services have attracted increasing attention especially since 2009 (Fig. 5a). The number of publications increased from 1 in 1980s to 12 in 2009, 37 in 2012, and 55 in 2018. These publications mentioned 33 GESs, with varying frequencies (Fig. 5b). Regulating and provisioning services received more attention. In terms of the specific services, carbon sequestration, forage production, and recreation were the most commonly examined regulating services, provisioning services, and cultural services, respectively. These three kinds of ESs were studied, respectively, in 79, 46, and 17 of 299 publications (excluding reviews and studies about monetization assessment of GESs). Some articles mentioned services such as wool production, sources of natural medicines, raw material, waste treatment,

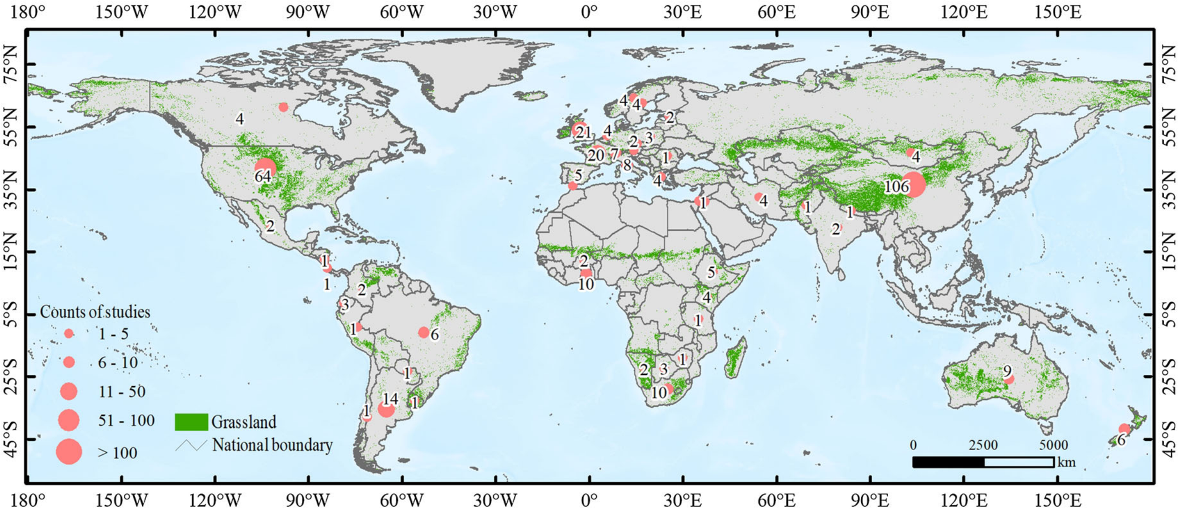

**Fig. 4** Global distribution of studies on grassland ecosystem services. *Note* the grassland was extracted from CCI-LC (Climate Change Initiative-Land Cover) products generated by the European Space Agency CCI projects (http://maps.elie.ucl.ac.be/CCI)

and prevention of endoparasitic disease, but did not do any detailed analysis.

## Advances in GES research

Data used for evaluating GESs are usually of three kinds: administrative boundary-based data from governmental statistics yearbooks (e.g. milk production) (Smit et al. 2008; Pan et al. 2014), local-scale data from field observations, surveys, and experiments (Honigova et al. 2012; Wen et al. 2013), and large-scale remote sensing data (Xia et al. 2014). ESs are quantified mainly by statistical analysis and modeling, or a combination of both. Some integrated models have emerged to meet the needs for quantitative assessment of ESs. For example, the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model consists of a series of modules and algorithms which can be used to quantify various ESs such as water yield, soil, and water conservation (Tallis et al. 2013). The model is publicly available and has been widely used in GES research because of its simplicity and flexibility. The ARtificial Intelligence for Ecosystem Services (ARIES) model, which is capable of simulating ES flows (Bagstad et al. 2011), and the Social Values for Ecosystem Services (SolvES) model, which is good at quantifying the social value of ESs such as aesthetics and leisure, have also been used for measuring GESs (Sherrouse and Semmens 2015). However, validation of these models against field surveys and experimental data is still lacking.

### Provisioning services of grasslands

Provisioning services refer to the basic materials that ecosystem provides for maintaining human survival and life. Grasslands provide food, fresh water, fiber, and bioenergy, as well as ornamental plants, a genetic library, and habitat for animals and plants (Table 2).

#### *Food supply*

Grasslands support numerous domestic animals ranging from cattle, sheep, horses to buffalos, which are sources of meat, milk, wool, and leather products for humans (Whiter et al. 2000; Archer and Predick 2014; Brown and MacLeod 2017; Pogue et al. 2018). Data from statistic yearbooks, field surveys and grazing experiments have helped obtain data on forage production and livestock production (Kemp et al. 2013; Petz et al. 2014; Ferner et al. 2018). Grasses accounted for 57% of the cattle forages in America (Barnes and Nelson 2003). The presence of semi-natural herbs and legumes directly affected the livestock performance and even the development of animal husbandry (Honigova et al. 2012). Meat and milk are an important part of the global food supply. In 2010, beef and mutton supply accounted for about 28% of the total global meat supply. Global ruminant meat and milk energy supply exceeded the total food energy supply from pig meat and poultry meat by 37% (O'Mara 2012). Anadon et al. (2014) found that a 1% increase in tree encroachment into grasslands resulted in a 2.5% decrease in mean livestock production in the United States. The global demand for beef, sheep meat, and dairy products is predicted to grow by 13.9%, 22%, and 22.2%, respectively, from 2011 to 2020 (OECK/FAO 2011). The shrinkage and degradation of grasslands and the increasing demands for high quality meat and milk already make grassland food supply services challenging (Conant 2010; O'Mara 2012).

#### *Fresh water supply*

Grassland ecosystems are often mosaicked with permanent and seasonal wetlands such as rivers, lakes, and marshes, and provide freshwater resources to humans. These wetland ecosystems are the main source of drinking water and irrigation, and also form the nomadic pastoral culture of living with grass and water. Water yield and runoff are common indicators for evaluating fresh water supply such as water use structure and water for irrigation (Egoh et al. 2008, 2011; Hao et al. 2017a, b). With local observation data on precipitation, evapotranspiration, and soil infiltration, the InVEST model can be used to estimate water yield in grasslands at the sub-watershed to watershed scales (Hao et al. 2017a). The total amount of water yield in grasslands depends on the quantity and pattern of rainfall as well as the abiotic factors such as regional climate and topography. Because of climate change and excessive human activities such as overgrazing and coal mining, grasslands have been degrading, thus seriously affecting freshwater supply services. For example, the Mongolian Plateau

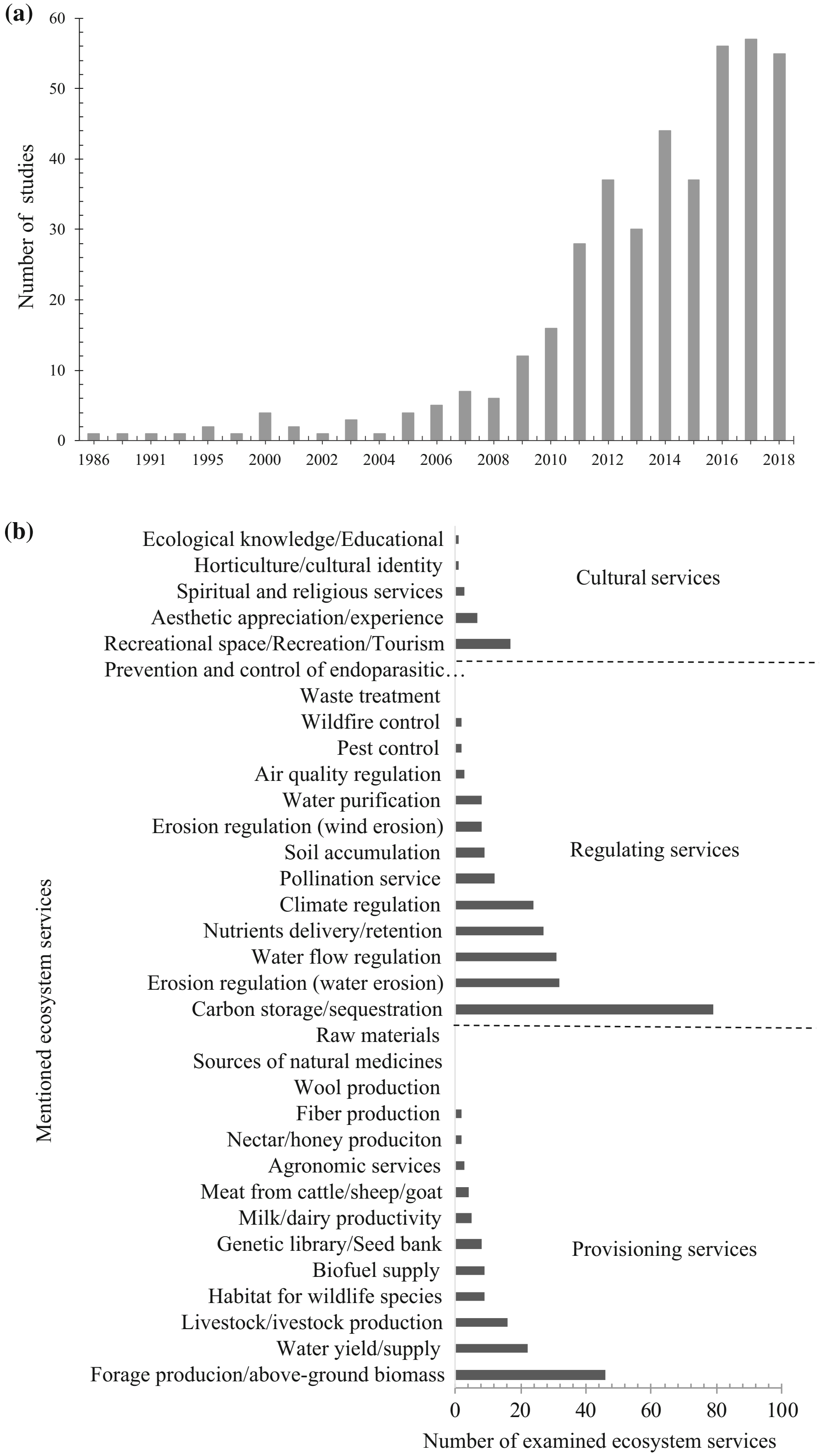

**Fig. 5** Research perspectives of grassland ecosystem services. **a** Evolution of selected publications on grassland ecosystem services over time, 1986–2018. **b** The mentioned and examined ecosystem services throughout selected publications

**Table 2** Detailed description of provisioning, regulating, and cultural services provided by grasslands

| Ecosystem services | | What to measure | Valuation methods/formula | Measurement | Typical studies |
|---|---|---|---|---|---|
| Provisioning services | Food supply | Forage production | Quadrants survey; modeling (e.g. CASA) | Standing biomass (tCkm$^{-2}$/year) | Martinez-Estevez et al. (2013), Petz et al. (2014) |
| | | Livestock production | Grazing experiments; modeling; sensus database | Stocking rate/maximum livestock capacity (kg sheep equivalent/km$^2$) | Kemp et al. (2013), Anadon et al. (2014) |
| | | Meat/milk production | Statistics collection | Quantity of meat and milk (kg/year) | Silvestri et al. (2013), Pan et al. (2014) |
| | | Honey production | Field sampling; modeling | Honey bee colony population size; annual honey yield (g/m$^2$/year) | Mu et al. (2016), Affek (2018) |
| | Fresh water supply | Water yield | Field sampling; modeling (e.g. InVEST) | Annual runoff (m$^3$/km$^2$/year); Water yield (mm/year) | Egoh et al. (2008), Hao et al. (2017a) |
| | Fuel supply | Biomass available for collection | Field sampling; modeling | Biomass stock (g/m$^2$) | Liu et al. (2012), Petz et al. (2014) |
| | Habitat supply | Bio corridors and stepping stones | Field sampling | Corridor area (km$^2$) | Honigova et al. (2012), Auffret and Cousins (2018) |
| | Genetic library/seed bank | Gene biodiversity; biological diversity | Field sampling | Species originated in grasslands | Sala and Paruelo (1997), Helm et al. (2009) |
| | Other biotic material (e.g. medicinal, fibers) | Quantity of the material | Field sampling | Production of the material | Honigova et al. (2012) |
| Regulating services | Amelioration of weather | Meteorological factors | Field observations; modeling (e.g. WRF) | Temperature (°C) cooling extent (km$^2$) | Cao et al. (2015), Monteiro et al. (2016) |
| | Carbon sequestration | Carbon sequestered | Sampling; modeling (e.g. CASA, CENTURY, TEM, statistical model) | Carbon storage (gC/m$^{-2}$/year) | Farley et al. (2004), Lal (2011), Farley et al. (2013), Feng et al. (2013) |
| | Erosion control | Soil conservation during water erosion | Field experiment (e.g. runoff plot); modeling (e.g. RUSLE) | Soil conservation quantity (t/km$^2$/year); soil conservation rate (%) | Hao et al. (2017a), Petz et al. (2014) |
| | | Soil conservation during wind erosion | Field observations and experiments (e.g. wind tunnel experiment); modeling (e.g. RWEQ) | | Hao et al. (2017a), Zhang et al. (2018) |
| | Water regulation | Water flow regulation | The single-ring infiltrometer method; modeling | Runoff coefficient (ratio between runoff and rainfall, %); water infiltration rate (mm/hour) | Honigova et al. (2012), Martinez-Estevez et al. (2013) |
| | | Water purification | Modeling (e.g. InVEST) | Nutrient retention (g/m$^3$) | Lavorel et al. (2017) |
| | Air quality regulation | Interception of pollutants and respirable particulate matter | Field observation; modeling | Pollutant concentration (g/m$^2$); Dust/PM2.5 emmisions (g/m$^2$) | Chen et al. (2014), Lu et al. (2018) |
| | Soil accumulation/formation | Accumulation of organic matter | Field sampling; soil survey; modeling | Soil depth (cm); litter cover (%) | Egoh et al. (2008), van Eekeren et al. (2010) |
| | Nutrient cycling | Rate of nutrient cycling | Field sampling; modeling | Abundance of legumes; leaf nitrogen content (mg/g) | Wehn et al. (2018) |
| | Pest control | Diversity and density of predators | Field experiment | Diversity of predators and parasitoids; number of trap nesting pest insects | Allan et al. (2015); Lindgren et al. (2018) |
| | Pollination service | Pollination provision | Field sampling | Number of flower visitors; abundance of the food plants for insects | Bennett and Isaacs (2014), Allan et al. (2015), Wehn et al. (2018) |

**Table 2** continued

| Ecosystem services | | What to measure | Valuation methods/formula | Measurement | Typical studies |
|---|---|---|---|---|---|
| Cultural services | Recreation and ecotourism | Satisfaction of visitors | Questionnaire and statistical analysis | Satisfaction degree; return rate (%); | Gray and Bond (2013), Silvestri et al. (2013) |
| | | Ecotouristic suitability | Modeling | Attractive scenery; accessibility; amount of wildlife | Petz et al. (2014) |
| | Aesthetic appreciation | Flower cover; canopy and shrub layer cover | Field experiments; questionnaire | Total flower cover (%); number of flower colors; percent cover of canopy and shrub layer (%) | Allan et al. (2015), Wehn et al. (2018) |
| | Ecological knowledge/education | Cognitive level | Questionnaire | Number of research stations; scientific achievement | Bai and Wang (2017) |
| | Horticulture/cultural identity | Nomadic pastoral culture | Questionnaire | Number of nomadic families | Oteros-Rozas et al. (2013) |

experienced significant grassland degradation and lake shrinkage from 1980s to 2010, with the number of lakes larger than 1 km$^2$ decreasing from 785 to 577 (Tao et al. 2015).

### *Fuel supply*

Grassland biomass is also a potential resource of bioenergy via numerous ways for producing energy, including the production of lignocellulosic bioethanol, synthetic biofuels, or synthetic natural gas (Prochnow et al. 2009; Liu et al. 2012). Some have argued that low-input high-diversity grasslands not only provide opportunities for producing biofuels but also improve biodiversity and services like erosion control and water storage (e.g., Tilman et al. 2006; Machovina and Feeley 2017). In general, developed countries with surplus grassland resources may have a greater potential of grasslands for bioenergy production than developing countries where animal feed and food production usually take priority over bioenergy production due to the rising demand of milk and meat (Ceotto 2008; Prochnow et al. 2009). But the tradeoffs between energy and food/fodder production have been an issue in contention, and the long-term sustainability of bioenergy production has been seriously questioned (Dirks et al. 2012; Robledo-Abad et al. 2017; Wang et al. 2017b).

### *Other provisioning services*

Other provisioning services of grasslands include providing gene pools for a variety of economically important plant, insect, bird, and fungal species (Honigova et al. 2012). The genetic resources of grasslands have a disproportionately large conservation value for humankind. A large number of domesticated plants and animals such as wheat, onions, goats, sheep, and cattle originated in the grasslands of the Mediterranean region (Sala and Paruelo 1997), and many medicinal plants also originated in the grasslands, such as *Agrimonia pilosa* and *Plantago lanceolata* (Akhtar et al. 2013; Lian et al. 2014). The fragmentation of grasslands and the dense population density had a negative impact on genetic diversity (Helm et al. 2009). As the number of threatened and endangered grassland species continues to increase, the role of grasslands as genetic sources becomes more important (Trolliet et al. 2016; Enri et al. 2017). In addition, other services such as providing habitat for biological species and fiber supply were also mentioned in some studies (e.g., Honigova et al. 2012).

## Regulating services of grasslands

Grasslands provide numerous regulating services, including climate regulation, carbon sequestration, erosion control, water regulation, air quality regulation, soil formation, pest control, waste treatment, and pollination services. Quantitative studies on regulating services have been done more frequently than other kinds of GESs.

### *Climate regulation*

Different management regimes of grasslands can change the composition of the atmosphere by regulating the content of greenhouse gases (e.g. $CO_2$, $CH_4$, $N_2O$) and consequently regulating air temperature (Horrocks et al. 2015). Grazing ruminants are an important source of $CH_4$ in the temperate grassland (Wang et al. 2009; Pogue et al. 2018). Moreover, the changes in surface properties of grasslands directly change the surface albedo, affecting the surface radiation budget and energy balance and leading to changes in weather factors (Cao et al. 2015). Temperature, precipitation, wind speed, surface albedo, and surface radiative forcing are widely used variables to characterize weather ameliorating services. At the local scale, the effects of grassland on climatic conditions can be directly monitored by meteorological sensors or using high-resolution remote sensing images (e.g., thermal infrared images) (Monteiro et al. 2016; Sun and Chen 2017). At the regional or broader scales, remote sensing and dynamic models (e.g. the Weather Research and Forecasting Model, WRF) have become the main research tools, especially in studies of urban heat islands and urban cold islands (Sun and Chen 2017).

The application of the WRF model in the agropastoral ecotone in China showed that grassland degradation in Inner Mongolia, China, during 2001–2010, led to a significant increase in near-surface temperature, whereas vegetation restoration in the southern part of the agropastoral ecotone had significant cooling effects (Cao et al. 2015). Grasslands in the urban environments can increase summer comfort and alleviate heat island effect and are useful to decrease the land surface temperature, by approximately 1 °C, on average (Sun and Chen 2017). Though grassland greenspaces provide less cooling than treed greenspaces in the hours immediately after sunset, through the night cooling by grasslands is intensified while in treed greenspaces the canopy reduces longwave radiation (traps heat) from the ground (Monteiro et al. 2016).

### *Carbon sequestration*

Carbon sequestration, which is the additional storage of carbon over time, is one of the most important and the most commonly examined regulating services of grassland ecosystems (Fig. 5b). Though carbon stocks of grasslands per unit area are lower than those of forest ecosystems, they play an important role in global carbon storage because of their wide distribution (MEA 2005). Grassland carbon stocks include four carbon pools of aboveground biomass, below ground biomass, soil, and dead organic matter. Commonly used methods for estimating grassland carbon sequestration include field sampling (Manning et al. 2015), satellite-based statistical modeling (Piao et al. 2007), and dynamic modeling based on ecosystem processes (e.g. CASA) (Feng et al. 2013). The ratio of aboveground to belowground carbon storage and the ratio of vegetation to soil carbon storage for different grassland types around the world have been quantified (Ni 2002; Piao et al. 2007).

Carbon storage in grasslands has been studied on different spatial scales and using various methods. The global carbon storage of grasslands is between 412 and 820 million tons, accounting for about one-third of the total carbon storage of all terrestrial ecosystems (Wen et al. 2013). During 1982–2006, the annual total average aboveground live biomass carbon stock of global grasslands was 1.05 PgC and showed the same spatial pattern as the regional precipitation pattern. Europe and Asia accounted for 41.7%, North America 19.7%, Africa 17.8%, South America 13.5%, and Australia and New Zealand 7.3% (Xia et al. 2014). The global potential of C sequestration in soils of grasslands and savannas is about 0.3–0.5 billion tons C/year (Lal 2011). Land use/cover change, including both land restoration/degradation and land use conversion, was widely considered a key factor affecting grassland carbon sequestration. Ecosystem carbon storage significantly decreased with increasing grassland degradation (Wen et al. 2013; Zhang et al. 2016). Also, the average soil carbon sequestration rates were higher following a farmland-to-grassland conversion than after a farmland-to forest/shrub conversion, but the absolute quantity varied across different rainfall zones (Deng et al. 2014).

### *Soil erosion control*

The regulating services of soil erosion control by grasslands include both wind and water erosion control (Fu et al. 2011; Zhao et al. 2017; Jiang et al. 2019). These services are commonly estimated using soil conservation amounts or soil conservation rates based on the actual soil erosion of grasslands and potential soil erosion under bare soil conditions (Fu et al. 2011).

Soil erosion by water can be measured by field runoff plots and rainfall simulations, or estimated using water erosion equations (Zhang et al. 2016; Jiang et al. 2018). The Revised Universal Soil Loss Equation (RUSLE) developed by US Department of Agriculture is the most commonly used empirical model (Renard et al. 1991, 2011; Fu et al. 2011). The Water Erosion Prediction Project (WEPP) and its improved version, the Rangeland Hydrology and Erosion Model (RHEM), are commonly used mechanistic models, which include complex ecological processes and are suitable for modeling grassland soil conservation under different degradation conditions (Nearing et al. 1989, 2005, 2011). Jiang et al. (2018) found that the ecological restoration such as conversion from farmlands to grasslands since 2000 substantially decreased the sediment yield in the Loess Plateau of China.

Grasslands can also reduce aeolian soil erosion by increasing aerodynamic roughness and increasing the threshold wind velocity. Soil loss during the wind erosion process can be estimated via wind tunnel experiments, filed observations, and modeling (Gong et al. 2014). Field observations (e.g. $^{137}$Cs concentration) and wind tunnel experimental data are important for the calibration and validation of models (Zobeck et al. 2000, 2003; Zhang et al. 2018a, b). Several wind erosion models, including Wind Erosion Equation (WEQ), Revised Wind Erosion Equation (RWEQ), and Wind Erosion Prediction System (WEPS), have been used for evaluating soil conservation services on landscape and broader scales (Hao et al. 2017a; Zhao et al. 2017; Zhang et al. 2018a, b; Chi et al. 2019). Yan et al. (2011) showed that when the semi-grassland vegetation cover became 75%, the ability of vegetation to intercept sand dust was 2.1 times that of non-vegetated surfaces. Zhao et al. (2017) found that vegetation cover of grasslands has nonlinear and threshold effects on wind erosion through constraining the maximum soil loss. Chi et al. (2019) found that the wind erosion modulus of dense grass was approximately only one-seventh of that of deserts, which was even lower than that of woodland.

### *Water regulation*

Water is a key limiting factor for biodiversity and ecosystem processes in grasslands. Grasslands are important for regulating local and regional water redistribution and water quality (MEA 2005). Grassland vegetation affects the temporal and spatial patterns of surface runoff, floods, and aquifer water recharge (Egoh et al. 2008; Fu et al. 2013). Water flow is a function of the storage and retention components of the water supply based on the water balance principle (Byrd et al. 2015; Zhang et al. 2016). Grassland ecosystems are not only an important complement to forest and wetland ecosystems on water regulation, but also have unique and irreplaceable key roles in the vast semi-arid/arid regions. Its ability to reduce surface runoff is 20% higher than that of farmlands and 50% higher than that of urban areas (Honigova et al. 2012). Saha and Kukal (2015) found that the maximum water holding capacity of 0–15 cm surface soil in grasslands (38.8%) is the highest, followed by that in forests (37.1%) and farmlands (20.7%) in the lower Himalayas in northwestern India. The mean flood mitigation values of grasslands in the Upper Yangtze River Basin was approximately 29.66 mm/a, which was about 1.88 times and 1/2.6 of the effect of rice fields and forests, respectively (Fu et al. 2013).

Grasslands regulate the water quality by controlling the generation of pollutants, reducing the amount and toxicity of pollutants, and changing the migration process of pollutants (Egoh et al. 2008; Macleod and Ferrier 2011). The water purification nutrient retention model in the InVEST model has often been used for assessing this service (Tallis et al. 2013). Lavorel et al. (2017) found that, in the European alpine grassland, the conversion of crops to mowing grasslands resulted in an increase in water quality regulation service, and grassland abandonment would also result in the service increase because of better filtering capacity of extensively abandoned sites.

### *Other regulating services*

Additional regulating services such as air quality regulation, biological invasion and pest outbreaks control, waste treatment, nutrients maintenance, and pollination promotion cannot be ignored. Grasslands can intercept pollutants and respirable particulate matters. Field surveys on leaf area index along with parameters such as pollutant concentration and deposition rate have been commonly used to assess the ecosystem functions for reducing pollutants. Chen et al. (2014) found that, in Tianjin, China, the dust emission from grasslands was less than 1%, while over 99% was contributed by croplands. The increase of grassland area as well as the improvements of patch density and edge density can reduce PM2.5 concentrations (Lu et al. 2018).

Resistance to invasive species is one way in which grassland ecosystems control pests and diseases. Species diversity in grassland ecosystems can control the reproduction of pest populations, thereby increasing grassland productivity (Honigova et al. 2012). Chytry et al. (2008) found that, in the Czech Republic, castration and grazing grasslands showed a lower invisibility of alien plant species than low-altitude habitats with high human distributions. The nutrients can be restored in grasslands by livestock grazing, during which process, the large amount of excrement scattered in the grassland is degraded under the combined effects of natural weathering, leaching, and microbial decomposition, and returning to the ecosystem. Grasslands are also important habitats for some wild pollinated species, such as scorpion flies, bumblebees, and wild bees (Hegland and Boeke 2006; Holland et al. 2017). Therefore, pollination services by many wild plants are unique to grasslands and cannot be performed by other ecosystems.

## Cultural services of grasslands

The importance of provisioning and regulating services is obvious because of their close relations with human survival. Cultural services are becoming increasingly prominent with the improvement of human material life and education level (Yahdjian et al. 2015). Cultural services of grasslands include horse riding, bird watching, aesthetic appreciation, and cultural heritage (Pogue et al. 2018). In recent years, eco-tourism in grasslands has developed rapidly, increasing the income and improving the local life. Grassland ecosystems also have important educational and scientific values because of their unique biodiversity and many rare plant, animal, and insect species (Honigova et al. 2012; Sala et al. 2017).

A healthy grassland ecosystem can maintain the biodiversity and inherit the national culture. The nomadic pastoral culture, which heavily relies on rotation grazing to avoid overgrazing, is the basis of the development of the grassland culture. Compared with the farming culture, nomadic pastoralism is conducive to conserving environments, and studies found that the conflict between them had affected land desertification and regional sustainable development (Zhang et al. 2007; Wu et al. 2015). However, although traditional nomadic pastoralism could meet the “sustainable livelihood” in the past, it cannot meet the sustainable development needs in areas where the population and herds exceed the grassland carrying capacity (such as grasslands in Inner Mongolia, China). Optimizing the spatial and temporal scale of livestock mobility is critical for alleviating the current environmental problems and making the region more sustainable (Wu et al. 2015).

The quantification of cultural services, especially at large spatial scales, is a challenge because of their non-consumptive nature and the subjectivity of the generation and acquisition (Schaich et al. 2010). Global platforms of geo-tagged photographs (e.g. Google Earth web platforms, Facebook, Twitter, Flickr, and Panoramio), together with statistical analysis (e.g. redundancy analysis, detrended correspondence analysis) are useful tools to obtain in-depth knowledge of cultural services (Martinez Pastur et al. 2016; Oteros-Rozas et al. 2018). Participatory surveys including interviews, questionnaires, and seminars are also important methods to obtain information on grassland aesthetics, recreation, tourism, cultural heritage, education, and scientific research from different stakeholders (Garrido et al. 2017). The grassland percentage, tourist number, and indices on recreation potential of grassland landscape were commonly defined quantitative indicators (Lamarque et al.

2011; Weyland and Laterra 2014). Layerstack analysis based on GIS and cluster analysis could be used to combine quantitative and qualitative data for quantifying cultural services (Lamarque et al. 2011; Martinez Pastur et al. 2016).

## Knowledge gaps and future research directions

At present, studies on GESs are fewer than those on forests and wetlands. Although existing studies have discussed the benefits from grassland ecosystems from various perspectives and obtained some interesting findings, several knowledge gaps and challenges exist.

### Knowledge gaps in GES research

### *Lack of in-depth ecological and socioeconomic understanding of GESs*

ES valuation methods do not capture all the benefits that humans derive from ecosystems. Grassland ecosystems have intrinsic values beyond market prices, which are usually not considered by monetization. Also, the monetization of ESs often ignores the spatial heterogeneity (e.g., diverse grassland types) and dynamics within grassland ecosystems. The uncertainties were also related to the social-economic development and individual willingness to pay for ESs. All these led to a weak comparability of the monetization assessment of natural capital in space and time. Therefore, the ESs do not have to be monetized, and direct measurement of ESs is more fundamental, important and urgent, and requires more in-depth research by ecologists and other scientists (Wu 2013; Silvertown 2015).

From an ecological perspective, understanding ES provision requires a focus on the interactions between biodiversity and ecosystem function. Biodiversity change is often accompanied with shifts in the functional composition of the vegetation and further alters numerous ecosystem functions and services (Lavorel and Grigulis 2012). Biodiversity-function-services relationships remain theoretically unclear and empirically challenging to quantify. Increasing evidence has shown that biodiversity enhances biomass production and stability (Cardinale et al. 2007, 2013; Orford et al. 2016; Ren et al. 2016; Isbell et al. 2017; Sanaei et al. 2018). However, the effects of biodiversity on GESs have been less studied. For pollination service as an example, Hegland and Boeke (2006) reported that blossom density was more important than species richness in explaining the number of flower visitors in plots. Winfree et al. (2015) found that the abundance of common species, not species richness, drove the delivery of pollination services. Species diversity in grasslands enhanced the production of fodder but had mixed effects or even contrary expectations on many other services (Cardinale et al. 2007, 2012). The biodiversity-function-services relationship in grasslands needs to be better understood.

There is also a need for better understanding GESs from socioeconomic perspectives (Kemp et al. 2013; Anadon et al. 2014; Lamarque et al. 2014). This could avoid mistakes caused by narrow assumptions about “natural” systems (Huntsinger and Oviedo 2014). Human reliance on GESs (e.g., water supply for irrigation for food and forage production) is closely related to the sustainability of livelihoods. Understanding the mechanisms of how GESs support livelihood and the services supply–demand interconnections can help sustainable land management (Reed et al. 2015; Wang et al. 2017a; Cui et al. 2019). Most attention has been devoted to the GES supply side, and the focus has been shifting to reconciling supply and demand (Yahdjian et al. 2015; Sala et al. 2017). However, how GESs promote the protection and management of grassland ecosystems, thereby improving human well-being, has not been well documented. The “operational” ecological knowledge for decision-making is still rare partly because of scale-mismatch between research and application, idiosyncrasies of grassland systems, and inadequacies of ES indicators.

### *Lack of multi-scale and scaling research*

GESs are often scale-dependent because the structure and function of grassland ecosystems, as well as human demands for ESs, vary with spatial and temporal scales (Wu and Li 2006a, b; Huntsinger and Oviedo 2014; Qiu et al. 2018). Long-term trends of ESs and their underlying processes are not likely to be revealed by short-term studies. The dynamics of and interactions among GESs differ across local, landscape, regional, and global scales. For example, Qiu et al. (2018) systematically examined the relationships among ESs across spatiotemporal scales in an urbanizing agricultural watershed in the United States, and found that the interactions among ESs (e.g., perennial grass production vs. crop production) could change markedly across different scales. However, most of the existing studies of GESs have focused on single scales, and the multi-scale examination of interactions among GESs is still lacking. Thus, conducting GES studies on multiple scales to identify the characteristic scales, and to understand cross-scale relations, of GESs is urgently needed. Insights from such studies are essential for decision making in sustainable grassland management.

Scaling across time and space is challenging but fundamentally important in ecological and sustainability research (Wu and Li 2006a). How do the intrinsic, observational, modeling/analysis, and policy scales of GESs differ from, and relate to, each other? How do GESs at different scales interact hierarchically? Are GESs on broad scales simply the total sums of small-scale GESs, or are there “emergent” GESs on broader scales? “Landscape services”, such as pest control and certain cultural services provided by a cluster of local ecosystems altogether, are “emergent” ESs at the regional landscape level (Wu 2013; Duarte et al. 2018). To translate the information on GESs across scales, the scaling relations of GESs need to be investigated, but such studies are currently lacking. With the rapid developments of ecological observation networks, remote sensing techniques, and process-based models during the past few decades, however, multi-scale and scaling studies of GESs now are both feasible and desirable.

### *Lack of comprehensive and mechanistic studies on GESs*

A better understanding of the driving forces and mechanisms of GES production and dynamics is needed for effective protection and sustainable utilization of grasslands. Limited by such factors as data acquisition and quantification methods, however, most mechanistic studies of GESs have focused primarily on a select group of provisioning services (e.g. livestock production, milk production) (Ferner et al. 2018) and regulating services (e.g. carbon sequestration, water regulation) (Eze et al. 2018). The spatiotemporal patterns and underlying mechanisms of other services provided by grasslands (e.g. soil erosion control, wool production, pest control, waste treatment, cultural heritage) still need more in-depth exploration. Taking the soil erosion control service as an example, the roles of wind, rainfall, soil texture, vegetation cover and landscape pattern are still unclear (Jiang et al. 2019). In addition, a number of factors can cause changes in GESs, such as climate change (Parton et al. 1995; Xia et al. 2014), land cover conversion from grasslands to farmlands (Wang et al. 2008), harvest regimens (Stahlheber et al. 2016; Conkling et al. 2017), and livestock grazing (Papanastasis et al. 2017; Li et al. 2019; Wang et al. 2019). How do grassland succession and human land use activities interactively affect grassland ecosystem processes and thus GESs? How do climate change and human activities together affect grassland ecosystem functions and GESs? Such questions deserve further investigation.

Exploring synergies and tradeoffs between GESs is essential for producing actionable knowledge for sustainable management of grassland ecosystems. The tradeoffs between GESs included tradeoffs across ESs (e.g. forage provisioning may affect erosion control or decrease the value of grassland for recreation), tradeoffs in space (e.g. the overgrazing of the upstream grasslands will increase the sediment in downstream areas), and tradeoffs in time (e.g., immediate increase of livestock provision may be at the expense of the same ESs or other services such as soil conservation in the future) (Rodriguez et al. 2006). In general, increasing fodder production of grassland ecosystems may lead to a reduction in regulating services such as water retention and carbon sequestration (Pan et al. 2014). Tradeoffs and synergies of GESs can be affected by land use intensity or grassland management (Favretto et al. 2016; Wu et al. 2017; Laura et al. 2018). Proper grazing management is a critical factor for complementarily maximizing ESs (Onatibia et al. 2015). However, current studies in this research area rely mainly on statistical methods (Hao et al. 2017b; Jiang et al. 2018), coincidence analysis (Egoh et al. 2008, 2009), and overlaying methods (Petz et al. 2014), lacking experiment-based mechanistic explorations. More research on scale effects, multi-factor interactions, and underlying mechanisms of GES tradeoffs and synergies is much needed.

## Future research directions

To address the research gaps, we propose a conceptual framework for advancing GES research by combining the Pressure-State-Response (PSR) sustainability assessment framework and a 3 M (multi-scale, multi-method, and multi-perspective) methodology (Fig. 6). Our framework also draws insights from existing ES frameworks (as reviewed in Fisher et al. 2013) and landscape sustainability science (Wu 2013). The PSR framework helps connect grassland conditions, ecosystem processes, and GESs with the drivers of their changes and societal responses. We argue that future GES research should focus on the tradeoffs and synergies of provisioning, regulating, and cultural services, supply–demand interactions, linkages among biodiversity, ecosystem function, ES, and human wellbeing, and independent and combined impacts of climate change and landscape dynamics. Such studies need to adopt the "3 M" methodology, and emphasize mechanistic approaches whenever feasible.

ESs are generated and utilized in landscapes in which people live, work, and interact, and thus a landscape-centered, multi-scale approach is essential for studying and managing GES in coupled human–environment systems (Wu 2013; Bastian et al. 2014; Duarte et al. 2018; Angelstam et al. 2019). As Wu (2013) has argued recently, regional landscapes represent the most operational scale domain for linking biodiversity, ecosystem function, and ES for achieving sustainability although other spatial scales (local to global) should also be considered. GES research also needs to be done using multiple methods, including different data acquisition means (e.g., remote sensing,

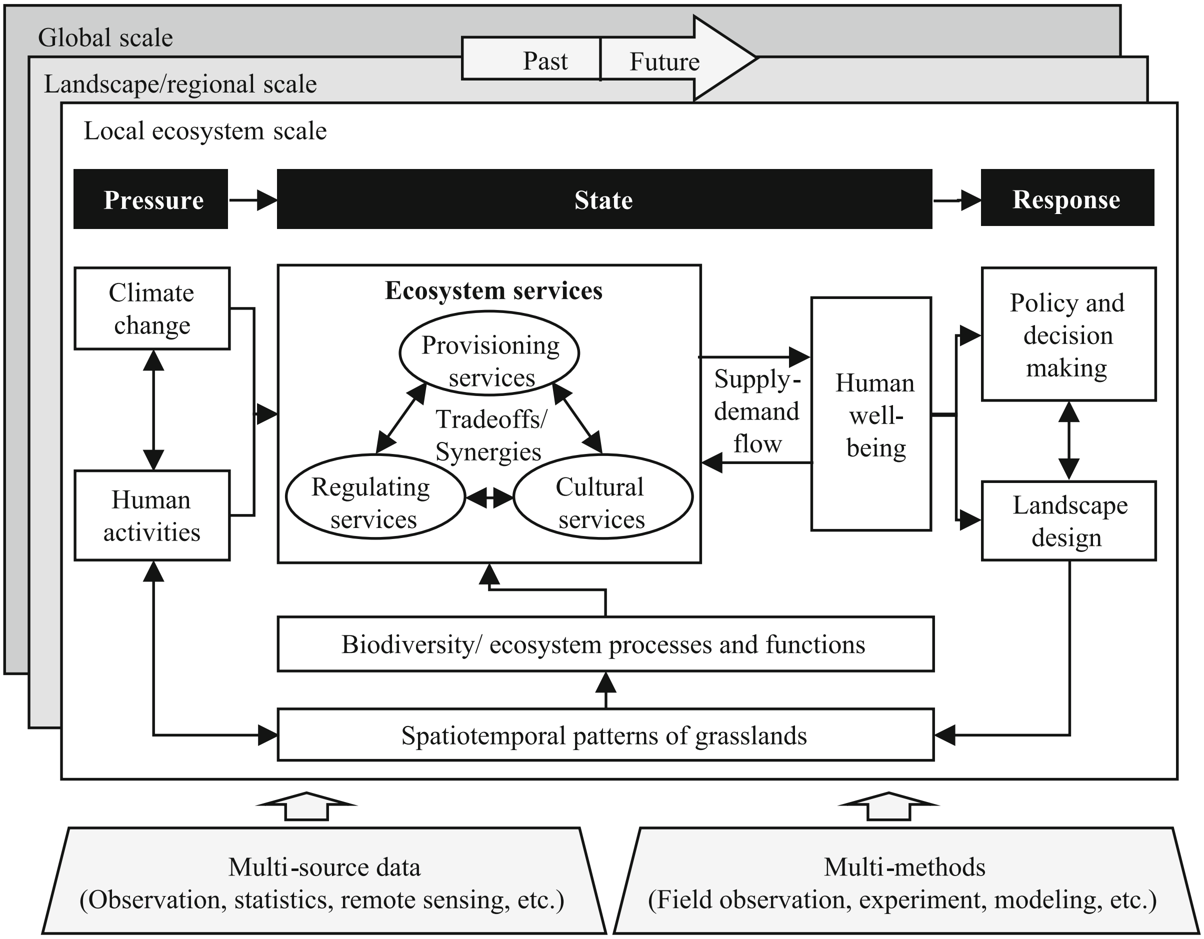

**Fig. 6** A conceptual framework for studying and improving grassland ecosystem services, which combines the Pressure-State-Response sustainability assessment framework with a multi-scale, multi-method, and multi-perspective (3M) methodology

field observations, and social surveys) as well as a variety of metrics/indicators and statistical/modeling techniques. In addition, GES must be understood and managed from multiple perspectives that together enhance, not compromise, the balance among the three pillars of sustainability—environmental integrity, economic development, and social equity.

## Conclusions

Based on a comprehensive review and synthesis of the existing studies, we have presented the state-of-the-science in GES research and discussed several future directions. Our review shows that grasslands, among the most widely distributed ecosystems in the world, provide diverse ESs essential for human populations within and beyond grassland regions. However, ES research has so far focused much more on forests, wetlands, and urban greenspaces than grasslands. Although there are already a number of GES studies, they tend to be sporadic in geographical locations and imbalanced in topical coverage. To move forward, we propose a research framework that links grassland ecosystem functions/services and human wellbeing/policy actions, with a multi-scale, multi-method, and multi-perspective methodology.

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