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REVIEW ARTICLE

Grassland Research

The economic value of grassland ecosystem services: A global meta-analysis

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Abstract

Background: Grasslands provide a wide variety of ecosystem services that contribute to human wellbeing. While an increasing number of studies are evaluating the monetary value of grassland ecosystem services, most of them focus on specific grassland ecosystem services at regional or local scales, and they use different assessment methods.

Methods: This paper provides a comprehensive assessment of the economic value of global grassland ecosystem services based on a meta-analysis of 702 observations from 134 primary studies.

Results: The economic values of different ecosystem services cover a wide range of grassland types, regions, and estimation methods. The annual economic value per hectare ranges from $3955 for semidesert grasslands to $5466 for tropical grasslands. On average, regulating services have the highest value, which is approximately four times that of provisioning services or approximately eight times that of food supply services. Several factors impact the estimated ecosystem service values, including the evaluation method, source and year of publication, and study site. The results indicate that the annual economic value of global grasslands exceeds $20.8 trillion.

Conclusions: The findings of this study not only provide useful information for understanding the economic value of various ecosystem services associated with different types of grasslands but also have important policy implications for the ecological conservation of grassland globally.

KEYWORDS

ecosystem services, economic value, grassland, screening criteria, systematic literature review

INTRODUCTION

Grasslands play an important role in global ecosystem service conservation. They provide a wide range of ecosystem services that contribute to the continued existence and well-being of humans (TEEB, 2010). These services include provisioning, regulating, habitat, and cultural services, ranging from direct uses (such as providing food and raw materials) to indirect uses (such as climate regulation), as well as intangible services, such as cultural services. However, most of these services are public goods with no market value and are often ignored in private land management decisions. That is, due to market failure, the benefit of many ecosystem services provided by grasslands cannot be reflected in market prices, hindering the optimal provision of grassland ecosystem services. It is crucial for grassland sustainability and human welfare to take the potential monetary value of grassland ecosystem services into consideration in the real world to ensure grassland sustainability and human welfare.

While existing studies on ecosystem service value assessment mainly focus on the forest, wetland, and cropland ecosystems, studies on grasslands in different countries are increasing. For instance, the study by Gashaw et al. (2018) explored the monetary value of each ecosystem service of tropical grassland in Ethiopia. Huang et al. (2019) conducted a case study in a typically ecologically fragile mountainous area of China to examine the effects of land-use changes on grassland ecosystem service value, primarily on regulating services. Christie and Rayment (2012) estimated the aggregated economic value of ecosystem services derived from an acidic grassland in England and Wales using a choice experiment method. In summary, most literature focuses on the economic value assessment of specific grassland ecosystem services at regional or local scales, thus failing to provide a complete picture at the global scale.

Meta-analysis is a well-established method for quantitatively analyzing large amounts of existing information to provide clear guidance and insights for land-use decision-making and policy formulation (Nelson & Kennedy, 2008). As the number of studies on grassland ecosystem valuation grows, policy and decision making can best be assisted by the synthesis and statistical analysis of the estimates reported in existing studies (Acharya et al., 2019; Folkersen et al., 2018). Meta-analysis can achieve synthesis well by integrating different ecosystem service values from various ecosystems and different valuation methods across countries or regions. The results based on a meta-analysis of grassland economic values can help us understand the current status of grassland ecosystem service value estimation and identify the major factors associated with the estimated values of various ecosystem services (Taye et al., 2021). In addition, statistical analysis using the meta-analytical approach also allows us to better understand the differences in economic value assessments and to visualize the inherent trade-offs in grasslands and land-use decisions. Such an analysis can help promote and design financial incentives, for example, the Grassland Ecological Compensation Policy (GECP) in China, which aims to enhance the provision of nonmarket ecosystem services for grasslands.

While a few meta-analytical studies of grassland ecosystem service value assessment have been performed at the regional or country scale, no studies have been conducted at the global level. For example, Huber and Finger (2020) undertook a meta-analysis focusing on the recreation service of grasslands with samples from European countries. B. Kang et al. (2020) reported meta-regression results on grassland ecosystem service values considering valuation methods based only on observations from Qinghai Province in China. The meta-analysis conducted by Ren et al. (2016) reported the monetary value changes of grassland biodiversity services before and after restoration in China. N. Kang et al. (2022) evaluated the economic value of various ecosystems in China by synthesizing a variety of influencing factors, including evaluation methods and types of ecosystem services, but excluded grassland types in their analysis.

This paper aims to evaluate the economic value of various ecosystem services in different types of grasslands globally based on primary studies through a meta-analysis. Specifically, we identify and further analyze the major factors affecting the economic values of grassland ecosystem services, evaluate the variations in ecosystem service values with respect to different grassland types, ecosystem services, and valuation methods, estimate the total economic value of ecosystem services across different grassland types globally, and provide insights for grassland management decisions and policy-making.

MATERIALS AND METHODS

Sampling and data

Following the standard protocols of meta-analysis proposed by Nelson and Kennedy (2008) and Moher et al. (2015), the database was set up in four steps (Figure 1). First, we established an original literature database. The relevant literature published before August 2020 was searched using the following query terms: ("grassland*" or "rangeland" or "prairie" or "meadow" or "steppe") AND ("valu*" or "economic cost" or "economic loss" or "monetary" or "benefit" or "estimat*" or "willingness to pay" or "WTP") AND ("eco* service*" or "eco* function" or "eco* goods" or "environmental service*" or "environmental function" or "environmental goods" or "natural capital"). The search process was conducted on the Web of Science, Scopus and Engineering Village databases. In addition, the reference list of each primary study was cross-checked and the relevant studies were incorporated into the database. Finally, a total of 2050 primary studies were yielded after removing duplicates and non-English language literature.

Second, the relevant studies were preliminarily screened by reading the title, abstract, and keywords and deciding whether the study was relevant to the economic value assessment of grassland ecosystem services. Then, these studies were further screened based on the following criteria by reading the full text: a primary study included in the data set must (1) have estimated the economic value for either one or multiple grassland ecosystem services, (2) provide sufficient information for value standardization, (3) have a clear valuation method, and (4) be written in English. For the above two stages of screening, all the primary studies were reviewed by one postdoctoral researcher and one PhD student on the team, and some conflicts were resolved by a third independent professor in the field. After screening, 134 studies were finally included in the initial database. A list of these 134 articles is provided in Supporting Information Appendix A. Third, the economic value of ecosystem services was extracted from primary studies together with other information. As individual studies sometimes reported multiple value estimates for different ecosystem services, 746 observations were finally obtained. The last step was to eliminate outliers based on the interquartile range method, resulting in a total of 702 observations in the final database.

Values extracted from the primary studies are reported in different currency forms and need to be organized in a standardized and contextually clear manner to aid in direct comparison and aggregation. First, the estimated values reported in other currencies were converted to US dollars using the purchasing power parity index provided by the World Bank (2022), following Barrio and Loureiro (2010), L. Brander et al. (2013), and Chaikumbung et al. (2016). Furthermore, since the research covered the years 1982 to 2020, the estimated values were converted to a constant price for 2017 using the USA consumer price index (Federal Reserve Bank of St. Louis, 2021).

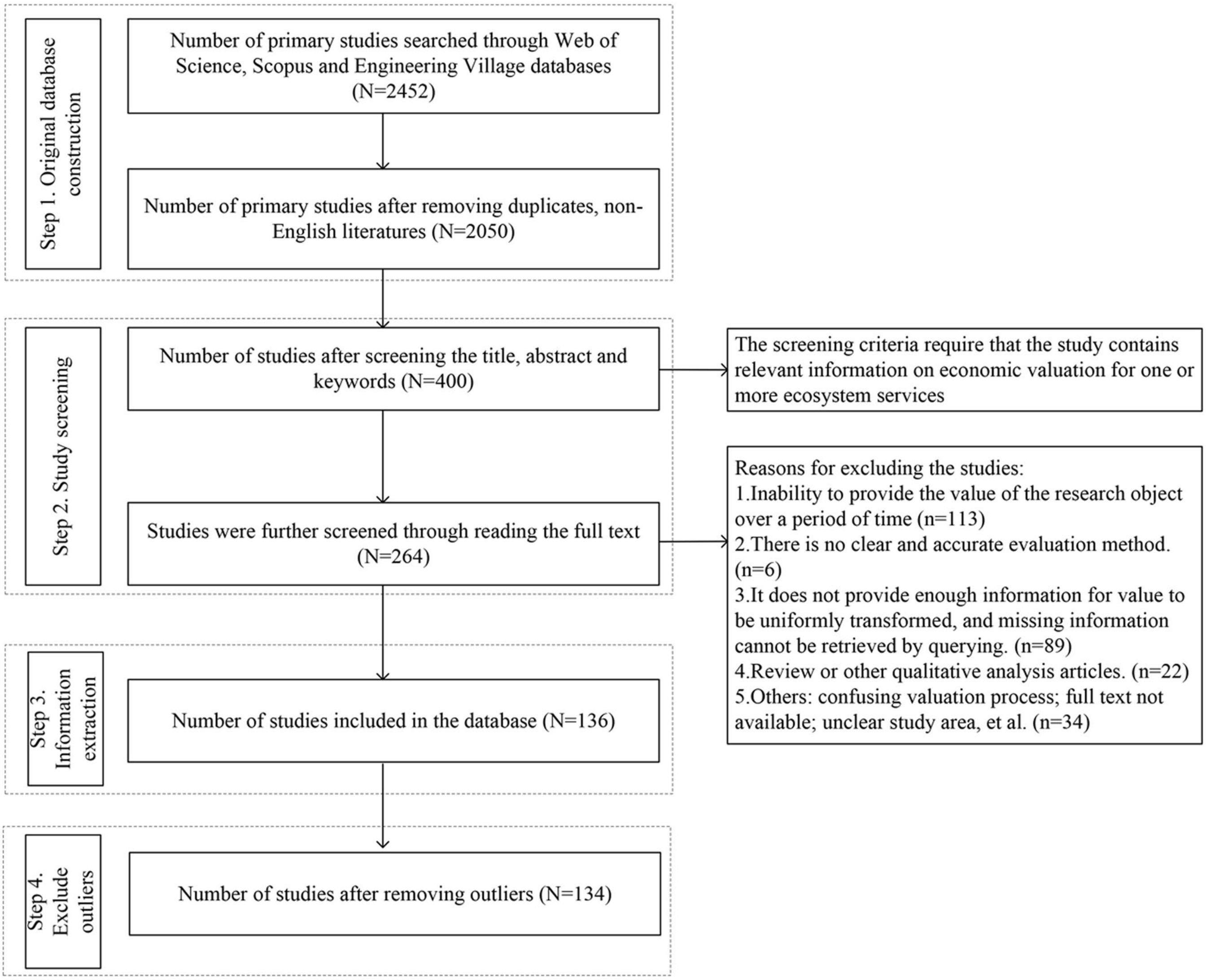

FIGURE 1 Flowchart for the construction of the global grassland ecosystem service value database.

Additional normalization was conducted for values reported at per individual or per household level. These values were converted into annual monetary units per hectare by summing the individual or household values assumed to benefit from ecosystem services, provided that this information was given in the primary study (Chiabai et al., 2011; Taye et al., 2021).

Explanatory variables

Following De Groot et al. (2012), N. Kang et al. (2022), and Quintas-Soriano et al. (2016), we focus on four types of factors that affect the economic values of grassland ecosystem services (Table 1): (1) grassland characteristics, (2) valuation methods for grassland ecosystem services, (3) research characteristics, and (4) study site characteristics.

Grassland features

Grassland features include the type of grassland, protection status, and type of ecosystem services. Grasslands are classified into five types (Table 1). Following the International Vegetation Classification (Faber-Langendoen et al., 2016) and Dixon et al. (2014), four different grassland types were classified, namely, tropical grasslands, Mediterranean grasslands, temperate grasslands, and semidesert grasslands. In addition, grassland types that were unspecified in the primary studies were categorized as "grasslands unspecified" (Table 1). Grassland conservation status was categorized by protection status as either "protected" or "unprotected." The grasslands identified as protected, that is, in areas especially dedicated to protecting and maintaining biodiversity and natural and related cultural resources, are managed through legal or other effective means. To determine the specific ecosystem service value, grassland ecosystem services were classified into 10 categories under four major types according to the definitions of Costanza et al. (1997), Millennium Ecosystem Assessment MEA (2005) and TEEB (2010). Specifically, the categories include three supply services (food supply, raw material supply and water supply); four regulating services (climate regulation, soil fertility maintenance, waste treatment, and water flow regulation); genetic diversity under habitat services; and recreation under cultural services. Ecosystem services with few

TABLE 1 Detailed variable descriptions

Variable name	Variable description	Obs.	Mean	Std.
Dependent variable				
Ecosystem value	The economic value of ecosystem services in US dollars per hectare at a constant price in 2017	702	487.6	566.8
Explanatory variables				
Grassland feature				
Type of grassland	Category dummy variable (1 = yes, 0 = no)			
	Tropical grasslands, including tropical grassland, tropical savanna, and tropical montane grassland	244	0.34	0.48
	Mediterranean grasslands, including Mediterranean scrub and grassland	43	0.06	0.24
	Temperate grasslands, including temperate grassland and boreal grassland and temperate boreal alpine grassland	266	0.38	0.49
	Semidesert grasslands, including warm semidesert grassland and cool semidesert grassland	124	0.18	0.38
	Unspecified grasslands, including all others unspecified in the primary studies	25	0.04	0.19
Protected grassland	Category dummy variable (1 = protected, 0 = unprotected)	81	0.12	0.32
Ecosystem services	Category dummy variable (1 = yes, 0 = no)			
	Food supply service	79	0.11	0.32
	Raw material service	68	0.10	0.30
	Water supply service	32	0.05	0.21
	Climate regulation service	99	0.14	0.35
	Soil fertility maintenance	92	0.13	0.34
	Waste treatment service	60	0.09	0.28
	Water flow regulation service	50	0.07	0.26
	Genetic diversity service	71	0.10	0.30
	Recreation service	110	0.16	0.36
	Other services	41	0.06	0.23
Valuation method	Category dummy variable (1 = yes, 0 = no)			
	Direct market method	67	0.10	0.29
	Avoided cost method	14	0.02	0.14
	Replacement cost method	42	0.06	0.24
	Travel cost method	11	0.02	0.12
	Stated preference method	52	0.07	0.26
	Benefit transfer method	516	0.74	0.44
Research characteristics				
Type of journal	Category dummy variable (1 = yes, 0 = no)			
SSCI	SSCI-listed journals only	77	0.11	0.31
SCI	SCI-listed journals only	415	0.59	0.49
SCI&SSCI	Both SCI- and SSCI-listed journals	126	0.18	0.38
Non-SCI/SSCI	Not in any SCI/SSCI-listed journal	84	0.12	0.32
Research year	The year when the research was conducted	702	2008.83	6.06
Study site characteristics				
GDP per capita	GDP per capita in US dollars at the constant price in 2017	702	15 762.53	15 025.53
Asia	Dummy (1 = if the study is in an Asian country; 0 = otherwise)	702	0.73	0.44

TABLE 1 (Continued)

Variable name	Variable description	Obs.	Mean	Std.
Longitude	Continuous, longitude of the study area	702	81.94	58.55
Latitude	Continuous, latitude of the study area	702	32.51	20.02

Abbreviations: GDP, gross domestic product; SCI, Science Citation Index; SSCI, Social Science Citation Index.

observations or not belonging to any of the above categories were classified as "other services" (Table 1). Detailed definitions of the ecosystem services are provided in Table A1.

Valuation method

The economic value of ecosystem services reported in primary studies was estimated using a wide range of valuation methods, including the direct market, avoided cost, replacement cost, travel cost, stated preference, and benefit transfer methods. The *valuation method* variable was directly extracted from the primary studies. These methods are also commonly applied for valuing ecosystem services. The direct market method is usually used for services that can be directly traded in the market, and the price is used to reflect the value of the ecosystem service (H. Liu et al., 2022). The avoided cost method uses either the value of property protected or the cost of actions taken to avoid damages as a measure of the benefits provided by an ecosystem or ecosystem service (TEEB, 2010). The replacement cost method is similar to the avoided cost method in that both are cost-based methods. The difference is that the replacement cost method considers the replacement cost of an ecosystem or its services as an estimate of the value of an ecosystem or its services (X. Liu, 2009). The travel cost method is normally used to estimate economic use values associated with ecosystems or sites that are used for recreation. The stated preference method is used to assess the economic value of various ecosystems and ecosystem services based on a hypothetical scenario (Huber & Finger, 2020). We categorized the choice experiment method and the contingent valuation method into the stated preference method. The benefit transfer method is a unit value-based method, and it evaluates economic values by transferring existing benefit estimates from completed studies to other sites or ecosystem services (TEEB, 2010).

Characteristics of the research and study sites

To determine the influence of the research characteristics, the journal type of the primary study and research year was incorporated into our analysis (Chaikumbung et al., 2016). The type of journal was classified into three categories based on the database in which the study was published, including SSCI, SCI, SSCI&SCI, and non-SCI/CSSCI. SSCI&SCI represents the studies published in both the SCI and SSCI-listed journals. *Research year* was based on the time when the primary study was conducted to capture possible changes in the value of ecosystem services over time. Three variables were used to capture the study site characteristics. First, the per-capita GDP of the country in which the study site is located (*GDP per capita*) was used to characterize the economic level (World Bank, 2022). Second, considering that there are more primary studies on Asia than on other regions, *Asia* was included as a variable to examine whether the ecosystem values obtained in Asia differ from those from the rest of the world after controlling for all variables included in the regression model. Finally, the *latitude* and *longitude* of the study area were incorporated into the model to explore the spatial distribution of grassland ecosystem service values.

Econometric model

Following L. M. Brander et al. (2012) and Bockarjova et al. (2020), the linear regression model can be specified as

$$Y = \beta + \sum_{j=1}^{J} \alpha_j X_j + e, \tag{1}$$

where Y is the annual economic value of ecosystem services in $\$\,\mathrm{ha}^{-1}$, X_j is a vector with four groups of explanatory variables presented in Table 1, j is the number of variables in each group, α are the estimated coefficients, and e is the normally distributed error term.

However, three problems are often encountered in meta-analysis: publication bias, multicollinearity, and heteroskedasticity. When a meta-analysis is conducted, publication bias can arise, that is, where statistically significant results are more likely to be published (Hirsch, 2018; Huber & Finger, 2020; Stanley, 2005). In this case, the square root of the sample size was added as a weight to the above model to check for publication bias (Chaikumbung et al., 2016; Stern, 2012), and the results showed that the observed estimates varied randomly around the "true" effect, that is, that there was no publication bias in our study selection (see Supporting Information Appendix B). The potential multicollinearity problem was also checked via the variance inflation factor (VIF), and the mean VIF for the four groups of variables was 2.30 (far less than 10), implying that multicollinearity was not an issue. Furthermore, the White test was used to check for heteroskedasticity. Following Quintas-Soriano et al. (2016), Barrio and Loureiro (2010), and L. M. Brander et al. (2006), Huber–White robust standard errors were used in Equation (1) to address heteroskedasticity.

Using the data on grassland ecosystem service values from empirical studies, the relationships between the ecosystem service values and various groups of explanatory variables are discussed below. In addition, based on the estimated coefficients of different ecosystem services, their economic values were predicted when the other variables were measured as means. All statistical analyses were conducted using Stata 16.0 (StataCorp). The map of the sampling sites was plotted with ESRI ArcGIS 10.3 (ESRI).

RESULTS

Statistical description

As shown in Figure 2, our data set covers 702 value observations from 134 primary studies after retrieval, screening, information extraction, and value standardization. The annual number of publications increases slowly between 1982 and 2009 and more rapidly from 2010 onward. This indicates that more attention has been paid to the economic valuation of grassland. Approximately 86% (115 primary studies) of the primary studies were obtained from peer-reviewed journals, with the remaining from conference papers and government and nongovernment reports.

Judging from the spatial distribution, the samples cover many regions, although the number of studies varies among the regions or countries. The samples included primary studies from all continents of the world. At the regional level, approximately half of the primary studies are from Asia ($n = 67$), although the grassland area in Asia accounts for only 21% of the global grassland area. Relatively few studies have been conducted in North America, Africa, and Oceania, accounting for 14%, 8%, and 4%, respectively. This indicates that more attention should be given to the less evaluated area, especially in Africa and Oceania. At the country level, our data cover 34 countries, among which China and the United States have the largest number of primary studies.

The data covers all five major types of grasslands, although the number of observations varies between different types (Table 2). However, it is also noted that a specific type of grassland with only a few observations should be considered with caution when interpreting the results. Among all grasslands, temperate grasslands represent the largest share of observations ($n = 266$), followed by tropical grasslands ($n = 244$) and semidesert grasslands ($n = 124$). Mediterranean grassland is the least represented grassland type. This study distribution by country is consistent with the area distribution, which indicates relatively balanced study distributions across countries.

On the type of ecosystem services, this study covers all types of ecosystem services, and the number of observations is reasonable for each ecosystem (the last column of Table 2), except for water supply (32 observations). The number of observations for recreation services is the largest (110 observations). The "climate regulation" and "soil fertility maintenance" under regulation services are the next most represented, with 99 and 92 observations, respectively.

Of all the valuation methods, the benefit transfer method is the most commonly used, accounting for over 74% (516/702) of the total observations (Table 3). The ecosystem service values based on the direct market method and the stated preference method account for approximately 10% and 7% of the total, respectively. In contrast, the value estimated by the revealed preference method is small, with travel costs accounting for less than 2%.

The choice of valuation methods depends on specific ecosystem services when assessing the economic value. The benefit transfer method can evaluate the value of various ecosystem services because of its secondary transfer characteristics, while other methods are usually

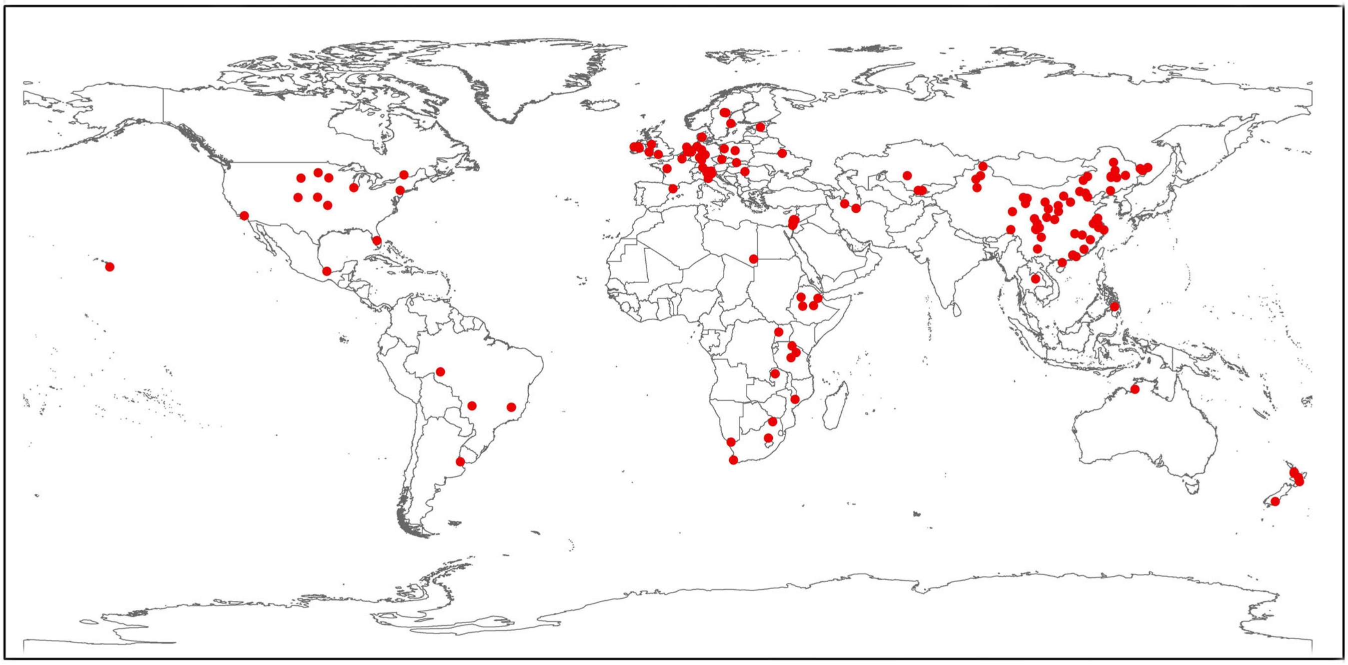

FIGURE 2 Global distribution of the observations

TABLE 2 The number of observations across different grassland types and ecosystem services.

Ecosystem service	Grassland types: Tropical grasslands	Mediterranean grasslands	Temperate grasslands	Semidesert grassland	Grasslands [unspecified]	Total
Food supply	30	3	27	16	3	79
Raw materials	23	5	24	14	2	68
Water supply	13	0	10	7	2	32
Climate regulation	37	3	37	16	6	99
Soil fertility maintenance	33	6	32	17	4	92
Waste treatment	22	1	21	13	3	60
Water flow regulation	15	5	21	8	1	50
Genetic diversity	27	4	25	13	2	71
Recreation	32	5	56	15	2	110
Other services	12	11	13	5	0	41
Total	244	43	266	124	25	702

Source: Based on the data used for meta-analysis in this study.

TABLE 3 Number of observations across different ecosystem services and valuation methods

Ecosystem service	Valuation methods: DMP	AC	RC	TCM	SPM	BTM	Total
Food supply	13	4	0	0	2	60	79
Raw materials	9	0	3	0	0	56	68
Water supply	2	1	1	0	0	28	32
Climate regulation	23	1	2	0	5	68	99
Soil fertility maintenance	6	3	10	0	0	73	92
Waste treatment	1	1	5	0	0	53	60
Water flow regulation	2	4	5	0	2	37	50
Genetic diversity	0	0	6	0	8	57	71
Recreation	2	0	4	11	32	61	110
Other services	9	0	6	0	3	23	41
Total	67	14	42	11	52	516	702

Abbreviations: AC, avoided cost method; BTM, benefit transfer method; DMP, direct market method; RC, replacement cost method; SPM, stated preference method; TCM, travel cost method.

applied to assess specific types of ecosystem services. For example, the direct market method is mainly used to estimate the values of raw materials and food supply services, and the stated preference method is mainly used to estimate the economic value of recreation services.

Meta-analysis

Table 4 shows the results of the meta-analysis based on Huber–White robust standard errors. As the results show, many variables are significant at the 5% or 1% level. Model estimation was conducted using 702 observations, with an R^2 value of 0.33. For all dummy variables, the coefficient of variable in the model is interpreted as the difference in ecosystem service value in $\$\,ha^{-1}\,year^{-1}$ between the variable and the base category. For continuous variables such as gross domestic product (GDP) per capita, the estimated coefficient is the marginal value of ecosystem services.

Grassland characteristics

The results show that the economic value of ecosystem services is the highest for the tropical grasslands (Table 4). The estimated coefficients imply that the annual economic values of temperate grasslands and semidesert grasslands are significantly lower than that of tropical grasslands by $\$121.1\,ha^{-1}$ and $\$151.0\,ha^{-1}$, respectively. The results also show that while the estimated value of ecosystem services is lower ($\$\,-86.4\,ha^{-1}$) in Mediterranean grasslands than in tropical grasslands, the difference is not significant.

The high economic value of tropical grasslands may be attributed to their developed animal husbandry and the innate geographical conditions of sufficient water and heat. Tropical grasslands typically include tropical montane shrubland, grassland and savanna, which are mainly distributed in Africa, Brazil, the northern and eastern parts of Australia and southern China, among other regions. These grasslands provide diverse ecosystem services with multiple regulating, provisioning and cultural services, which contributes to their higher ecosystem service value (Boval et al., 2017). Previous studies on grassland economic value or that employed meta-analysis focused more on ecosystem services, without paying much attention to different grassland types (Huber & Finger, 2020; B. Kang et al., 2020).

The regression results show that the economic value varies greatly among different ecosystem services.

TABLE 4 Regression results of grassland ecosystem service values (\$ ha^{-1} $year^{-1}$) based on meta-analysis

Variables	Coef.	SE	*p* value
Grassland characteristics			
Grassland types (baseline = Tropical grasslands)			
Mediterranean grasslands	−86.4	94.8	0.363
Temperate grasslands	−121.1**	58.8	0.040
Semidesert grasslands	−151.0***	51.6	0.004
Grasslands (unspecified)	−102.9	71.8	0.152
Protected grassland	66.5	65.4	0.310
Ecosystem services (baseline = food supply)			
Raw materials	−229.4***	58.5	0.000
Water supply	20.3	70.9	0.774
Climate regulation	595.4***	101.9	0.000
Soil fertility maintenance	401.7***	74.2	0.000
Waste treatment	163.8**	65.3	0.012
Water flow regulation	106.7	65.8	0.106
Genetic diversity	343.9***	74.2	0.000
Recreation	−73.4	59.7	0.219
Other services	112.7	94.1	0.231
Valuation method (baseline = direct market method)			
Avoided cost method	−290.2***	101.1	0.004
Replacement cost method	301.4**	136.4	0.028
Travel cost method	4.4	120.7	0.971
Stated preference method	−62.2	112.1	0.579
Benefit transfer method	−193.1*	106.6	0.071
Research characteristics			
Publication types (baseline = SSCI)			
SCI	−233.8***	63.8	0.000
SCI&SSCI	−263.7***	74.2	0.000
Non-SCI/SSCI	−143.2*	81.0	0.077
Year of research	−3.8	3.6	0.294
Study site characteristics			
GDP per capita	−0.0	0.0	0.889
Latitude	5.2***	1.7	0.002
Longitude	2.2***	0.6	0.001
Asian studies	178.4*	95.4	0.062
Constant	7904.2	7299.5	0.279
Observations	702		
VIF	2.30		
R^2	0.328		

Abbreviations: Coef., coefficient; GDP, gross domestic product; SCI, Science Citation Index; SE, Standard Error; SSCI, Social Science Citation Index; VIF, variance inflation factor.

*$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

Compared to that of food supply, the economic values of climate regulation, soil fertility maintenance, waste treatment, and genetic diversity are significantly higher. The economic value of climate regulation ranks highest, with an annual value of \$595.4 ha^{-1} (Table 4) higher than that of food supply, followed by soil fertility maintenance (\$401.7 ha^{-1}), genetic diversity (\$343.9 ha^{-1}), and waste treatment (\$163.8 ha^{-1}). The raw material service of grasslands has the lowest estimated annual value among all the ecosystem services and is lower than that of the food supply by \$229.4 ha^{-1} (Table 4).

Valuation method

The valuation methods used to estimate values of ecosystem services significantly affect the results. The annual ecosystem service value estimated with the replacement cost method is significantly higher than that estimated with the direct market method (the baseline category) by \$301.4 ha^{-1} (Table 4). Conversely, the annual values estimated using the avoided cost method and benefit transfer method have values of \$290.2 ha^{-1} and \$193.1 ha^{-1}, respectively, lower than the values estimated using the direct market method.

The evaluation method is an important factor affecting the economic value of grassland. We found a significant difference between the cost-based and direct market methods, with the replacement cost method being associated with higher estimated values than the direct market method and the avoided cost method giving lower estimated values. Consistent with previous studies (Grammatikopoulou & Vačkářová, 2021; Taye et al., 2021), no significantly higher value estimates were found when using the direct market method versus the travel cost or stated preference methods that are based on hypothetical transactions. Furthermore, the results indicated that estimates based on benefit transfer are lower than those based on the direct market, which may be due to the secondary transfer of this valuation method, as found in previous studies (N. Kang et al., 2022; Zhou et al., 2020). This indicates that the valuation methods should be applied with caution, for example, benefit transfer usage guidelines should be strictly followed to minimize transfer errors, as potential errors of the chosen method may obscure estimated values of ecosystem services (Johnston & Rosenberger, 2010; Schild et al., 2018). Collectively, these findings suggest that it is important to consider the impact of different valuation methods on ecosystem service value estimates.

Characteristics of the research and the study site

The estimated economic values of grassland ecosystem services also vary among the types of journals that publish the primary papers. The estimated coefficients show that the papers published in SSCI (Social Science Citation Index) listed journals (the baseline category) have higher estimates of annual ecosystem service value by \$233.8 ha^{-1}, \$263.7 ha^{-1}, and \$143.2 ha^{-1} compared to the SCI, SCI&SSCI, and non-SCI/SSCI sources, respectively (Table 4). These results are consistent with the recent findings by N. Kang et al. (2022). This may be related to the fact that studies published in SSCI journals are more likely to be conducted by economists who tend to estimate grassland values in more dimensions.

Our results also reveal the impact of the geographic features of the study site on the value of grassland ecosystem services. The estimated coefficient of the Asian dummy variable is significant and positive, implying that studies of grasslands in Asia yield higher annual values (\$178.4 ha^{-1}) than the value estimated for other continents after controlling for the effects of all other factors. This result is consistent with those of previous studies, such as that of Taye et al. (2021), who conducted a meta-analysis on the economic values of global forest ecosystem services. The regression coefficients of latitude and longitude illustrate the spatial variation trend of grassland values. This trend shows that for a one-degree increase in latitude and longitude, the estimated annual value of ecosystem services increases by \$5.2 ha^{-1} and \$2.2 ha^{-1}, respectively.

The economic values by types of grasslands and ecosystem services

The economic values by types of grasslands and ecosystem services are estimated based on the estimated coefficients presented in Table 4 and the sample means of the variables used as baselines for comparisons. In addition, with global areas of different types of grasslands, we also estimate total global values of ecosystem services by type of grassland. The estimated results are presented in Table 5.

While each number, its meaning and its comparison with other numbers in Table 5 are obvious, it is worth mentioning a few points here. The annual economic value per hectare of grassland ranges from \$3955 in semidesert grasslands to approximately \$5466 ha^{-1} in tropical grasslands (Table 5). The regulating services are the most valuable (Table 5) among all types of grasslands, which sums to \$2877 $\text{ha}^{-1}\,\text{year}^{-1}$, accounting for 53% of the total monetary value of tropical grasslands (Table 5). On average, for all grassland ecosystems, the economic value of regulating services is approximately four times that of provisioning services or approximately eight times that of food supply services. Globally, the annual economic value of grassland ecosystem services ranges from \$0.73 trillion for

TABLE 5 Predicted values by type of ecosystem service for different grassland types

Ecosystem services	Type of grassland (\$ $\text{ha}^{-1}\,\text{year}^{-1}$) Tropical grasslands	Mediterranean grasslands	Temperate grasslands	Semidesert grasslands	Grasslands (unspecified)
Provisioning services					
Food supply	402.4	316.0	281.3	251.4	299.5
Raw materials	173.0	(86.6)	(51.9)	(22.0)	(70.0)
Water supply	422.7	336.3	301.6	271.7	319.8
Regulating services					
Climate regulation	997.8	911.4	876.7	846.7	894.8
Soil fertility maintenance	804.1	717.7	683.0	653.0	701.1
Waste treatment	566.2	479.8	445.1	415.2	463.3
Water flow regulation	509.1	422.7	388.0	358.0	406.1
Habitat services					
Genetic diversity	746.3	659.9	625.2	595.3	643.4
Cultural services					
Recreation	329.0	242.6	207.9	178.0	226.1
Other services	515.1	428.7	394.0	364.1	412.2
Total value	5465.7	4601.7	4254.7	3955.4	4436.2
			Million ha		
Grassland area	1662.2	159.5	894.3	869.2	837.0
			\$ Trillion year^{-1}		
Total global value	9.08	0.73	3.80	3.44	3.71

Note: Estimated values in brackets are not statistically significant.

Mediterranean grasslands to more than $9 trillion for tropical grasslands (Table 5).

DISCUSSION AND CONCLUSION

This study estimated the economic values of major grassland ecosystem services for global grasslands using a meta-analysis based on the most updated literature. Our study reveals that the major factors associated with grassland ecosystem service values include grassland characteristics such as types of grasslands and ecosystem services, valuation methods, and the features of the research and study site. Based on the estimated results from the meta-analysis, we generate a matrix of the economic values of grasslands by type of grassland and type of ecosystem service. We also estimated the total economic values of global grasslands using a back-of-the-envelope calculation.

Several main findings from the meta-analysis are summarized here. First, the ecosystem service value of grasslands is high, and its annual economic value per hectare ranges from approximately $4000 to nearly $5500 for different types of grasslands. Second, regulating services are the most valuable among all ecosystem services. This finding clearly demonstrates that the value of regulating ecosystem services without a market price has been largely discounted in the real world (N. Kang et al., 2022; Manlike et al., 2020). In the real world, many ecosystem services remain undervalued or ignored in decision making due to market failure. Therefore, the trade-off and synergies of grassland ecosystem services should be fully considered for better decision making in relation to grassland conservation and land use (Bengtsson et al., 2019; Pan et al., 2014; Wu et al., 2017). Third, the methods used to estimate ecosystem service values matter. The replacement cost method often tends to provide much higher estimates, followed by direct market valuation and travel cost methods. However, avoided cost and benefit transfer methods tend to provide lower estimate values. Further study is needed to examine the appropriate method(s) for more accurate ecosystem service values. Fourth, estimated values may differ among researchers from different disciplines. For example, the papers published in SSCI-listed journals with more authors who are social scientists often report higher values of ecosystem services than the papers published in SCI-listed journals with more authors who are natural scientists. These findings provide useful insights into the multiple economic values of ecosystem services globally and the factors contributing to the differences in such estimates as reported in the current valuation literature.

Most importantly, the estimated total annual value of grasslands worldwide is $20.8 trillion, which exceed 17% of the global GDP in 2017. Unlike previous studies, our study illustrates the total annual value of different types of grasslands globally by multiplying the grassland area of each type by the unit values. The annual value per hectare of the tropical grasslands is $5466, which is almost equivalent to that of the cropland system estimated by Costanza et al. (2014). This demonstrates the huge ecological value potential of grassland ecosystems, which are often ignored in land-use decisions.

Another important thing to note is that regulating services that have no market values are often neglected in land-use decision making and need more conservation efforts (Taye et al., 2021). On average, the economic value of regulating services is approximately four times that of provisioning services or approximately eight times that of food supply services. Capturing the value of food production, however, could lead to a decline in the economic value of other ecosystem services (Jiang et al., 2020). Failing to balance regulating services and food supply could lead to the continued degradation of grasslands. Thus, enhancing conservation by combining protection policy with the monetary value of regulating services might be a means with which to address this issue, such as increasing the amounts of subsidies for GECPs and designing better grassland conservation strategies for local communities. Our analysis of grassland economic values can help identify policy interventions in grassland conservation efforts by providing information on the relevant determinants.

Although encouraging results are provided in this study, the paper also has some limitations. First, the primary studies report grassland value estimates at different scales, from small patches to national or even continental grasslands, and the standardization of the value observations by similar formulas might not account for all relevant spatial attributes. Second, the meta-regression analysis provides only a general assessment of the factors influencing grassland ecosystem services in monetary units, including primary study characteristics and national-level variables, without considering local contexts properly at a more micro- or site-specific scale. Furthermore, comparisons of economic values based on different valuation methods are challenging, as all of these methods may be reasonable and self-consistent in theory.

To sum up, by conveying information about differences in economic value associated with different characteristics, these findings help to assess the economic value of grassland ecosystem services globally, further informing grassland management decisions (Grammatikopoulou & Vačkářová, 2021). Furthermore, they enable better assessment of the services provided by different types of grasslands, which has important implications for sustainable ecosystem management.

AUTHOR CONTRIBUTIONS

Huifang Liu: Methodology; data curation; writing—original draft; writing—review and editing. **Lingling Hou**: Conceptualization; methodology; writing—review and editing. **Nannan Kang**: Data curation; writing—review and editing. **Zhibiao Nan**: Conceptualization; supervision; project administration. **Jikun Huang**: Conceptualization; methodology; data curation; writing—review and editing; supervision; funding acquisition; project administration.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

Acharya, R. P., Maraseni, T., & Cockfield, G. (2019). Global trend of forest ecosystem services valuation–An analysis of publications. *Ecosystem Services*, *39*, 100979. https://doi.org/10.1016/j.ecoser.2019.100979

Barrio, M., & Loureiro, M. L. (2010). A meta-analysis of contingent valuation forest studies. *Ecological Economics*, *69*(5), 1023–1030. https://doi.org/10.1016/j.ecolecon.2009.11.016

Bengtsson, J., Bullock, J. M., Egoh, B., Everson, C., Everson, T., O'Connor, T., & Lindborg, R. (2019). Grasslands—More important for ecosystem services than you might think. *Ecosphere*, *10*(2), e02582. https://doi.org/10.1002/ecs2.2582

Bockarjova, M., Botzen, W. J. W., & Koetse, M. J. (2020). Economic valuation of green and blue nature in cities: A meta-analysis. *Ecological Economics*, *169*, 106480. https://doi.org/10.1016/j.ecolecon.2019.106480

Boval, M., Angeon, V., & Rudel, T. (2017). Tropical grasslands: A pivotal place for a more multi-functional agriculture. *Ambio*, *46*(1), 48–56. https://doi.org/10.1007/s13280-016-0806-5

Brander, L., Brouwer, R., & Wagtendonk, A. (2013). Economic valuation of regulating services provided by wetlands in agricultural landscapes: A meta-analysis. *Ecological Engineering*, *56*, 89–96. https://doi.org/10.1016/j.ecoleng.2012.12.104

Brander, L. M., Florax, R. J., & Vermaat, J. E. (2006). The empirics of wetland valuation: A comprehensive summary and a meta-analysis of the literature. *Environmental and Resource Economics*, *33*(2), 223–250. https://doi.org/10.1007/s10640-005-3104-4

Brander, L. M., Wagtendonk, A. J., Hussain, S. S., McVittie, A., Verburg, P. H., de Groot, R. S., & van der Ploeg, S. (2012). Ecosystem service values for mangroves in Southeast Asia: A meta-analysis and value transfer application. *Ecosystem Services*, *1*(1), 62–69. https://doi.org/10.1016/j.ecoser.2012.06.003

Chaikumbung, M., Doucouliagos, H., & Scarborough, H. (2016). The economic value of wetlands in developing countries: A meta-regression analysis. *Ecological Economics*, *124*, 164–174. https://doi.org/10.1016/j.ecolecon.2016.01.022

Chiabai, A., Travisi, C. M., Markandya, A., Ding, H., & Nunes, P. A. L. D. (2011). Economic assessment of forest ecosystem services losses: Cost of policy inaction. *Environmental and Resource Economics*, *50*(3), 405–445. https://doi.org/10.1007/s10640-011-9478-6

Christie, M., & Rayment, M. (2012). An economic assessment of the ecosystem service benefits derived from the SSSI biodiversity conservation policy in England and Wales. *Ecosystem Services*, *1*(1), 70–84. https://doi.org/10.1016/j.ecoser.2012.07.004

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., & Paruelo, J. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*(6630), 253–260. https://doi.org/10.1038/387253a0

Costanza, R., De Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S. J., Kubiszewski, I., & Turner, R. K. (2014). Changes in the global value of ecosystem services. *Global Environmental Change*, *26*, 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002

De Groot, R., Brander, L., Van Der Ploeg, S., Costanza, R., Bernard, F., Braat, L., & Hein, L. (2012). Global estimates of the value of ecosystems and their services in monetary units. *Ecosystem Services*, *1*(1), 50–61. https://doi.org/10.1016/j.ecoser.2012.07.005

Dixon, A. P., Faber-Langendoen, D., Josse, C., Morrison, J., & Loucks, C. J. (2014). Distribution mapping of world grassland types. *Journal of Biogeography*, *41*(11), 2003–2019. https://doi.org/10.1111/jbi.12381

Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Josse, C. W., A., Tart, D., Navarro, G., & Helmer, E. (2016). *Classification and description of world formation types* (Gen. Tech. Rep. RMRS-GTR-346, 222pp). US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Federal Reserve Bank of St. Louis. (2021). *Federal reserve economic data*. Retrieved November 12, 2021, from https://fred.stlouisfed.org/series/CPIAUCSL

Folkersen, M. V., Fleming, C. M., & Hasan, S. (2018). The economic value of the deep sea: A systematic review and meta-analysis. *Marine Policy*, *94*, 71–80. https://doi.org/10.1016/j.marpol.2018.05.003

Gashaw, T., Tulu, T., Argaw, M., Worqlul, A. W., Tolessa, T., & Kindu, M. (2018). Estimating the impacts of land use/land cover changes on Ecosystem Service Values: The case of the Andassa watershed in the Upper Blue Nile basin of Ethiopia. *Ecosystem Services*, *31*, 219–228. https://doi.org/10.1016/j.ecoser.2018.05.001

Grammatikopoulou, I., & Vačkářová, D. (2021). The value of forest ecosystem services: A meta-analysis at the European scale and application to national ecosystem accounting. *Ecosystem Services*, *48*, 101262. https://doi.org/10.1016/j.ecoser.2021.101262

Hirsch, S. (2018). Successful in the long run: A meta-regression analysis of persistent firm profits. *Journal of Economic Surveys*, *32*(1), 23–49. https://doi.org/10.1111/joes.12188

Huang, A., Xu, Y., Sun, P., Zhou, G., Liu, C., Lu, L., & Wang, H. (2019). Land use/land cover changes and its impact on ecosystem services in ecologically fragile zone: A case study of Zhangjiakou City, Hebei Province, China. *Ecological Indicators*, *104*, 604–614. https://doi.org/10.1016/j.ecolind.2019.05.027

Huber, R., & Finger, R. (2020). A meta-analysis of the willingness to pay for cultural services from grasslands in Europe. *Journal of Agricultural Economics*, *71*(2), 357–383. https://doi.org/10.1111/1477-9552.12361

Jiang, W., Lü, Y., Liu, Y., & Gao, W. (2020). Ecosystem service value of the Qinghai–Tibet Plateau significantly increased during 25 years. *Ecosystem Services*, *44*, 101146. https://doi.org/10.1016/j.ecoser.2020.101146

Johnston, R. J., & Rosenberger, R. S. (2010). Methods, trends and controversies in contemporary benefit transfer. *Journal of Economic Surveys*, *24*(3), 479–510. https://doi.org/10.1111/j.1467-6419.2009.00592.x

Kang, B., Shao, Q., Xu, H., Jiang, F., Wei, X., & Shao, X. (2020). Research on grassland ecosystem service value in China under climate change based on meta-analysis: A case study of Qinghai province. *International Journal of Climate Change Strategies and Management*, *12*(5), 617–637. https://doi.org/10.1108/IJCCSM-06-2020-0073

Kang, N., Hou, L., Huang, J., & Liu, H. (2022). Ecosystem services valuation in China: A meta-analysis. *Science of the Total Environment*, *809*, 151122. https://doi.org/10.1016/j.scitotenv.2021.151122

Liu, H., Hou, L., Kang, N., Nan, Z., & Huang, J. (2022). A meta-regression analysis of the economic value of grassland ecosystem services in China. *Ecological Indicators*, *138*, 108793. https://doi.org/10.1016/j.ecolind.2022.108793

Liu, X. (2009). *Study on methods in the valuation of ecosystem services—Taking Qixinghe wetland in Heilongjiang Province as example*. China Agriculture Press.

Manlike, A., Sawut, R., Zheng, F., Li, X., & Abudukelimu, R. (2020). Monitoring and analysing grassland ecosystem service values in response to grassland area changes—An example from northwest China. *The Rangeland Journal*, *42*(3), 179–194. https://doi.org/10.1071/RJ20014

Millennium Ecosystem Assessment (MEA). (2005). *Ecosystems and human well-being: Synthesis*. Island Press.

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., & Group, P. -P. (2015). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Systematic Reviews*, *4*(1), 1. https://doi.org/10.1186/2046-4053-4-1

Nelson, J. P., & Kennedy, P. E. (2008). The use (and abuse) of meta-analysis in environmental and natural resource economics: An assessment. *Environmental and Resource Economics*, *42*(3), 345–377. https://doi.org/10.1007/s10640-008-9253-5

Pan, Y., Wu, J., & Xu, Z. (2014). Analysis of the tradeoffs between provisioning and regulating services from the perspective of varied share of net primary production in an alpine grassland ecosystem. *Ecological Complexity*, *17*, 79–86. https://doi.org/10.1016/j.ecocom.2013.11.001

Quintas-Soriano, C., Martín-López, B., Santos-Martín, F., Loureiro, M., Montes, C., Benayas, J., & García-Llorente, M. (2016). Ecosystem services values in Spain: A meta-analysis. *Environmental Science & Policy*, *55*, 186–195. https://doi.org/10.1016/j.envsci.2015.10.001

Ren, Y., Lü, Y., & Fu, B. (2016). Quantifying the impacts of grassland restoration on biodiversity and ecosystem services in China: A meta-analysis. *Ecological Engineering*, *95*, 542–550. https://doi.org/10.1016/j.ecoleng.2016.06.082

Schild, J. E., Vermaat, J. E., de Groot, R. S., Quatrini, S., & van Bodegom, P. M. (2018). A global meta-analysis on the monetary valuation of dryland ecosystem services: The role of socio-economic, environmental and methodological indicators. *Ecosystem Services*, *32*, 78–89. https://doi.org/10.1016/j.ecoser.2018.06.004

Stanley, T. D. (2005). Beyond publication bias. *Journal of Economic Surveys*, *19*(3), 309–345. https://doi.org/10.1111/j.0950-0804.2005.00250.x

Stern, D. I. (2012). Interfuel substitution: A meta-analysis. *Journal of Economic Surveys*, *26*(2), 307–331. https://doi.org/10.1111/j.1467-6419.2010.00646.x

Taye, F. A., Folkersen, M. V., Fleming, C. M., Buckwell, A., Mackey, B., Diwakar, K. C., & Ange, C. S. (2021). The economic values of global forest ecosystem services: A meta-analysis. *Ecological Economics*, *189*, 107145. https://doi.org/10.1016/j.ecolecon.2021.107145

TEEB. (2010). *The economics of ecosystems and biodiversity: ecological and economic foundations*. UNEP/Earthprint.

World Bank. (2022). *World Bank Open Data*. Retrieved February, 2022, from https://data.worldbank.org.cn/

Wu, J., Zhao, Y., Yu, C., Luo, L., & Pan, Y. (2017). Land management influences trade-offs and the total supply of ecosystem services in alpine grassland in Tibet, China. *Journal of Environmental Management*, *193*, 70–78. https://doi.org/10.1016/j.jenvman.2017.02.008

Zhou, J., Wu, J., & Gong, Y. (2020). Valuing wetland ecosystem services based on benefit transfer: A meta-analysis of China wetland studies. *Journal of Cleaner Production*, *276*, 122988. https://doi.org/10.1016/j.jclepro.2020.122988

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APPENDIX A

See Table A1.

TABLE A1 Detailed definitions for ecosystem services.

Ecosystem services	Detailed definition
Provisioning services	
Food supply	Meat, plant/vegetable food, milk Food [general]
Raw materials	Fiber, Timber, Fodder, Other raw material [general]
Water supply	Drinking water, Irrigation water, Industrial water, etc.
Regulating services	
Climate regulation	C-Sequestration, Microclimate regulation, Gas regulation Climate regulations [general]
Water flow regulation	Drainage, River discharge, Natural irrigation Water regulation [general]
Soil fertility maintenance	Maintenance of soil structure, Deposition of nutrients Soil formation, Nutrient cycling Maintenance of soil fertility [general]
Waste treatment	Water purification, Soil detoxification Waste treatment [general]
Habitat services	
Genetic diversity	Biodiversity protection
Cultural services	
Recreation	Recreation, Tourism, Ecotourism, etc.
Other services	Ecosystem services other than those above, e.g., erosion control, pollination, medical resources, etc.

Note: Ecosystem service category refers to TEEB (2010).