Geography and Sustainability 4 (2023) 318–328

Contents lists available at ScienceDirect

Geography and Sustainability

journal homepage: www.elsevier.com/locate/geosus

Research Article

Dynamics and controls of ecosystem multiserviceability across the Qingzang Plateau

Ruowei Li[a,b], Guodong Han[a,*], Jian Sun[b,*], Tiancai Zhou[b], Junhe Chen[b], Wen He[c], Yi Wang[d]

[a] College of Grassland, Resources and Environment, Key Laboratory of Grassland Resources of the Ministry of Education of China, Inner Mongolia Agricultural University, Hohhot 010019, China

[b] State Key Laboratory of Tibetan Plateau Earth System, Environment and Resources (TPESER), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

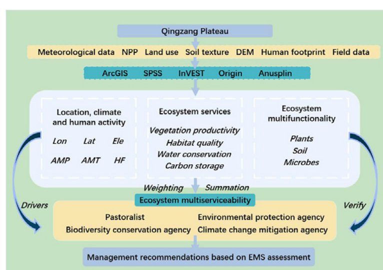
[c] Institute for Disaster Management and Reconstruction, Sichuan University-Hongkong Polytechnic University, Chengdu 610207, China

[d] School of Life Sciences, Sun Yat-sen University, Guangzhou 510275, China

HIGHLIGHTS

- Ecosystem multiserviceability of the Qingzang Plateau was quantified.
- Spatial-temporal patterns of ecosystem multiserviceability in the Qingzang Plateau were clarified.
- Main driving factors of ecosystem multiserviceability in the Qingzang Plateau were identified.
- An ecosystem multiserviceability management method for Qingzang Plateau is proposed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 14 December 2022
Received in revised form 28 June 2023
Accepted 29 June 2023
Available online 11 July 2023

Keywords:
Ecosystem multiserviceability
Qingzang Plateau
Spatial-temporal patterns
Drivers

ABSTRACT

Ecosystem multiserviceability (EMS), a comprehensive and significant ecological indicator, reflects the capacity of ecosystems to offer multiple services concurrently. Intensified climate change and human activity are continuously altering ecosystem functions, services, and EMSs. However, numerous studies have only focused on one or a few ecosystem services, rarely taking into account spatial-temporal distribution and drivers of EMS on behalf of different agencies. We calculated EMS including pastoralist (PA), environmental protection agency (EPA), biodiversity conservation agency (BCA), and climate change mitigation agency (CCMA) using grassland production, habitat quality, water conservation, and carbon sequestration. Then, the effects of geographical features, climate factors, and human activities on spatial-temporal patterns of EMS were explored. The result indicated that EMS showed a decreasing tendency from the southeast to northwest on the Qingzang Plateau (QZP). Meanwhile, there were no obvious fluctuations in four simulated scenarios (PA, EPA, BCA and CCMA) among different vegetation types during 2000 to 2015. Notably, EMS of all simulated scenarios decreased in the alpine steppe ecosystem, but negligible changes were found in other ecosystems from 2015 to 2020. Moreover, the relative importance of precipitation in annual mean value (from 2000 to 2020) of PA, EPA, BCA and CCMA were 0.13, 0.11, 0.30 and 0.19, respectively. Overall, precipitation played the dominant role on the dynamics of EMS, followed by elevation and human footprint. Our findings highlighted that understanding the patterns and drivers of EMS could provide a reference for the regional management and maintenance of ecosystem stability on QZP.

* Corresponding authors: Inner Mongolia Agricultural University, 1038 No. 29 Erdos East Street, Hohhot 010019, PR China.
E-mail addresses: hanguodong@imau.edu.cn (G. Han), sunjian@itpcas.ac.cn (J. Sun).

https://doi.org/10.1016/j.geosus.2023.06.004

1. Introduction

Ecosystem services contain nature resources, climate regulation, defense against natural disasters, recreation, and inspiration (Hernández-Blanco et al., 2022), which also is crucial for supporting human well-being since they serve as a link between natural and human systems (Hernández-Blanco et al., 2020). In recent decades, numerous research focused on calculating value (Costanza et al., 1997; Gallai et al., 2009; Jiang et al., 2020), mapping the supply and demand (van Jaarsveld et al., 2005; Deutsch et al., 2007; Chen et al., 2021), analyzing potential threats (Tilman et al., 2001), understanding the mechanisms (Venter et al., 2016) and forecasting changes in ecosystem services (Carpenter et al., 2006; Hernández-Blanco et al., 2022). Regrettably, although the ecological processes simultaneously generate multiple associated ecosystem services, most studies have centered on a single or a few ecosystem services (Peterson et al., 2003; Chan et al., 2006; Rodriguez et al., 2006; Brauman et al., 2007). Furthermore, the required ecosystem services are diverse according to the different agencies, and the impacts of climate change and human activities on ecosystem services are not always homogeneous. Consequently, we ought to pay more attention to the multiple relationships among ecosystem services and the establishment of the concept of ecosystem multiserviceability (EMS) (Turner et al., 2003; Kremen, 2005; Carpenter et al., 2006; Manning et al., 2018; Jing and He, 2021).

EMS was defined initially as ecosystem service multifunctionality by Manning et al. (2018), but other scholars have argued that the ability of ecosystem to provide multiple ecosystem services simultaneously was more strictly defined as ecosystem multiserviceability (Jing and He, 2021). Obviously, the main limitation of the current research on ecosystem services is that there is no systematic indicators to represent multiple facets of ecosystem services (Manning et al., 2018). Therefore, Manning et al. (2018) proposed a quantitative approach which is divided into consulting stakeholders, quantifying weights, quantifying ecosystem services, standardizing ecosystem services, and finally weighting calculations. Furthermore, Jing and He (2021) integrated Manning's method, and then summarized the EMS quantization method according to grassland ecosystem. Generally, it is necessary to integrate various services into one index (i.e., EMS) to match the different requirements of stakeholders (Manning et al., 2018). In summary, the most core of the steps of quantifying EMS are determining the ecosystem services needed by various stakeholders in different regions, and entitling the weight of different ecosystem services.

Climate change and human activities have produced profound impacts on the ecosystem, such as loss of biodiversity (Butchart et al., 2010), melting of glaciers (Nie et al., 2021), greenhouse effect (Parmesan and Yohe, 2003), ecosystem degradation (Li et al., 2021) and so on. Accurate understanding of the complex impacts of global changes on ecosystem services is conducive to ecosystem management decision-making (Jäger et al., 2020; Lavorel et al., 2018). Climate change conditions will change the flow of energy and material in ecosystems, and eventually affect the spatial pattern of ecosystem services (Cavanagh et al., 2021). Besides, human activities would accelerate or amplify such effects, leading to changes in ecosystem services (Nolan et al., 2018). Meanwhile, geographical factors also have a certain impact on ecosystem services, especially in the high-altitude areas, where elevation plays an important role in the regulation of ecosystem services (Chen et al., 2021). Further, these drivers interact with the different ecosystem management practices intensified changes in ecosystem services (Jing and He, 2021). Therefore, it is necessary to identify the relative importance of climate factors, geographical factors and human activities on EMS. Apparently, quantification and ascertaining drivers of EMS have become a hot topic in current studies (Maes et al., 2012; Rodriguez-Loinaz et al., 2015).

The Qingzang Plateau (QZP) is a vital supply area of ecosystem services (Sun et al., 2012), providing primary productivity, economic development for herdsmen, and culture inheritance (Wang and Dai, 2020; Sun et al., 2020). It was taken as an important carbon sink and biodiversity conservation area with the increased vegetation coverage and productivity in recent decades (Peng et al., 2009; Chen et al., 2014). In addition, the QZP regulates water supply of arid Central Asia and Southeast Asia (Mu et al., 2020; Pfeffer et al., 2014). Currently, the QZP is ongoing the great pressure owing to increased human activities and the volatile climate, and the degraded habitat quality, melted glacier, and extended lake affect the EMSs of QZP (Xie et al., 2003; Xu et al., 2020; Sun et al., 2018). Furthermore, the changed EMSs have alerted and hurt the local different stakeholders' production and life (Sun et al., 2022a). Therefore, it is necessary to clarify the driving mechanism of different stakeholders and draw a blueprint for the sustainable management across the QZP.

In this study, we calculated EMS by involving the environmental protection agency, pastoralist, biodiversity conservation agency, and climate change mitigation agency on the QZP, using four critical important ecosystem services (e.g., grassland productivity, habitat quality, water conservation, and carbon sequestration). According to the needs of different agencies, we assigned weights to each ecosystem service. The aims of this study were to: (1) quantify the EMS of four important agencies on the QZP, (2) figure out the spatial-temporal patterns and drivers of EMS on the QZP, and (3) illustrate how EMS affects ecosystem management and ecosystem protection on the QZP. Furthermore, we provide insights that can guide the future conservation and maintenance of EMS in response to climate change and human pressure in the alpine region.

2. Materials and methods

2.1. Study area

The Qingzang Plateau (26°00′N–39°47′N, 73°19′E–104°47′E) is located in southwestern China and is characterized by a harsh environment and fragile ecosystems, with an average elevation of 4,000 m (Sun et al., 2022b). It covers an area of more than 2.50×10^6 km^2, which accounts for a quarter of the total land area of China (Ye et al., 2020). The region includes Xizang, Qinghai, southern Xinjiang, southwestern Gansu, western Sichuan and northwestern Yunnan (Fig. 1). The QZP supports the development of animal husbandry, maintains the living standards of farmers and herdsmen, provides productivity, and serve as an irreplaceable ecological barrier for water conservation, biodiversity conservation, carbon storage and other ecological services. In addition, it provides EMS for China and the surrounding areas, the region is also highly sensitive to global climate change and can play a role in balancing water and heat and regulating climate (Xie et al., 2003; Zhang et al., 2020).

2.2. Data and preprocessing

The meteorological database included annual total precipitation and annual mean temperature, which were recorded by weather station from 2000 to 2020 and collected from the China Meteorological Administration (http://cdc.cma.gov.cn). Here, the spatial interpolation of precipitation and temperature were analyzed using Anusplin 4.2 software (Center for Resource and Environmental Studies, Australian National University, Canberra). Human footprint data (Luo et al., 2020) was obtained from the Tibetan Plateau Scientific Data Center (http://data.tpdc.ac.cn/). These data are used for the analysis of the EMS driving force.

Terrestrial vertebrate data is used to validate ecosystem services, including data on reptiles, birds, amphibians and mammals. For birds, we used Birdlife's breeding range data. For mammals and amphibians, we used the latest Global Mammal and Global Amphibian Assessment data published by the International Union for Conservation of Nature (Jenkins et al., 2013). For reptiles, we used data collected and com-

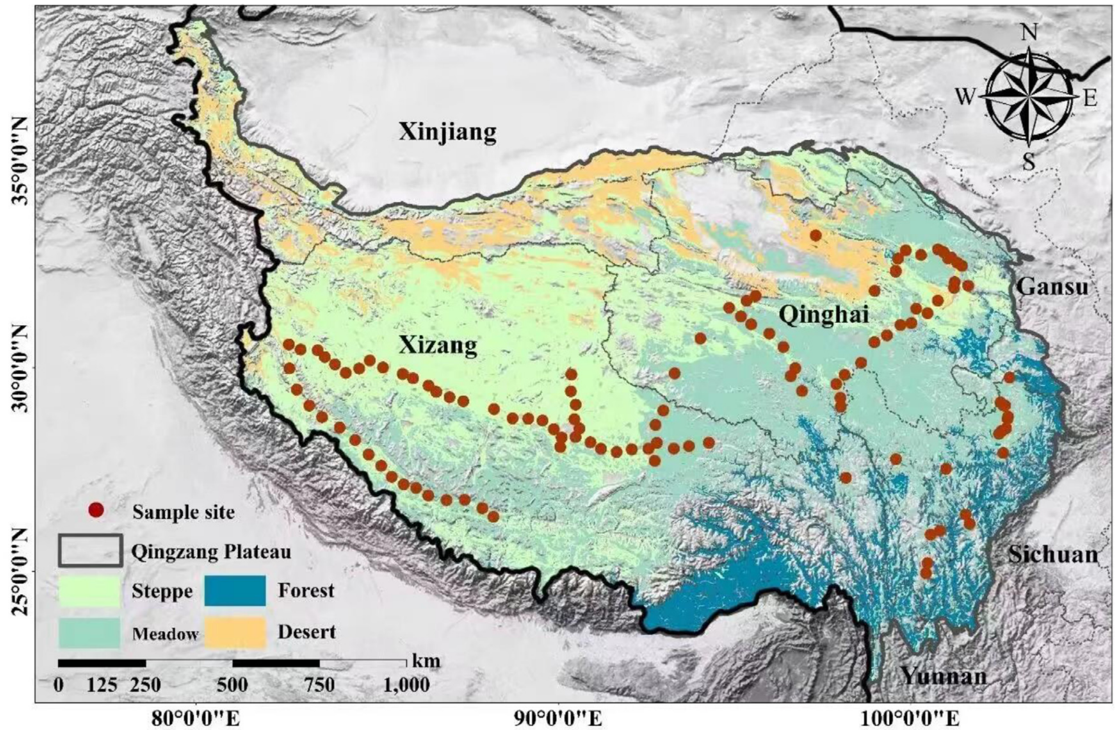


Fig. 1. Location of the sampling sites across Qingzang Plateau.

Table 1
Data types and sources.

Data	Resolution	Data source
Net primary production (NPP)	500 m	MOD17A3H NPP (https://ladsweb.modaps.eosdis.nasa.gov)
Land use	1 km	Resource and Environment Science and Data Center (https://www.resdc.cn)
Meteorological data	1 km	China Meteorological Data Service Center (http://data.cma.cn)
Soil texture	1 km	Resource and Environment Science and Data Center (https://www.resdc.cn)
Digital elevation model (DEM)	250 m	Resource and Environment Science and Data Center (https://www.resdc.cn)
Vegetation distribution map	—	Resource and Environment Science and Data Center (https://www.resdc.cn)
Carbon density	—	2010s China Terrestrial ecosystem carbon density dataset (https://www.escience.org.cn/)

piled by the Global Assessment Group on Reptile Distribution (Roll et al., 2017).

The data preprocessing programs primarily include cropping, splicing, and reprojection. The resolution of the raster data was unified to 1 km.

2.3. Quantification of ecosystem services

In order to further illustrate dynamics and controls of the ecological services of the QZP, we selected four important ecosystem services of grassland productivity, habitat quality, water conservation, and carbon storage to calculate EMSs. The four ecosystem services are quantified as follows and the required data sources are shown in Table 1.

(1) *Grassland productivity (GP)*

We used the net primary production (NPP) to calculate GP.

(2) *Habitat quality (HQ)*

The habitat quality was simulated using the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model manual and related research. This study determined relevant parameter values combined with the actual situation of the research area and designed the input parameter table of the habitat quality module (Liu et al., 2021) (Tables S1 and S2) calculated using the following formula:

$$Q_{xj} = H_j\left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + K^z}\right)\right) \tag{1}$$

where Q_{xj} is the habitat quality index of grid x in land use type j, and its value ranges between 0 and 1. The higher the value, the better the habitat quality. H_j is the habitat suitability of land use type j, and its value ranges from 0 to 1, in which 1 indicates the most suitable. K is a half-saturation constant, generally taken as 1/2 of the maximum value of the habitat degradation degree D_{xj}. The z value is the default parameter and is a normalized constant whose value is usually set as 2.5. The total threat level D_{xj} of grid cell x in habitat type j can be expressed as:

$$D_{xj} = \sum_{r=1}^{R}\sum_{y=1}^{Y_r}\left(\frac{w_r}{\sum_{r=1}^{R} w_r}\right) r_y i_{rxy} \beta_x S_{jr} \tag{2}$$

where R is the number of threat factors, w_r is the weight of the threat factor r with a value of 0–1, indicating the relative destructive power of the stress factor to all habitats, Y_r is the total number of grid cells of the threat factor r in land use map, r_y is the number of stress factors on each grid in the land use map, and S_{jr} is the relative sensitivity of land use type j to threat factor r with a value of 0–1. The calculation formula of the stress level i_{rxy} of the threat factor r in the grid y to the habitat grid x is as follows:

$$i_{rxy} = 1 - \left(d_{xy}/d_{r\max}\right) \tag{3}$$

$$i_{rxy} = \exp\left(-\left(2.99/d_{r\max}\right)d_{xy}\right) \tag{4}$$

where d_{xy} is the linear distance between grid x and grid y, and $d_{r\max}$ is the maximum impact distance of threat factor r on the habitat.

(3) *Water conservation (WC)*

This study is based on InVEST model water yield module to calculate the WC of the QZP (Lan et al., 2021).

$$Y_{xj} = \left(1 - \frac{\mathrm{AET}_{xj}}{P_x}\right) \times P_x \tag{5}$$

where Y_{xj} is the annual water yield and AET_{xj} the actual evapotranspiration for pixel x on the landscape j. P_x is the annual precipitation on pixel x.

The relationship between AET_{xj} and P_x is based on the methodology developed by Budyko (Zhang et al., 2004), $\mathrm{AET}_{xj}/\mathrm{PET}_{xj}$, and it is estimated in a spatially explicit way on pixel x:

$$\frac{\mathrm{AET}_{xj}}{P_x} = \frac{1 + \omega_x + R_{xj}}{1 + \omega_x R_{xj} + \left(1/R_{xj}\right)} \tag{6}$$

where R_{xj} is the dryness index of grid unit x on land use type j, which can be obtained from the ratio of potential evapotranspiration to rainfall.

The parameter ω_x is the ratio of modified vegetation annual water availability to expected precipitation:

$$\omega_x = Z \times \frac{\mathrm{PAWC}_x}{P_x} \tag{7}$$

$$R_{xj} = \frac{k_{ij} \times \mathrm{ET}_0}{P_x} \tag{8}$$

where parameter Z, as a constant, represents the precipitation characteristics with a value from 1 to 30 and it is larger when the rainfall events are more frequent. K_{ij} is the planting evapotranspiration coefficient and is the ratio of crop evapotranspiration (ET) to the reference evapotranspiration (ET_0) in different growth stages. The ET_0 data were calculated using the Penman-Monteith model modified by Food and Agriculture Organization of the United Nations (FAO).

PAWC is the water content available to plants:

$$\mathrm{PAWC}_x = 54.509 - 0.123\mathrm{sand} - 0.03(\mathrm{sand})^2$$

$$0.055\mathrm{silt} - 0.006(\mathrm{silt})^2 - 0.738\mathrm{clay} + 0.007(\mathrm{clay})^2 - 2.688\mathrm{OM} + 0.501(\mathrm{OM})^2 \tag{9}$$

where, "sand" is the soil sand content (%), "silt" is the soil silt content (%), "clay" is the soil clay content (%), and "OM" is the soil organic matter content (%).

According to the water balance equation, the difference between annual water output equal to rainfall and total evapotranspiration can be calculated by the following formula:

$$\mathrm{WR}_{xj} = Y_{xj} - \mathrm{Runoff}_{xj} \tag{10}$$

$$\mathrm{Runoff}_{xj} = P_{xj} \times C_j \tag{11}$$

where WR for grid cells on land cover types $j \times$ years the amount of WC. Grid cells on "Runoff_a" for land cover types $j \times$ years surface runoff. C for the surface runoff coefficient of land cover types is j.

(4) *Carbon storage (CS)*

The CS was simulated using InVEST model, and for the use of equations in the model parameters refer to (Li et al., 2021). The model parameters can be seen in Table S3.

2.4. Quantifying ecosystem multiserviceability

We calculate the EMSs according to four different agencies. Firstly, four stakeholder groups were identified, which include environmental protection agency (EPA), pastoralist (PA), biodiversity conservation agency (BCA) and climate change mitigation agency (CCMA). Next, the ecosystem services required by each agency and their weights are determined, and then the identified ecosystem services are standardized. The standardized ecosystem services are multiplied by the weights of stakeholders and added to obtain the index of EMS (Jing and He, 2021) (Fig. 2). The specific formula is as follows:

$$\mathrm{EPA} = \frac{1}{3}\mathrm{HQ} + \frac{1}{3}\mathrm{WR} + \frac{1}{3}\mathrm{CS} \tag{12}$$

$$\mathrm{PA} = 0.7\mathrm{GP} + 0.1\mathrm{HQ} + 0.1\mathrm{WR} + 0.1\mathrm{CS} \tag{13}$$

$$\mathrm{BCA} = 0.1\mathrm{GP} + 0.7\mathrm{HQ} + 0.1\mathrm{WR} + 0.1\mathrm{CS} \tag{14}$$

$$\mathrm{CCMA} = 0.1\mathrm{GP} + 0.1\mathrm{HQ} + 0.1\mathrm{WR} + 0.7\mathrm{CS} \tag{15}$$

2.5. Validation and sensitivity test

(1) *Verification of EMS*

In order to test the feasibility of EMS, we selected the ecosystem multifunctionality (EMF), which is closely related to EMS, to test the simulated products. We collected plant and soil samples from 115 study sites in 2015 (July to August) on the QZP (Fig. 1). Quantitative EMF specific index selection and calculation methods refer to (Wang et al., 2021). The EMF was calculated using study sites to extract the values of EPA, PA, BCA and CCMA, and analyze the correlation between EMF and each EMSs. Statistical significance was considered at a $P < 0.05$ level.

(2) *Sensitivity test of weight*

We tested the weight-sensitivity of EMS, and then increased weight of maximum of the ecosystem service by 10% or decreased it by 10%. Increasing the weight by 10% means multiplying the original weight of ecosystem service by 1.1, while decreasing the weight by 10% means multiplying that by 0.9 (Hua et al., 2022a). We calculated the four new EMS based on the adjusted weights, and compared the new EMSs with the original EMS. According to the correlation of the original and new EMS, we judge the robustness of the evaluation.

(3) *Validation of individual ecosystem services*

We used the database of above-ground biomass, terrestrial vertebrate diversity, water conservation (Lan et al., 2021) and carbon storage (Li et al., 2021) to verify GP, HQ, WC and CS, respectively.

2.6. Data analysis

The software SPSS24 (SPSS Inc., Chicago, IL., USA) and Origin 2018 (Origin Lab, Northampton, Massachusetts, USA) was used to analyze the data, and draw the graph, respectively. And the relative importance analysis was performed using the generic gradient regression model of the "*gbm*" package in R 4.0.4 software (R Core Team, 2013), where "*gbm*" calculated Friedman's H-statistic to evaluate the relative strength of interaction effects in the nonlinear model. ArcGIS10.6 (ESRI, Inc., Redlands, CA, USA) was applied to map spatial patterns of EMSs, extracted the climatic data, and geographic information, and human footprint, and standardized ecosystem services via fuzzy membership tool.

The detailed research framework is shown in Fig. 3.

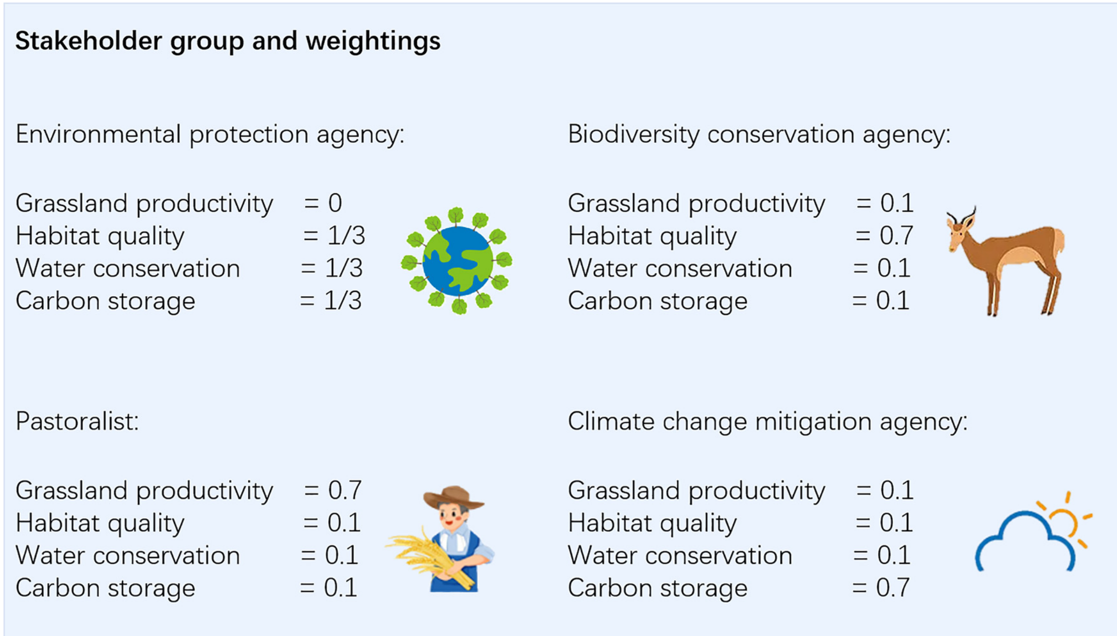


Fig. 2. Quantization method of ecosystem multiserviceability. We show four ecosystem services including vegetation productivity, habitat quality, water conservation and carbon storage (referenced from Jing and He (2021)). Then ecosystem service multifunctionality is calculated based on different weighting scenarios of stakeholder groups.

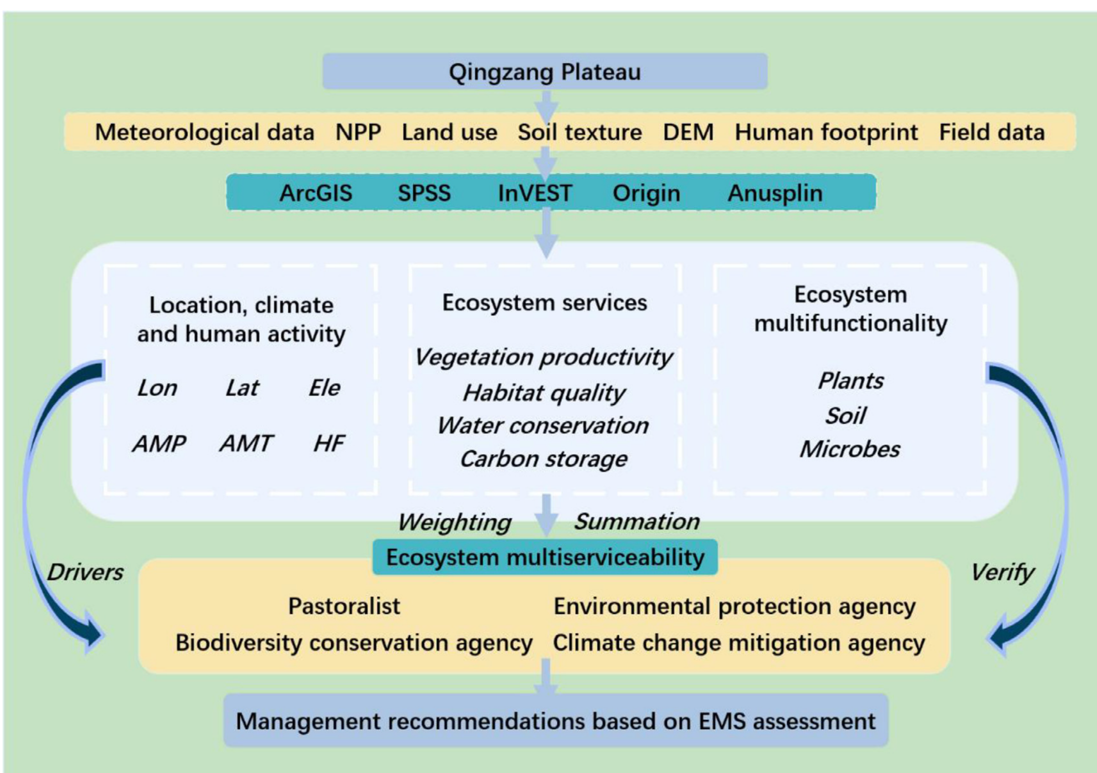


Fig. 3. Flowchart of this study. *Note*: EMS, ecosystem multiserviceability; Lon, longitude; Lat, latitude; Ele, elevation; AMP, annual mean precipitation; AMT, annual mean temperature; HF, human footprint; NPP, net primary production; DEM, digital elevation model.

3. Results

3.1. Model validation and sensitivity test

There were remarkably positive linear correlations of EMSs with EMF ($P < 0.05$). Specifically, R^2 of PA and EMF was 0.4, while the EPA, BCA and CCMA explained the variation of EMF by 25%, 5% and 29% at 0.05 significant level. Apparently, CCMA is more sensitive to EMF, whereas BCA is relatively lower (Fig. 4, Table S1). Besides, the results of weight test are shown in Fig. S1. The correlation coefficient between the original EMS and the adjusted EMS were all above 0.9 ($P < 0.05$). Furthermore, R^2 was 0.37 between the reference value and the estimated value of WC (Fig. S2(a)). For GP, R^2 was 0.51 between the actual value and the estimated value ($P < 0.05$, Fig. S2(b)). While HQ showed a remarkable exponential growth trend ($R^2 = 0.54$) at 0.05 significant level (Fig. S2(c)). All results demonstrated that model is reliable.

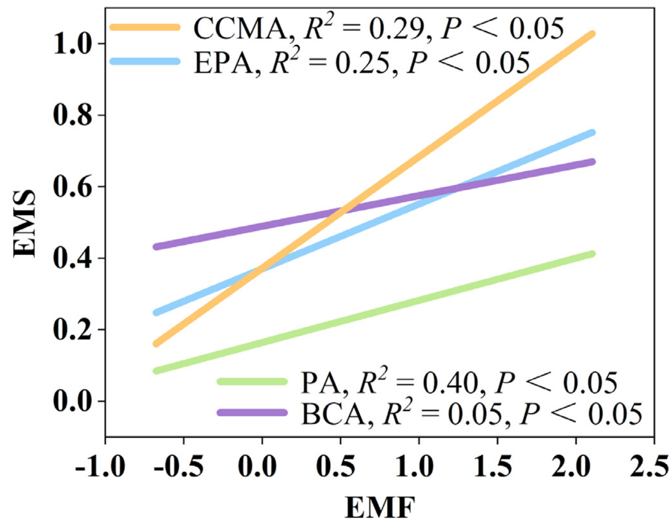


Fig. 4. Ecosystem multifunctionality validation ecosystem multiserviceability. *Note*: EMS, ecosystem multiserviceability; EMF, ecosystem multifunctionality; EPA, environmental protection agency; PA, pastoralist; BCA, biodiversity conservation agency; CCMA, climate change mitigation agency.

3.2. The spatial-temporal pattern of the ecosystem multiserviceability

The spatial-temporal heterogeneity of four EMSs were revealed in Fig. 5. Overall, all of EMSs gradually were weakening from southeast to northwest across the QZP, and a strengthening trend was observed in the northwestern margin. From 2000 to 2020, with the exception of PA, the high value of the other three EMSs were mainly distributed in the lower reaches of Yarlung Zangbo River, northern Yunnan and western Sichuan forest ecosystems in the southeast of QZP. The high values of PA

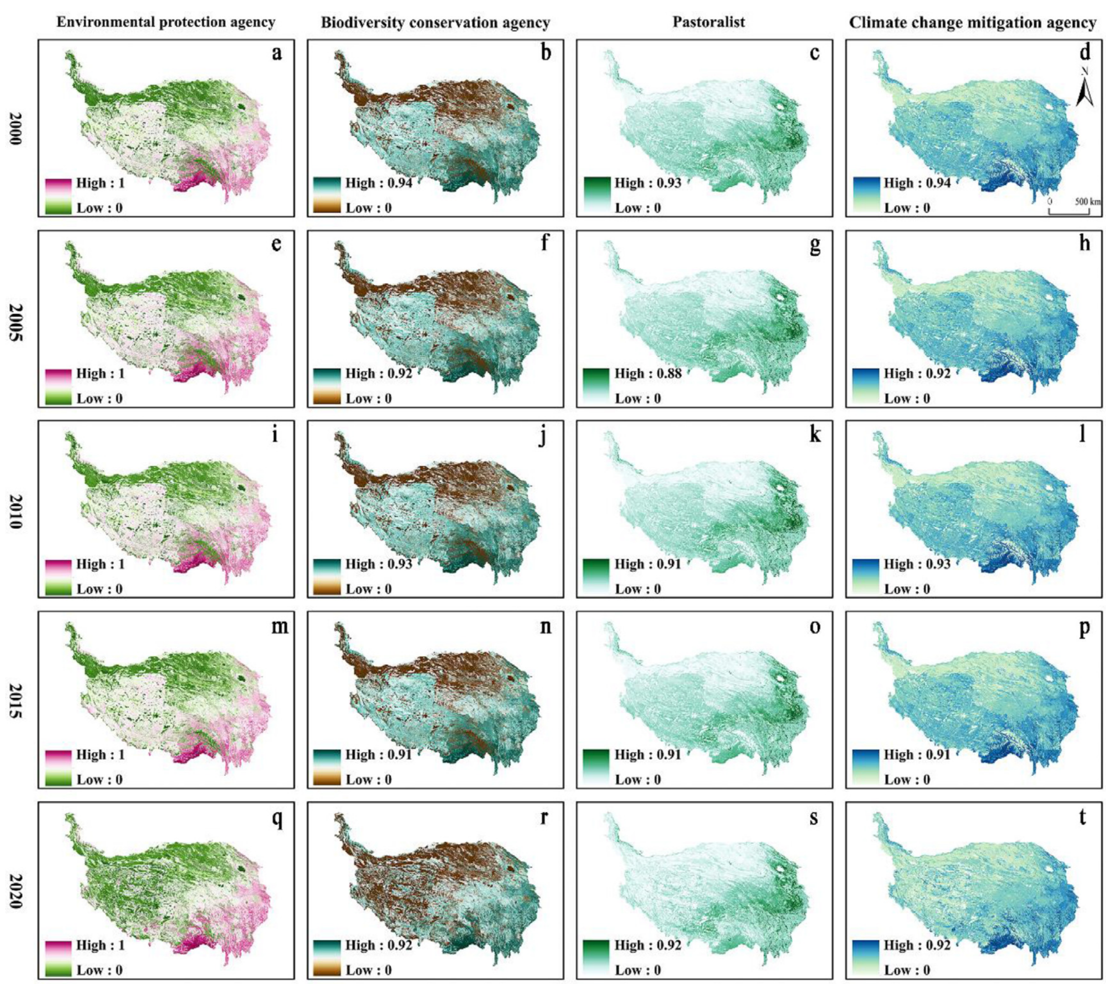


Fig. 5. Spatio-temporal pattern of ecosystem multiserviceability. The colors depict the value of the EMS, with low values in the EMS being shown in light color and high values in dark color.

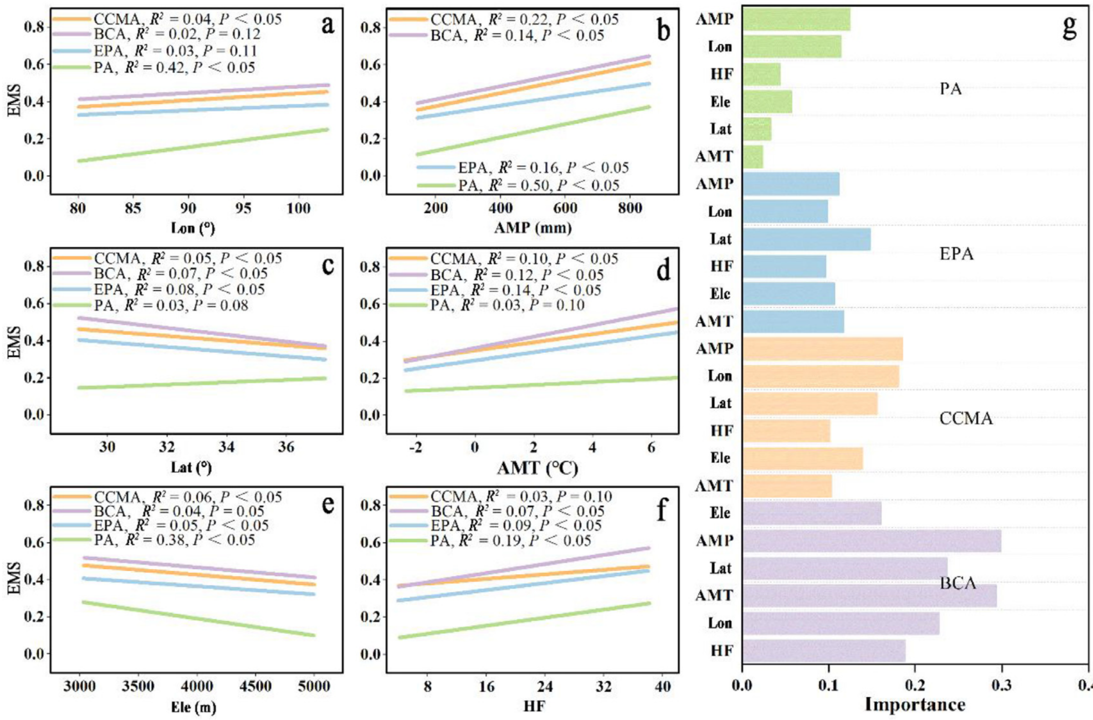


Fig. 6. (a)-(f) Relationships of geographical, climate and human footprint factors with EMS; (g) relative importance of geographical factors, climate factors and human footprint to EMS. *Note*: EMS, ecosystem multiserviceability; EPA, environmental protection agency; PA, pastoralist; BCA, biodiversity conservation agency; CCMA, climate change mitigation agency; Lon, longitude; Lat, latitude; Ele, elevation; AMP, annual mean precipitation; AMT, annual mean temperature; HF, human footprint.

were distributed in the meadow ecosystem in the southeast of Qinghai, while the low values were distributed in the desert ecosystem in the north of the QZP. Notably, we compared EMS in 2020 with that in four periods (2000, 2005, 2010, and 2015), and found that four EMSs showed declining trends in the grassland ecosystem of Xizang.

3.3. Drivers of ecosystem multiserviceability

According to Fig. 6, we found that EMSs of EPA, BCA and CCMA were significantly negatively correlated with latitude (Lat) ($P < 0.05$), while PA was not significantly correlated with it ($R^2 = 0.03$, $P = 0.08$) (Fig. 6(b)). Nonetheless, when analyzing the correlation between elevation (Ele) and EMS, only BCA showed an insignificant situation ($R^2 = 0.04$, $P = 0.05$), and CCMA, EPA and PA were significant ($P < 0.05$) (Fig. 6(c)). Additionally, the four EMSs increased significantly with the increase in the annual mean precipitation (AMP) ($P < 0.05$) (Fig. 6(d)). It is worth noting that compared with other EMS, AMP has the highest interpretation of PA ($R^2 = 0.50$) while annual mean temperature (AMT) is not significantly correlated with PA ($P = 0.10$, Fig. 6(e)). Furthermore, the relationships between human activities and EMS were explored in Fig. 6(f), which shows that CCMA is not significantly correlated with human footprint (HF) ($R^2 = 0.03$, $P = 0.10$), but HF affects EMSs of PA, EPA and BCA remarkably ($P < 0.05$). The relative importance contribution of AMP to EMS was higher (important values are 0.13, 0.11, 0.19 and 0.30) (Fig. 6(g)).

4. Discussion

4.1. Ecosystem multiserviceability of the QZP

In general, the main findings showed that there has been considerable spatial heterogeneity of EMSs on the QZP ecosystem, and all of PA, BCA, CCMA and EPA decreased from southeast to northwest (Fig. 5). The decrease of PA is mainly caused by the spatial patterns of precipitation and temperature across QZP, which regulating the dynamics of NPP (Piao and Fang, 2002). Specifically, the precipitation is much higher in the southeast than northwest of QZP according to the influence of the warm and humid air current of Pacific and Indian monsoon (Yang et al., 2015). Consequently, mesic coniferous forests and broad-leaved forests with high coverage and biomass are the dominant vegetation types in the southeast of QZP (Mao et al., 2015). Most areas of the northern QZP with low rainfall, high elevation, and low temperatures, are characterized by sparse shrub, low-cover grassland, and alpine meadow (Zheng and Zhao, 2017), which are associated with low PA. Moreover, the lowest PA in the Ali region is due to the low temperature and precipitation, as well as the serious desertification (Chen et al., 2020). It is worth noting that our study area has abundant nature reserves, which are highly productive but cannot be used by PA (Hua et al., 2022b).

The biodiversity rich areas of the QZP are mainly distributed in the southeast, but the natural protected areas are mainly distributed in the central and western parts of the plateau. The highest BCA was observed in the protected areas. Meanwhile, the Qiangtang and Kekexili national reserves have played an important role in the conservation of endangered species on the QZP (Fu et al., 2021). In contrast, BCA is low in the dry climate of the Tsaidam Basin where there is an enclosed basin surrounded by the Kunlun and Qilian Mountains (Xin et al., 2021).

CCMA is higher in the mountainous area located in the southeast of QZP comparing to other regions. The mountainous area is characterized by abundant plants, rapid decomposition rate of litter, and continuous increase in soil organic matter (Wang et al., 2017; Wang et al., 2019). Similarly, higher carbon storage and water conservation was observed in the mountainous area of southeast Xizang, northwest Sichuan, and the headwaters of the Sanjiang Nature Reserve, probably due to the higher vegetation cover and rainfall interception, and lower transpiration and runoff (Qian et al., 2018; Zhang et al., 2016). Furthermore, these areas are covered by forest or grassland ecosystems which have relative great water-heat equilibrium conditions (Wu and Meng, 2022).

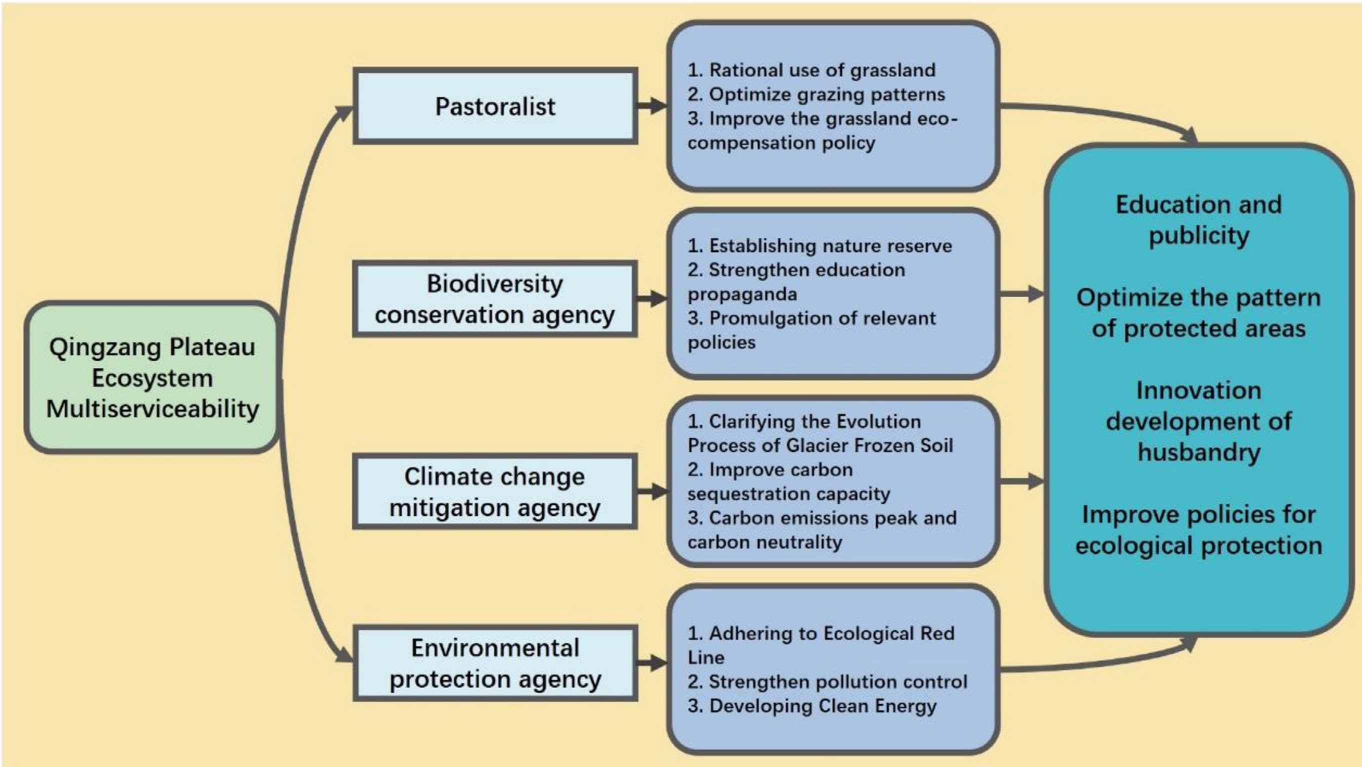


Fig. 7. Approaches for managing ecosystem multiserviceability.

Generally, the southeast part of QZP is the hotspot of EMS. It is believed that strengthening the management and protection of this area is beneficial to improve the EMSs capability of QZP.

4.2. Precipitation and human activities dominate EMS

The spatial heterogeneity of EMS is driven by climate, topography, and human activities (Fig. 6). Currently, climate change and human activities are reshaping ecosystem services at an alarming rate (Shaw et al., 2011). Our findings also presented that EMS were significantly positively regulated via AMP (Fig. 6(d)), indicating that precipitation was the main factor controlling EMS across the QZP. As previously reported, soil organic carbon and plant productivity in alpine grassland is mainly controlled by water availability (Fang et al., 2010), so PA and CCMA increased with increasing AMP. Additionally, BCA showed the same tendency in the alpine grasslands of QZP, which also is associated with precipitation given its great effect on species richness (Yang et al., 2004). Hence, changes in precipitation patterns related to the climate change will likely have important effects on ecological processes and ecosystem services (Bai et al., 2019).

Human activity is another important factor in the regulation of EMS. Before 2000, QZP was rarely affected by human activities (Li et al., 2018), and the urbanization slowed down (Cui et al., 2017). After 2000, a series of major ecological projects (e.g., fencing, aerial seeding afforestation and rodent control) have been implemented on the QZP (Zhang et al., 2017; Gao et al., 2022; Zhang and Jin, 2021; Li et al., 2011), which have remarkably improved vegetation productivity, optimized habitat quality, increased carbon storage, and played a positive role in EMSs of PA, EPA, CCMA and BCA. Previous study also demonstrated that the ecological state on the QZP continues to improve due to the implemented ecological projects (Bardgett et al., 2021). Besides, grazing is one of the main human activities on QTP, which affect materials and energy cycling of ecosystem, alert ecological functioning, and regulate ecosystem services. Consequently, rational livestock management and conservation projects would increase the EMS (Sun et al., 2020). For example, well-managed grazing can minimize greenhouse gas emissions, maintain a balance between livestock and wildlife, enhance biodiversity (Peyraud, 2011; Bellarby et al., 2013), and thus bring high returns to herders.

4.3. Implications for management

Given the important role of the QZP in animal husbandry production, biodiversity conservation and global climate change, we evaluated the EMSs according to four stakeholder groups which involves PA, BCA, EPA, and CCMA, and designed the management framework for guiding the sustainable development of the QZP (Fig. 7).

Grasslands provide a series of ecosystem functions and services on the QZP. Scientific management of grassland can strengthen ecosystem stability and improve local herdsmen' livelihoods and further promote regional economic development. Therefore, it is crucial to achieve a sustainable grassland ecosystem across the QZP (Ren et al., 2015; Sun et al., 2020). Specifically, future management measures can concentrate on the following aspects: firstly, grassland use practices should be planned according to grassland health status and socioeconomic characteristics. Grassland ecosystem can be divided into grazing area, tourism and leisure area, cultural functional area, which provides different ecosystem service functions (Kemp et al., 2013). Secondly, optimizing grazing management to achieve the balance between grass production and number of livestock. Thus, PA need to determine the reasonable stocking rate based on the grassland productivity and distribution with scientific management methods such as fencing, zonal rotation grazing, and seasonal grazing (Xu et al., 2020; Bennett and Gosnell, 2015; Ostrom, 2007a, 2007b). Third, the government, scientists and local herders should work together to actualize grassland sustainable management, including improve the grassland eco-compensation policy and supervision capacity, strength research on grassland management, and improve grassland construction and production (Kemp et al., 2018; Wang et al., 2017).

It is essential to protect biodiversity on the QZP since it is a global biodiversity hotspot. However, in the latest IUCN (International Union for Conservation of Nature), many species on the QZP are listed as threatened. To protect the threatened wild animals and plants effectively, abundant nature reserve was established (Xu et al., 2017). Nevertheless, existing protected areas may have spatial overlaps (Fu et al., 2021). Hence, the nature protected areas should be re-evaluated and analyzed to further adjust and optimize the protected scope (Li et al., 2020). Furthermore, it is necessary to enhance people's awareness of biodiversity protection through relevant publicity and education, and increase local participation in biodiversity conservation. Simultaneously, rational policies and strategies are also needed to maintain local biodiversity (Zhang et al., 2018).

QZP is more sensitive to global climate change owning to its unique geographical environment. Evidence demonstrated climate crisis has increased surface evaporation, accelerated large-scale glaciers and frozen soil melting across QZP, which resulted in vegetation and soil degradation (Kuang and Jiao, 2016). Therefore, clarifying the evolution process of glaciers and permafrost as well as their internal carbon cycle patterns are crucial to addressing climate change and has attracted massive attention from CCMA (Wang et al., 2019; Yao et al., 2012). In addition, the QZP has implemented corresponding carbon sequestration projects to cope with climate crisis, such as the natural forest protection project, returning grazing land to grassland project, and wind prevention and sand control project. Meanwhile, China has also implemented climate actions like carbon emissions peak and carbon neutrality, which is significant to mitigate climate change (Mallapaty, 2020).

For the ecologically fragile region, we suggested that EPA should center on ecology protection across the QZP, strictly maintain the ecological protection red line, and develop demonstration areas for promoting ecological civilization (Chen et al., 2021). In addition, air/water pollution should be controlled to reduce the negative impact of human activities on the environment (Xu et al., 2017). Furthermore, clean energy like photovoltaic energy, wind energy, and hydroenergy are conducive to the sustainable development of the QZP. All in all, objectives of EPA are to build an ecological security barrier across the QZP (Tang et al., 2023).

5. Conclusions

Quantifying EMSs and exploring their patterns and drivers have become a hot topic in ecological or sustainable management fields. Our findings demonstrated EMSs of all agencies showed a decreasing trend from southeast to northwest over QZP, and the dynamics of EMSs were governed via both precipitation and human activities. Furthermore, we highlighted the scientific workflow for sustainable development which contains optimizing grassland practices, enlarging nature reserves, strengthening environmental management, and promoting carbon sink for corresponding PA, BCA, CCMA, and EPA, respectively. Nevertheless, sampling sites were relatively sparse in some ecosystems, which introduces uncertainty into mapping EMSs of the QZP. Hence, we will supplement observation sites in the future work to reduce the uncertainty, and add more service indicators to quantify EMS scientifically and comprehensively.

Declaration of Competing Interests

The authors declare that there are no known competing financial interests or personal relationships that influenced the work reported in this paper.

Acknowledgements

This work was supported by the National Science Foundation of China (Grant No. 41871040), the Second Tibetan Plateau Scientific Expedition and Research (Grant No. 2019QZKK0405), and the Joint Research Project of Three-River-Resource National Park Funded by the Chinese Academy of Sciences and Qinghai Provincial People's Government (Grant No. LHZX-2020–08).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geosus.2023.06.004.

References

Bai, Y., Ochuodho, T.O., Yang, J., 2019. Impact of land use and climate change on water-related ecosystem services in Kentucky, USA. Ecol. Indic. 102, 51–64.
Bardgett, R.D., Bullock, J.M., Lavorel, S., Manning, P., Schaffner, U., Ostle, N., Chomel, M., Durigan, G., Fry, E.L., Johnson, D., Lavallee, J.M., Le Provost, G., Luo, S., Png, K., Sankaran, M., Hou, X., Zhou, H., Ma, L., Ren, W., Li, X., Ding, Y., Li, Y., Shi, H., 2021. Combatting global grassland degradation. Nat. Rev. Earth Environ. 2, 720–735.
Bellarby, J., Tirado, R., Leip, A., Weiss, F., Lesschen, J.P., Smith, P., 2013. Livestock greenhouse gas emissions and mitigation potential in Europe. Glob. Change Biol. 19, 3–18.
Bennett, D.E., Gosnell, H., 2015. Integrating multiple perspectives on payments for ecosystem services through a social-ecological systems framework. Ecol. Econ. 116, 172–181.
Brauman, K.A., Daily, G.C., Duarte, T.K., Mooney, H.A., 2007. The nature and value of ecosystem services: An overview highlighting hydrologic services. Annu. Rev. Environ. Resour. 32, 67–98.
Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Baillie, J.E.M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G.M., Chanson, J., Chenery, A.M., Csirke, J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway, J.N., Genovesi, P., Gregory, R.D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M.A., McRae, L., Minasyan, A., Hernández Morcillo, M., Oldfield, T.E., Pauly, D., Quader, S., Revenga, C., Sauer, J.R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S.N., Symes, A., Tierney, M., Tyrrell, T.D., Vié, J.C., Watson, R., 2010. Global biodiversity: Indicators of recent declines. Science 328 (5982), 1164–1168.
Carpenter, S.R., DeFries, R., Dietz, T., Mooney, H.A., Polasky, S., Reid, W.V., Scholes, R.J., 2006. Millennium ecosystem assessment: Research needs. Science 314 (5797), 257–258.
Cavanagh, R.D., Melbourne-Thomas, J., Grant, S.M., Barnes, D., Hill, S.L., 2021. Future risk for Southern Ocean ecosystem services under climate change. Front. Mar. Sci. 7, 615214.
Chan, K.M.A., Shaw, M.R., Cameron, D.R., Underwood, E.C., Daily, G.C., 2006. Conservation planning for ecosystem services. PLoS Biol. 4, 2138–2152.
Chen, B., Zhang, X., Tao, J., Wu, J., Wang, J., Shi, P., Zhang, Y., Yu, C., 2014. The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau. Agric. For. Meteorol. 189/190, 11–18.
Chen, S., Guo, B., Yang, F., Han, B., Fan, Y., Yang, X., He, T., Liu, Y., Yang, W., 2020. Spatial and temporal patterns of NPP and its response to climate change in the Qinghai-Tibet Plateau from 2000 to 2015. J. Nat. Resour. 35, 2511–2527 (in Chinese).
Chen, F., Ding, L., Piao, S., Zhou, T., Xu, B., Yao, T., Li, X., 2021. The Tibetan Plateau as the engine for Asian environmental change: The Tibetan Plateau earth system research into a new era. Sci. Bull. 66, 1263–1266.
Chen, J., Wang, Y., Sun, J., Liang, E., Shen, M., Yang, B., Jia, X., Zhang, J., 2021. Precipitation dominants synergies and trade-offs among ecosystem services across the Qinghai-Tibet Plateau. Glob. Ecol. Conserv. 32, e01886.
Costanza, R., D'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., Oneill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387 (6630), 253–260.
Cui, Y., Li, S., Yu, C., Tian, Y., Zhong, Z., Wu, J., 2017. Effects of the award-allowance payment policy for natural grassland conservation on income of farmer and herdsman families in Tibet. Acta Pratac. Sin. 26, 22–32 (in Chinese).
Deutsch, L., Gräslund, S., Folke, C., Troell, M., Huitric, M., Kautsky, N., Lebel, L., 2007. Feeding aquaculture growth through globalization: Exploitation of marine ecosystems for fishmeal. Glob. Environ. Change 17, 238–249.
Fang, J., Yang, Y., Ma, W., Mohammat, A., Shen, H., 2010. Ecosystem carbon stocks and their changes in China's grasslands. Sci. China-Life Sci. 53, 757–765.
Fu, B., Ouyang, Z., Shi, P., Fan, J., Wang, X., Zheng, H., Zhao, W., Wu, F., 2021. Current condition and protection strategies of Qinghai-Tibet Plateau ecological security barrier. Bull. Chin. Acad. Sci. 36, 1298–1306 (in Chinese).
Gallai, N., Salles, J.-M., Settele, J., Vaissiere, B.E., 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. Ecol. Econ. 68, 810–821.
Gao, W., Zheng, C., Liu, X., Lu, Y., Chen, Y., Wei, Y., Ma, Y., 2022. NDVI-based vegetation dynamics and their responses to climate change and human activities from 1982 to 2020: A case study in the Mu Us Sandy Land, China. Ecol. Indic. 137, 108745.
Hernández-Blanco, M., Costanza, R., Anderson, S., Kubiszewski, I., Sutton, P., 2020. Future scenarios for the value of ecosystem services in Latin America and the Caribbean to 2050. Curr. Res. Environ. Sustain. 2, 100008.
Hernández-Blanco, M., Costanza, R., Chen, H., DeGroot, D., Jarvis, D., Kubiszewski, I., Montoya, J., Sangha, K., Stoeckl, N., Turner, K., 2022. Ecosystem health, ecosystem services, and the well-being of humans and the rest of nature. Glob. Change Biol. 28, 5027–5040.

Hua, T., Zhao, W., Cherubini, F., Hu, X., Pereira, P., 2022a. Continuous growth of human footprint risks compromising the benefits of protected areas on the Qinghai-Tibet Plateau. Glob. Ecol. Conserv. 34, e02053.
Hua, T., Zhao, W., Cherubini, F., Hu, X., Pereira, P., 2022b. Effectiveness of protected areas edges on vegetation greenness, cover and productivity on the Tibetan Plateau, China. Landscape Urban Plann. 224, 104421.
Jäger, H., Peratoner, G., Tappeiner, U., Tasser, E., 2020. Grassland biomass balance in the European Alps: Current and future ecosystem service perspectives. Ecosyst. Serv. 45, 101163.
Jenkins, C.N., Pimm, S.L., Joppa, L.N., 2013. Global patterns of terrestrial vertebrate diversity and conservation. Proc. Natl. Acad. Sci. U.S.A. 110, E2602–E2610.
Jiang, W., Lü, Y., Liu, Y., Gao, W., 2020. Ecosystem service value of the Qinghai-Tibet Plateau significantly increased during 25 years. Ecosyst. Serv. 44, 101146.
Jing, X., He, J., 2021. Relationship between biodiversity, ecosystem multifunctionality and multiserviceability: Literature overview and research advances. Chin. J. Plant Ecol. 45, 1094–1111 (in Chinese).
Kemp, D.R., Han, G., Hou, X., Michalk, D.L., Hou, F., Wu, J., Zhang, Y., 2013. Innovative grassland management systems for environmental and livelihood benefits. Proc. Natl. Acad. Sci. U.S.A. 110, 8369–8374.
Kemp, D., Han, G., Hou, F., Hou, X., Li, Z., Sun, Y., Wang, Z., Wu, J., Zhang, X., Zhang, Y., Gong, X., 2018. Sustainable management of Chinese grasslands—Issues and knowledge. Front. Agric. Sci. Eng. 5, 9–23.
Kremen, C., 2005. Managing ecosystem services: What do we need to know about their ecology? Ecol. Lett. 8, 468–479.
Kuang, X., Jiao, J.J., 2016. Review on climate change on the Tibetan Plateau during the last half century. J. Geophys. Res. Atmos. 121, 3979–4007.
Lan, X., Sun, J., Wang, Y., Ye, C., Zeng, T., 2021. Spatiotemporal variation characteristics and its driving forces of water conservation function on the Tibetan Plateau from 1995 to 2014. Acta Agrestia Sin. 29, 80–92.
Lavorel, S., Colloff, M.J., Locatelli, B., Gorddard, R., Prober, S.M., Gabillet, M., Devaux, C., Laforgue, D., Peyrache-Gadeau, V., 2018. Mustering the power of ecosystems for adaptation to climate change. Environ. Sci. Policy 92, 87–97.
Li, H., Liu, G., Fu, B., 2011. Response of vegetation to climate change and human activity based on NDVI in the Three-River Headwaters region. Acta Ecol. Sin. 31, 5495–5504 (in Chinese).
Li, S., Zhang, Y., Wang, Z., Li, L., 2018. Mapping human influence intensity in the Tibetan Plateau for conservation of ecological service functions. Ecosyst. Serv. 30, 276–286.
Li, S., Zhang, H., Zhou, X., Yu, H., Li, W., 2020. Enhancing protected areas for biodiversity and ecosystem services in the Qinghai Tibet Plateau. Ecosyst. Serv. 43, 101090.
Li, R., Ye, C., Wang, G., Han, G., Sun, J., 2021. Carbon storage estimation and its drivering force analysis based on InVEST Model in the Tibetan Plateau. Acta Agrestia Sin. 29 (S1), 43–51 (in Chinese).
Li, X., Lyu, X., Dou, H., Dang, D., Li, S., Li, X., Li, M., Xuan, X., 2021. Strengthening grazing pressure management to improve grassland ecosystem services. Glob. Ecol. Conserv. 31, e01782.
Liu, M., Zhang, H., Wang, Y., Pei, H., 2021. Characteristics of habitat quality in the agro–pastoral ecotone of northern China based on land uses. Res. Soil. Water Conserv. 28, 156–162 (in Chinese).
Luo, L.H., Duan, Q.T., Wang, L.X., Zhao, W.Z., Zhuang, Y.L., 2020. Increased human pressures on the alpine ecosystem along the Qinghai-Tibet Railway. Reg. Environ. Change 20, 33.
Maes, J., Paracchini, M.L., Zulian, G., Dunbar, M.B., Alkemade, R., 2012. Synergies and trade-offs between ecosystem service supply, biodiversity, and habitat conservation status in Europe. Biol. Conserv. 155, 1–12.
Mallapaty, S., 2020. How China could be carbon neutral by mid-century. Nature 586 (7830), 482–483.
Manning, P., van der Plas, F., Soliveres, S., Allan, E., Maestre, F.T., Mace, G., Whittingham, M.J., Fischer, M., 2018. Redefining ecosystem multifunctionality. Nat. Ecol. Evol. 2, 427–436.
Mao, D., Luo, L., Wang, Z., Zhang, C., Ren, C., 2015. Variations in net primary productivity and its relationships with warming climate in the permafrost zone of the Tibetan Plateau. J. Geogr. Sci. 25, 967–977.
Mu, C., Abbott, B.W., Norris, A.J., Mu, M., Fan, C., Chen, X., Jia, L., Yang, R., Zhang, T., Wang, K., Peng, X., Wu, Q., Guggenberger, G., Wu, X., 2020. The status and stability of permafrost carbon on the Tibetan Plateau. Earth-Sci. Rev. 211, 103433.
Nie, Y., Pritchard, H.D., Liu, Q., Hennig, T., Wang, W., Wang, X., Liu, S., Nepal, S., Samyn, D., Hewitt, K., Chen, X., 2021. Glacial change and hydrological implications in the Himalaya and Karakoram. Nat. Rev. Earth. Environ. 2, 91–106.
Nolan, C., Overpeck, J.T., Allen, J.R.M., Anderson, P.M., Betancourt, J.L., Binney, H.A., Brewer, S., Bush, M.B., Chase, B.M., Cheddadi, R., Djamali, M., Dodson, J., Edwards, M.E., Gosling, W.D., Haberle, S., Hotchkiss, S.C., Huntley, B., Ivory, S.J., Kershaw, A.P., Kim, S.-H., Latorre, C., Leydet, M., Lézine, A.M., Liu, K.B., Liu, Y., Lozhkin, A.V., McGlone, M.S., Marchant, R.A., Momohara, A., Moreno, P.I., Müeller, S., Otto-Bliesner, B.L., Shen, C., Stevenson, J., Takahara, H., Tarasov, P.E., Tipton, J., Vincens, A., Weng, C., Xu, Q., Zheng, Z., Jackson, S.T., 2018. Past and future global transformation of terrestrial ecosystems under climate change. Science 361 (6405), 920–923.
Ostrom, E., 2007a. A diagnostic approach for going beyond panaceas. Proc. Natl. Acad. Sci. U.S.A. 104, 15181–15187.
Ostrom, E., 2007b. Multiorganizational arrangements and coordination: An application of institutional analysis. In: Kaufmann, F.X., Majone, G., Ostrom, V. (Eds.), Guidance, Control, and Evaluation in the Public Sector. Walter de Gruyter, Berlin and New York, pp. 495–510.
Parmesan, C., Yohe, G., 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421 (6918), 37–42.
Peng, S., Piao, S., Wang, T., Sun, J., Shen, Z., 2009. Temperature sensitivity of soil respiration in different ecosystems in China. Soil Biol. Biochem. 41, 1008–1014.
Peterson, G.D., Beard Jr., T.D., Beisner, B.E., Bennett, E.M., Carpenter, S.R., Cumming, G.S., Dent, C.L., Havlicek, T.D., 2003. Assessing future ecosystem services, a case study of the Northern Highlands Lake District. Wisconsin. Conserv. Ecol. 7 (3), 1.
Peyraud, J.L., 2011. The role of grasslands in intensive animal production in north-west Europe: Conditions for a more sustainable farming system. In: Lemaire, G., Hodgson, J., Chabbi, A. (Eds.), Grassland Productivity and Ecosystem Services. CABI, Wallingford, pp. 179–187.
Pfeffer, W.T., Arendt, A.A., Bliss, A., Bolch, T., Ranzi, R., 2014. The Randolph Glacier Inventory: A globally complete inventory of glaciers. J. Glaciol. 60, 537–552.
Piao, S., Fang, J., 2002. Terrestrial net primary production and its spatio-temporal patterns in Qinghai-Xizang Plateau, China during 1982–1999. J. Nat. Resour. 17, 373–380 (in Chinese).
Qian, C., Gong, J., Zhang, J., Liu, D., Ma, X., 2018. Change and tradeoffs-synergies analysis on watershed ecosystem services: A case study of Bailongjiang Watershed, Gansu. Acta Geogr. Sin. 73, 868–879 (in Chinese).
R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing Vienna, Austria.
Ren, H., Han, G., Ohm, M., Schnbach, P., Taube, F., 2015. Do sheep grazing patterns affect ecosystem functioning in steppe grassland ecosystems in Inner Mongolia? Agric. Ecosyst. Environ. 213, 1–10.
Rodriguez, J.P., Beard Jr., T.D., Bennett, E.M., Cumming, G.S., Cork, S.J., Agard, J., Dobson, A.P., Peterson, G.D., 2006. Trade-offs across space, time, and ecosystem services. Ecol. Soc. 11 (1), 28.
Rodriguez-Loinaz, G., Alday, J.G., Onaindia, M., 2015. Multiple ecosystem services landscape index: A tool for multifunctional landscapes conservation. J. Environ. Manage. 147, 152–163.
Roll, U., Feldman, A., Novosolov, M., Allison, A., Bauer, A.M., Bernard, R., Bohm, M., Castro-Herrera, F., Chirio, L., Collen, B., Colli, G.R., Dabool, L., Das, I., Doan, T.M., Grismer, L.L., Hoogmoed, M., Itescu, Y., Kraus, F., LeBreton, M., Lewin, A., Martins, M., Maza, E., Meirte, D., Nagy, Z.T., Nogueira, C.D.C., Pauwels, O.S.G., Pincheira-Donoso, D., Powney, G.D., Sindaco, R., Tallowin, O.J.S., Torres-Carvajal, O., Trape, J.-F., Vidan, E., Uetz, P., Wagner, P., Wang, Y., Orme, C.D.L., Grenyer, R., Meiri, S., 2017. The global distribution of tetrapods reveals a need for targeted reptile conservation. Nat. Ecol. Evol. 1, 1677–1682.
Shaw, M.R., Pendleton, L., Cameron, D.R., Morris, B., Bachelet, D., Klausmeyer, K., MacKenzie, J., Conklin, D.R., Bratman, G.N., Lenihan, J., Haunreiter, E., Daly, C., Roehrdanz, P.R., 2011. The impact of climate change on California's ecosystem services. Clim. Change 109, 465–484.
Sun, H., Zheng, D., Yao, T., Zhang, Y., 2012. Protection and construction of the national ecological security shelter zone on Tibetan Plateau. Acta Geogr. Sin. 67, 3–12 (in Chinese).
Sun, J., Zhou, T., Liu, M., Chen, Y., Shang, H., Zhu, L., Shedayi, A.A., Yu, H., Cheng, G., Liu, G., Xu, M., Deng, W., Fan, J., Lu, X., Sha, Y., 2018. Linkages of the dynamics of glaciers and lakes with the climate elements over the Tibetan Plateau. Earth-Sci. Rev. 185, 308–324.
Sun, J., Liu, M., Fu, B., Kemp, D., Zhao, W., Liu, G., Han, G., Wilkes, A., Lu, X., Chen, Y., Cheng, G., Zhou, T., Hou, G., Zhan, T., Peng, F., Shang, H., Xu, M., Shi, P., He, Y., Li, M., Wang, J., Tsunekawa, A., Zhou, H., Liu, Y., Li, Y., Liu, S., 2020. Reconsidering the efficiency of grazing exclusion using fences on the Tibetan Plateau. Sci. Bull. 65, 1405–1414.
Sun, J., Wang, Y., Piao, S., Liu, M., Han, G., Li, J., Liang, E., Lee, T.M., Liu, G., Wilkes, A., Liu, S., Zhao, W., Zhou, H., Yibeltal, M., Berihun, M.L., Browning, D., Fenta, A.A., Tsunekawa, A., Brown, J., Willms, W., Tsubo, M., 2022a. Toward a sustainable grassland ecosystem worldwide. Innovation 3, 100265.
Sun, J., Ye, C., Liu, M., Wang, Y., Chen, J., Wang, S., Lu, X., Liu, G., Xu, M., Li, R., Liu, S., Zhou, H., Du, Z., Peng, F., Tsunekawa, A., Tsubo, M., 2022b. Response of net reduction rate in vegetation carbon uptake to climate change across a unique gradient zone on the Tibetan Plateau. Environ. Res. 203, 111894.
Tang, W., Xu, S., Zhou, X., Yang, K., Wang, Y., Qin, J., Wang, H., Li, X., 2023. Meeting China's electricity demand with renewable energy over Tibetan Plateau. Sci. Bull. 68, 39–42.
Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven global environmental change. Science 292 (5515), 281–284.
Turner, R.K., Paavola, J., Cooper, P., Farber, S., Jessamy, V., Georgiou, S., 2003. Valuing nature: Lessons learned and future research directions. Ecol. Econ. 46, 493–510.
van Jaarsveld, A.S., Biggs, R., Scholes, R.J., Bohensky, E., Reyers, B., Lynam, T., Musvoto, C., Fabricius, C., 2005. Measuring conditions and trends in ecosystem services at multiple scales: The southern african millennium ecosystem assessment (SAfMA) experience. Philos. Trans. R. Soc. B-Biol. Sci. 360, 425–441.
Venter, O., Sanderson, E.W., Magrach, A., Allan, J.R., Beher, J., Jones, K.R., Possingham, H.P., Laurance, W.F., Wood, P., Fekete, B.M., Levy, M.A., Watson, J.E.M., 2016. Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. Nat. Commun. 7, 12558.
Wang, Y., Dai, E., 2020. Spatial-temporal changes in ecosystem services and the trade-off relationship in mountain regions: A case study of Hengduan Mountain region in Southwest China. J. Clean. Prod. 264, 121573.
Wang, J., Peng, J., Zhao, M., Liu, Y., Chen, Y., 2017. Significant trade-off for the impact of Grain-for-Green Programme on ecosystem services in North-western Yunnan, China. Sci. Total Environ. 574, 57–64.
Wang, Z., Han, G., Hao, X., Zhao, M., Ding, H., Li, Z., Wang, J., Hamilton, A., Liu, Y., Lata, A., Hexige, B., 2017. Effect of manipulating animal stocking rate on the carbon storage capacity in a degraded desert steppe. Ecol. Res. 32, 1001–1009.

Wang, Y., Zi, H., Cheng, R., Tang, L., Suoer, A., Luo, X., Li, J., Wang, C., 2019. Forest soil organic carbon and nitrogen storage and characteristics of vertical distribution in Qinghai Province. Acta Ecol. Sin. 39, 4096–4105 (in Chinese).

Wang, Z., Wang, H., Feng, X., Wang, X., Zhang, L., Fu, B., 2019. Evaluation index system of comprehensive benefits of ecological restoration in key ecologically vulnerable regions. Acta Ecol. Sin. 39, 7356–7366 (in Chinese).

Wang, Y., Sun, J., Ye, C., Zeng, T., 2021. Climatic factors drive the aboveground ecosystem functions of alpine grassland via soil microbial biomass nitrogen on the Qingzang Plateau. Chin. J. Plant Ecol. 45, 434–443 (in Chinese).

Wu, Y., Meng, J., 2022. Quantifying the spatial pattern for the importance of natural resource ecosystem services in China. J. Nat. Resour. 37, 17–33 (in Chinese).

Xie, G., Lu, C., Leng, Y., Zheng, D., Li, S., 2003. Ecological assets valuation of the Tibetan Plateau. J. Nat. Resour. 18, 189–196 (in Chinese).

Xin, Y., Shu, K., Dai, L., Qian, D., Guo, X., Du, Y., 2021. Spatial characteristics of soil organic carbon in Alpine Desert in the Qaidam Basin, Qinghai-Tibet Plateau. Chin. J. Grassland 43 (11), 113–118 (in Chinese).

Xu, W., Xiao, Y., Zhang, J., Yang, W., Zhang, L., Hull, V., Wang, Z., Zheng, H., Liu, J., Polasky, S., Jiang, L., Xiao, Y., Shi, X., Rao, E., Lu, F., Wang, X., Daily, G.C., Ouyang, Z., 2017. Strengthening protected areas for biodiversity and ecosystem services in China. Proc. Natl. Acad. Sci. U.S.A. 114, 1601–1606.

Xu, L., Yang, D., Liu, D., Lin, H., 2020. Spatiotemporal distribution characteristics and supply-demand relationships of ecosystem services on the Qinghai-Tibet Plateau, China. Mt. Res. 38 (4), 483–494 (in Chinese).

Xu, T., Zhao, X., Zhang, X., Wang, X., Geng, Y., Hu, L., Zhao, N., Mao, S., Liu, H., Kang, S., Ma, L., Han, X., Jia, G., Zhao, L., Dong, Q., Chai, S., Xu, S., 2020. Sustainable development of ecological grass-based livestock husbandry in Qinghai-Tibet Plateau Alpine area: Principle, technology and practice. Acta Ecol. Sin. 40, 6324–6337 (in Chinese).

Yang, Y., Rao, S., Hu, H., Chen, A., Ji, C., Zhu, B., Zuo, W., Li, X., Shen, H., Wang, Z., Tang, Y., Fang, J., 2004. Plant species richness of alpine grasslands in relation to environmental factors and biomass on the Tibetan Plateau. Biodiv. Sci. 12 (1), 200–205 (in Chinese).

Yang, B., Wang, S., Chang, Q., Sun, Y., Yin, H., Wang, X., 2015. Response of NPP to phenology changes in the Tibet Plateau. Geogr. Geo-inf. Sci. 31 (5), 115–120 (in Chinese).

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D.B., Joswiak, D., 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. Nat. Clim. Change 2, 663–667.

Ye, C., Sun, J., Liu, M., Xiong, J., Zong, N., Hu, J., Huang, Y., Duan, X., Tsunekawa, A., 2020. Concurrent and lagged effects of extreme drought induce net reduction in vegetation carbon uptake on Tibetan Plateau. Remote Sens. 12 (15), 2347.

Zhang, X., Jin, X., 2021. Vegetation dynamics and responses to climate change and anthropogenic activities in the Three-River Headwaters Region, China. Ecol. Indic. 131, 108223.

Zhang, L., Hickel, K., Dawes, W.R., Chiew, F.H.S., Western, A.W., Briggs, P.R., 2004. A rational function approach for estimatingmean annual evapotranspiration. Water Resour. Res. 40 (2), 89–97. doi:10.1029/2003WR002710.

Zhang, X., Niu, J., Zhang, Q., Dong, J., Zhang, J., 2016. Spatial pattern of water conservation function in grassland ecosystem in the Xilin River Basin, Inner Mongolia. Arid Zone Res. 33 (4), 814–821 (in Chinese).

Zhang, L., Fan, J., Zhou, D., Zhang, H., 2017. Ecological protection and restoration program reduced grazing pressure in the Three-River Headwaters Region, China. Rangeland Ecol. Manage. 70, 540–548.

Zhang, Z., Zhou, H., Zhao, X., Yao, B., Ma, Z., Dong, Q., Zhang, Z., Wang, W., Yang, Y., 2018. Relationship between biodiversity and ecosystem functioning in alpine meadows of the Qinghai-Tibet Plateau. Biodiv. Sci. 26 (2), 111–129 (in Chinese).

Zhang, G., Yao, T., Xie, H., Yang, K., Zhu, L., Shum, C.K., Bolch, T., Yi, S., Allen, S., Jiang, L., Chen, W., Ke, C., 2020. Response of Tibetan Plateau lakes to climate change: Trends, patterns, and mechanisms. Earth-Sci. Rev. 208, 103269.

Zheng, D., Zhao, D., 2017. Characteristics of natural environment of the Tibetan Plateau. Sci. Technol. Rev. 35 (6), 13–22 (in Chinese).