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Emergy-based ecosystem services valuation and classification management applied to China's grasslands

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ABSTRACT

Though grasslands cover one fifth area of global land and provide vital services for humans, half of them are degraded due to human interference and climate change. In this paper we perform evaluations of the delivery of ecosystem services (ES) of grasslands using a systems approach and the technique of emergy accounting. Firstly, we address the issue of anthropocentricity of ES through discussion and analysis using the concept of emergy as contrasted to economic value, i.e. willingness-to-pay. Secondly, we explore from a systems classification of provisioning, regulating, cultural and supporting services. Thirdly, we provide quantitative analysis of the value added (surplus value) to economies by ecosystems. An emergy-based index of classification management of grassland (ICG), is also implemented, together with a non-monetary benefit-cost analysis of grassland ES. It is established that emergy provides an approach to evaluating the contributions ecosystems make to the economy using the idea of net benefit ratio, computed as the emergy cost of providing a service through technology (aka replacement cost) divided by emergy required to sustain ecosystem functions. This study can provide a systematic biophysical accounting method for grassland ESV to implement future sustainable management practices.

1. Introduction

Globally, grassland ecosystems cover 3.2 billion ha, contributing to 20% of global land surface and playing important roles in ecological balance and human livelihood (Straton, 2006; Han et al., 2018; Villoslada Peciña et al., 2019). However, about 50% global grasslands have been degraded due to climate change and human disturbance (Harris, 2010; Seto et al., 2011; Zhan et al., 2017).

Grassland degradation leads to several ecosystem services (ES) decline, such as biomass and biodiversity loss, soil erosion and so on (Turner et al., 2001; Wei et al., 2017; Yang et al., 2019). To prevent a further degradation of grasslands, many countries implemented several projects, like the Conservation Reserve Program (CRP) Grasslands in the United States (USDA, 2014), the "Control grazing for grassland recovery" and the "Grassland ecological compensation incentive mechanism" in China (Liu et al., 2018). Yet, these practices remain unwelcome, because decrease in the intensity of grazing apparently reduces farmers' income (Guo et al., 2006). This public reaction unveiled two contrasting visions: conservation and production.

To solve this contradiction, Guo et al. (2003) proposed an index of classification management of grassland (ICG), i.e. the ratio of the monetary value of livestock productivity to the sum of monetary value of livestock productivity and ES, to assess the relative significance of production and ES (Liu et al., 2018).

Previously, ecosystem services valuation (ESV) measurements were mainly based on money as a common measure unit (Murray, 2013) because a monetary value is easier for decision-makers to monitor a policy (Greenhalgh et al., 2017). However, this application reflects a univocal perspective based only on human preferences (Franzese et al., 2017). Moreover, value expressed in monetary unit does not equal to market value (Costanza et al., 2017). Besides, this method reflects societal values with a limited time-horizon (Mellino et al., 2015), ignoring future generations and other species (Brown and Ulgiati, 2011), and offering a finite perspective on ecological benefits (Franzese et al.,

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2017). Then, a systemic perspective was suggested as an alternative to achieve a more comprehensive insights into ESV (Häyhä and Franzesea, 2014).

Among the available holistic approaches, emergy has gained a growing interest in scientific communities. Introduced by ecologist H.T. Odum and his followers, emergy refers to the available energy required directly and indirectly to make a service or good (Odum, 1996). Emergy is already applied to measure natural capital and ESV by assessing the costs of their generation from a donor-side perspective. For example, Brown and Ulgiati (1999) measured the natural resources flows and natural capital using emergy. Campbell and Tilley (2014) evaluated the forest ESV in Maryland applying biophysical measurement. Franzese et al. (2017) assessed the environmental costs to generate the ES flows and natural capital at marine protected areas.

Emergy-based grasslands ESV evaluation is still missing in the literature. To fill this research gap, this study proposes a coherent accounting method to assess grasslands ESV based on emergy to develop alternative efficient and sustainable grassland classification management strategies.

2. Accounting method on grassland ESV

2.1. China's grassland ecosystems classification

Grasslands are areas where the vegetation is dominated by grasses (Ma et al., 2016). China's grassland types are currently determined at 1-km resolution: meadows, steppe and tussock. Meadow is perennial grass and vegetation growing under low temperature and moderately humid conditions. Belonging to mesophytes and non-zonal vegetation, it includes dry mid-lying plants (Kang et al., 2007). Steppe is vegetation composed by xerophytes under temperate semi-arid climate with a single vegetation type. It is a zonal vegetation distributed in the north of China and the Qinghai-Tibet Plateau (NRC, 1992). Tussock is mesophyte, xerophyte and perennial herbaceous community, belonging to zonal vegetation distributed in the eastern and southern China.

2.2. Grassland ES classification system

Yang et al. (2018) divided ES into three categories: direct, indirect and existing. In this study, direct services include net primary production (NPP), carbon sequestration, soil building and groundwater replenishment. Indirect services include air, soil purification, soil retention and microclimate regulation. Existing services including climate regulation and biodiversity contribution, services based on human's preferences, such as cultural and educational ones. Fig. 1 shows the specific grasslands ES classification system.

2.3. Diagram representation

Fig. 2 shows the emergy diagram of grassland ES. From left to right side, renewable resources, such as sunlight and rain, drive the photosynthesis, resulting in NPP and carbon sequestrated from air to plants. Detritus, derived from dead plants and other components, is the main source of soil organic matter in the natural state. In parallel, soil minerals are formed through rock weathering. Both soil organic matter and minerals are sources of soil building. Due to the cover of grasslands, soil is retained, resulting in soil retention.

Grasslands also have the capacity to purify air, water and soil pollutants by various physical, chemical and biological processes, which benefit human health and ecosystem quality. From top to bottom, rainfall are the sources of surface and ground water. Groundwater can be recharged by both atmospheric precipitation and surface water infiltration. Meanwhile, water evaporation, also originating from rainfall, and plants transpiration have the function of regulating microclimate, such as humidification and cooling. From micro scale to macro scale, local grasslands play a role in regulating climate, contributing biodiversity, delivering cultural and educational information, which are at the right side of the boundary due to their higher hierarchy.

2.4. Accounting techniques on grassland ESV

2.4.1. Direct services

2.4.1.1. NPP. NPP refers to the photosynthetic gain of plants per unit area, minus respiratory costs (Jmo et al., 2002). Photosynthesis is driven by local renewable resources. Therefore, NPP is calculated as:

$$Em_{\mathrm{NPP}} = \sum_{i=1}^{n} (\mathrm{MAX}(R_i)) \tag{1}$$

where Em_{NPP} represents the emergy needed by NPP in a given area (sej/y); $\mathrm{MAX}(R_i)$ is the maximum value among the renewable resources in grassland ecosystem *i* (sej/y). According to Yang et al. (2018), it can be calculated as follows:

$$\begin{aligned}\mathrm{MAX}(R) &= \mathrm{MAX}[\Sigma(\text{solarenergy, tidalenergy, thermalenegry}), \text{waveenergy, windenergy, rain} \\ &\quad (\text{chemicalpotentialenergy}), \text{runoff(geopotentialenergy)}, \text{runoff(chemicalpotential)}]\end{aligned} \tag{2}$$

2.4.1.2. Carbon sequestration. It is estimated that 0.2–0.8 Gt CO_2 per year can be sequestrated by global grassland soils by 2030 (Ghosh and Mahanta, 2014). The calculation formula of carbon sequestration is:

$$Em_{\mathrm{CS}} = \sum \left(\frac{C_i}{T_i} * S_i * UEV_{\mathrm{cs}i} \right) \tag{3}$$

$$UEV_{\mathrm{cs}i} = \frac{(Em_i)/S_i}{NPP_i} \tag{4}$$

where Em_{CS} indicates the emergy used to sequestrate carbon in grasslands (sej/y); refers to the carbon sequestrated in grassland ecosystem *i* (g C/m^2); T_i is the average turnover time of carbon pool in grassland ecosystem *i* (y); S_i represents the area of grassland ecosystem *i* (m^2);$UEV_{\mathrm{cs}i}$ means the unit emergy value (UEV) of carbon sequestration in grassland ecosystem *i* (sej/g); $Em_{\mathrm{NPP}i}$ is the renewable emergy driving NPP of grassland ecosystem *i* (sej/y), which is $Em_{\mathrm{NPP}i}$ in Eq. (1); NPP_i is the NPP of grassland ecosystem *i* (g C/m^2/y).

2.4.1.3. Soil building. Soil formation through accumulation and decay of organic matter and mechanical and chemical weathering processes (Earle, 2015), which is the interaction of five main factors: parental material, vegetation, climate, topography and time (Jenny, 1994). It needs incredible long time to form soil varying with the climate factors: (1) 200–400 years to form 1 cm of soil in a mild climate; (2) around 200 years in wet tropical areas; (3) about 3000 years to accumulate sufficient substances to form soil fertile (Eni, 2019). In this study, we mainly consider annual contribution of vegetation and parent rocks to soil building.

2.4.1.3.1. Soil organic matter building. Organic matter input into grassland soil occurs in the form of plant tissue (Lemaire et al., 2011; Zhao et al., 2014). In grasslands, dead plants are transformed by different kinds of living organisms, which is the source of soil organic matter. Note that the dead plants here are the annually newly formed grasslands litter with the turnover time of one year. Consequently, the emergy used to build grassland soil organic matter is calculated as the reassignment of annual local renewable resources as follows:

$$Em_{\mathrm{OM}} = \sum_{i=1}^{n} (Em_{\mathrm{re}i} \times k_{1i} \times k_2) = \sum_{i=1}^{n} (Em_{\mathrm{NPP}i} \times k_{1i} \times k_2) \tag{5}$$

where Em_{OM} indicates the emergy applied to build soil organic matter (sej/y); $Em_{\mathrm{re}i}$ is the renewable emergy of grassland ecosystem *i* (sej/y), equal to Em_{NPP} in Eq. (1); k_{1i} means the ratio of the grassland detritus to the biomass of grassland ecosystem *i* (g/g, %); k_2 represents the carbon

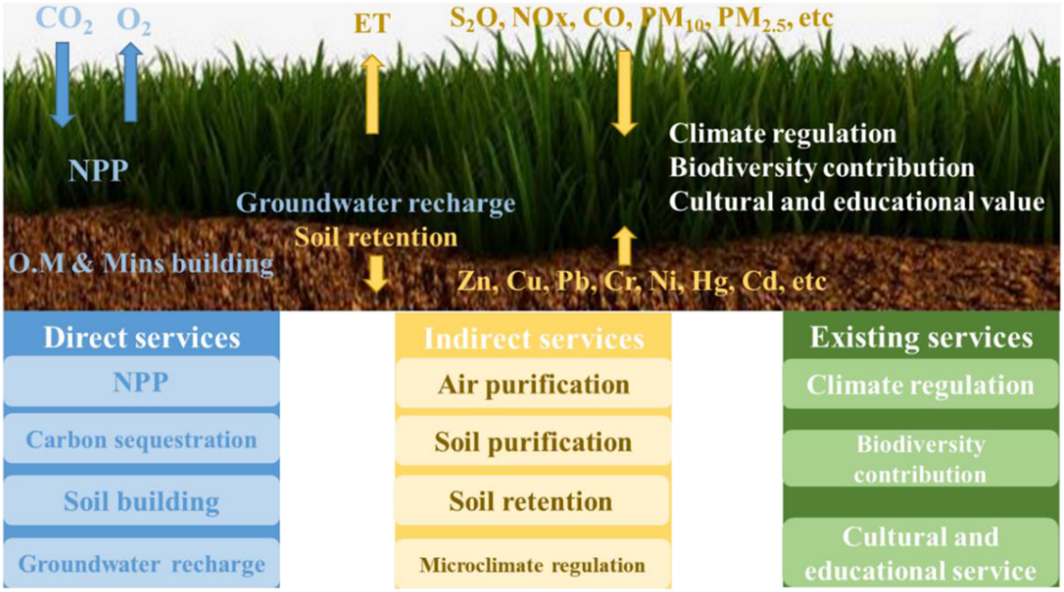


Fig. 1. The classification of grassland ES (OM: Organic matter; Mins: Minerals; ET: Evapotranspiration).

amount in detritus (g/g, %).

2.4.1.3.2. Soil minerals building. Parent rocks are sources of soil minerals through weathering driven by the interaction of geologic processes and climatic factors (Campbell, 2012). Geologic processes can drive various soil minerals formation simultaneously. Therefore, the maximum value of emergy required to form different minerals is taken as the final soil mineral building service and calculated as:

$$Em_{\mathrm{MIN}} = \mathrm{Max}(((P_{mij} \times BD_j \times D_j \times S_j \times R \times 10000)/T_i) \times UEV_{mi}) \tag{6}$$

where Em_{MIN} is the emergy used to build soil minerals (sej/y); P_{mi} is the proportion of ith mineral to total soil mineral of grassland ecosystem j (%); BD_j is the soil bulk density of j-th grassland ecosystem (g/cm^3); D_j represents the soil depth of the j-th grassland ecosystem (cm);S_j is the area of the j-th grassland ecosystem (m^2); R indicates the percentage of soil mineral to total soil mass (%), which is 95% in this study (Liu, 2009); 10,000 is the conversion factor from m^2 to cm^2; T_i is the turnover time of mineral i (y), estimated as 1000 years due to the lack of data; UEV_{mi} indicates the UEV of mineral i (sej/g).

Soil building service is quantified as:

$$Em_{\mathrm{SB}} = Em_{\mathrm{OM}} + Em_{\mathrm{MIN}} \tag{7}$$

2.4.1.4. Groundwater recharge. Groundwater recharge refers to a hydrologic process, through which surface water enters to groundwater (Freeze and Cherry, 1979). It can be esteemed as:

$$Em_{\mathrm{GR}} = \sum_{i=1}^{n} (P_i \times S_i \times \rho \times k_i \times 1000 \times G_w \times UEV_{\mathrm{wi}}) \tag{8}$$

where Em_{GR} indicates the emergy applied to recharge groundwater (sej/y); P_i means the precipitation in grassland ecosystem i (m/y);S_i represents the area of grassland ecosystem i (m^2); ρ means water density (kg/m^3); k_i refers to precipitation infiltration coefficient of grassland ecosystem i (%); 1000 is the conversion factor from kg to g; G_w means Gibbs free energy of water (J/g); UEV_{wi} indicates the UEV of rainfall (sej/J).

2.4.2. Indirect services

2.4.2.1. Air purification. Disability Adjusted Life Years (DALYs) and

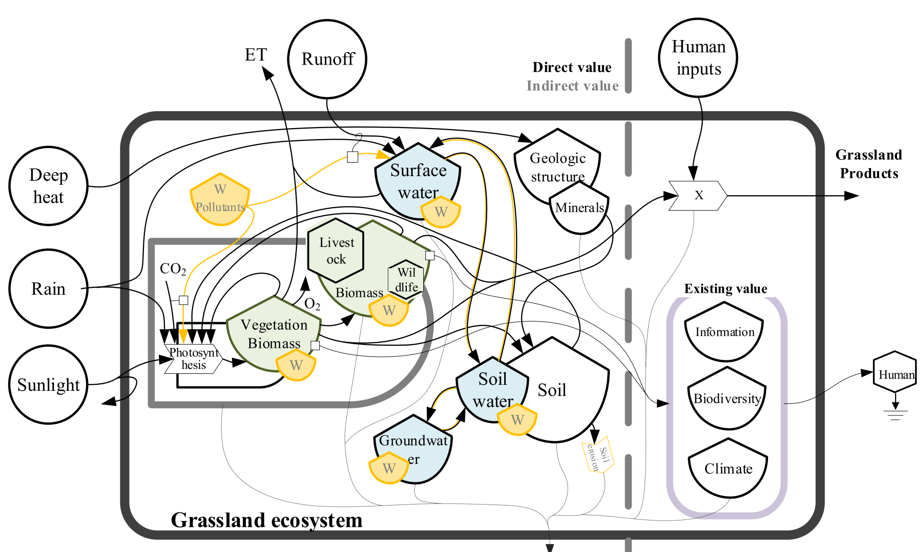


Fig. 2. The Emergy diagram of grassland ecosystems services (ET: evapotranspiration).

Potentially Disappeared Fraction (PDF) of species are applied to measure air purification service. These factors were introduced in the assessment framework of Eco-Indicator 99 proposed by Goedkoop and Spriensma (2001). The meaning of DALYs and PDF and the reason for selecting them as indicators related to ES were given by Goedkoop and Spriensma (2001) and Yang et al. (2018). Air pollutants including SO_2, fluoride, NO_x, CO, O_3, PM_{10} and $PM_{2.5}$ are investigated in this study. Considering the impacts of pollutants on human and ecosystem are variable, the benefits of air purification are given as the cumulative decline in human health losses and ecosystem quality degradation. The calculation formulas are detailed hereafter.

2.4.2.1.1. Decline in human health losses.

$$Em_{\mathrm{HH}} = \sum_{i=1}^{n} (M_{ij} \times S_j \times \mathrm{DALY}_i) \times \tau_H \tag{9}$$

where Em_{HH} is the emergy applied to reduce human health decline (sej/y); M_{ij} represents the capacity of grassland ecosystem j to absorb the ith air pollutant (kg/ha/y); S_j indicates the area of grassland ecosystem j (ha); DALY_i refers to the DALY of one individual generated by the ith air pollutant (cap*y/kg); τ_H is the emergy per capital (sej/cap).

2.4.2.1.2. Decline in ecosystem quality degradation.

$$Em_{\mathrm{EQ}} = \sum_{i=1}^{n} (M_{ij} \times \mathrm{PDF}_i \times Em_{\mathrm{sp}j}) = \sum_{i=1}^{n} (M_{ij} \times \mathrm{PDF}_i \times \mathrm{MAX}(R_j)) \tag{10}$$

where Em_{EQ} indicates the emergy needed to decrease the ecosystem quality degradation (sej/y); M_{ij} has the same meanings as M_{ij} in Eq. (9); PDF_i represents the PDF of species brought from air pollutant i (PDF × ha × y × kg^{-1}); $Em_{\mathrm{sp}j}$ means the emergy needed by the species in grassland ecosystem j (sej/y); $\mathrm{MAX}(R_j)$ has the same meaning as $\mathrm{MAX}(R_i)$ in Eq. (1) with the exception of different subscripts.

Air purification service (Em_{AP}) is measured as:

$$Em_{\mathrm{AP}} = Em_{\mathrm{HH}} + Em_{\mathrm{EQ}} \tag{11}$$

2.4.2.2. Soil purification. The same approach used for air purification service can be extended to calculate soil purification (Em_{SP}). Note that the M_{ij}, DALY_i and PDF_i in Eqs. (9) and (10) need to be replaced with the ability to purify soil pollutants and the damage indicators (DALY_i and PDF_i) referred to soil pollution.

2.4.2.3. Soil retention. Generally, on relatively flat grassland and/or forest-covered land, erosion rate ranges from a low level of 0.001–2 t/ha/y to a rate of 1–5 t/ha/y on mountainous areas with normal vegetation cover (Pimentel and Kounang, 1998). This soil retention ability is quantified as:

$$Em_{\mathrm{SR}} = \sum_{i=1}^{n} (G_i \times S_i \times r_{omi} \times 10^6 \times k_{r1} \times k_{r2} \times \mathrm{UEV}_{sl}) \tag{12}$$

where Em_{SR} is the emergy needed by soil retention (sej/y); G_i represents the amount of soil retention due to the cover of grassland ecosystem i (t/ha/y); S_i indicates the area of grassland ecosystem i (ha); r_{omi} is the soil organic matter content in grassland ecosystem i (%); 10^6 is the conversion factor from ton to gram (g/t); k_{r1} is the conversion factor from g to kcal (kcal/g); k_{r2} is the conversion factor from kcal to J (J/kcal); UEV_{sl} is the transformity of soil (sej/J).

2.4.2.4. Microclimate regulation. Vegetation helps cool microclimate by evapotranspiration. In particular, leaves decrease solar radiation, which reaches the area below plant canopy, leading to lower surface temperature there (Gaitani et al., 2011). Additionally, as water evaporates from the vegetation pores, it absorbs heat, cooling the ambient air during this process (Akbari et al., 1997; EPA, 2008; Picot, 2004). Therefore, microclimate regulation based on evapotranspiration is calculated as:

$$Em_{\mathrm{MR}} = \sum_{i=1}^{n} (E_{ei} \times S_i \times \rho_w \times 1000 \times (1 - \alpha_i) \times G_w \times \mathrm{UEV}_{we}) \tag{13}$$

where Em_{MR} represents the emergy applied to regulate microclimate (sej/y); E_{ei} is the evapotranspiration in grassland ecosystem i (m/y); S_i is the area of grassland ecosystem i (m^2); ρ_w is water density ($\mathrm{kg/m}^3$); 1000 represents the conversion factor from kg to g;α_i is the proportion of water consumed by photosynthesis in the evapotranspiration process (%); G_w has the same meaning as G_w in Eq. (8); UEV_{we} is the UEV of water transpiration (sej/J). Evapotranspiration (E_{ei}) here includes evaporation from grassland (i.e. evaporation from grassland soil and detritus layer), canopy interception and grass transpiration.

2.4.3. Existing services

2.4.3.1. Climate regulation. Globally, grasslands contribute approximate to 34% of the terrestrial carbon stock (WRI, 2000). Climate regulation service is quantified by the reduction of damages to human health considering greenhouse gases (GHGs) sequestrating by ecosystems. GHGs including CO_2, CH_4, NOx and HFCs are investigated in this study. The measurement of this service is:

$$Em_{\mathrm{cr1}} = \sum C_{ij} \times \frac{\mathrm{DALY}_i}{T_i} \times S_j \times \tau_H \tag{14}$$

$$Em_{\mathrm{cr2}} = \sum C_{ij} \times \frac{\mathrm{PDF}_i}{T_i} \times Em_{\mathrm{sp}j} \tag{15}$$

where Em_{cr1} is the emergy used to regulate climate resulting in the decline in human health losses in grassland ecosystem (sej/y); Em_{cr2} is the emergy applied to regulate climate leading to the decline in ecosystem quality degradation in grassland ecosystem (sej/y); C_{ij} represents the sequestration of greenhouse gas i in grassland ecosystem j ($\mathrm{kg/m^2/y}$); DALY_i is the DALY resulting from the greenhouse gas i (capital*year/kg); T_i means the lifetime of the ith greenhouse gas (y); S_j refers to the area of grassland ecosystem j (m^2); τ_H represents the emergy per capita in study area (sej/cap); PDF_i means the PDF of species caused by greenhouse gas i (PDF × ha × y × kg^{-1}); $Em_{\mathrm{sp}j}$ has the same meaning and measurement as the $Em_{\mathrm{sp}j}$ in Eq. (10).

The climate regulation (Em_{CR}) service is the sum of Em_{cr1} and Em_{cr2}.

2.4.3.2. Biodiversity contribution. Biodiversity contribution is the contribution of local biodiversity to global biodiversity. For example, China is the only habitat for giant panda. Consequently, the extinction of giant panda in China would cause the global extinction of giant panda. This indicates the biodiversity of giant panda in China is extremely relevant to global biodiversity of giant panda. Therefore, the global biodiversity importance index (BII) is needed to evaluate the relative contribution to global biodiversity, which can be accounted as:

$$Em_{\mathrm{bio}} = \sum (BII_{ij} \times GR) \tag{16}$$

where Em_{bio} represents the emergy needed by biodiversity contribution of grasslands (sej/y); BII_{ij} is the BII of the i-th specie in the j-th grassland (%); GR is the emergy of annual global renewable resources (sej/y).

Due to lack of ecosystems BII data, this service is not evaluated in this study.

2.4.3.3. Cultural and educational value. This study has not found a reasonable approach to assess cultural and educational value of grasslands. Previously, Abel (2013) introduced an information criterion to evaluate educational and cultural values on emergy basis. Yet, being the information carried by grassland ecosystems unavailable, this service is not evaluated in this study.

Because NPP, carbon sequestration, soil building and groundwater recharge are driven by local renewable resource, to avoid double counting, take the maximum of these four services as the final direct service. Therefore, the total ESV in one case area in this study can be calculated as follows:

$$\mathrm{ESV} = \sum (\mathrm{Max}(Em_{\mathrm{NPP}}, Em_{\mathrm{CS}}, Em_{\mathrm{SB}}, Em_{\mathrm{GR}}), Em_{\mathrm{AP}}, Em_{\mathrm{SP}}, Em_{\mathrm{SR}}, Em_{\mathrm{MR}}, Em_{\mathrm{CR}}) \tag{17}$$

2.5. ESV correction based on vegetation fraction

The same vegetation area and type may have different vegetation growth conditions and vegetation coverage features, indicating the ESV results based on ecosystem areas are needed to be modified using an indicator capturing these characteristics. Vegetation fraction (VF), i.e. the fraction of vegetation canopy coverage or occupation in a given ground area in vertical projection, is used to monitor these features. VF is commonly measured through a linear model based on Normalized difference vegetation Index (NDVI) as follows (Montandon and Small, 2008):

$$\mathrm{VF}_i = \frac{\mathrm{NDVI}_i - \mathrm{NDVI}_{\min}}{\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}} \tag{18}$$

$$S_i^{'} = S_i \times \mathrm{VF}_i \tag{19}$$

where VF_i is the VF of grassland ecosystem i; NDVI_i is the NDVI of the grassland i; $\mathrm{NDVI}_{\min}$ and $\mathrm{NDVI}_{\max}$ are the minimum and maximum NDVI in the study area respectively, which can be obtained from the remote sensing image; S_i is the area of grassland ecosystem i (m^2); $S_i^{'}$ is the area of grassland ecosystem i applied to calculated the modified ESVs (m^2). Specifically, ecosystem areas in Eqs. (1)–(15) should be multiplied their corresponding VFs to obtain the modified ESVs. Each of ESV result in this study are the modified ESVs and the indicators calculated by ESVs are based on the modified ESVs.

2.6. Emergy-based index of grassland classification management

2.6.1. The traditional ICG index

The monetary value of livestock productivity in ICG model proposed by Guo et al. (2003) is computed by the carrying capacity assessed through the product of sheep units and price (Liu et al., 2018). ICG is defined as:

$$\mathrm{ICG} = \frac{40 \times \mathrm{PS}^{'} \times \mathrm{CC}}{40 \times \mathrm{PS}^{'} \times \mathrm{CC} + \mathrm{ES}} = \frac{40 \times \mathrm{CC}}{40 \times \mathrm{CC} + \mathrm{ES}} \tag{20}$$

where 40 indicates 40 kg live weight in the market; $\mathrm{PS}^{'}$ means a fixed price of sheep, which is 1$/kg in this model (Guo et al, 2003); CC represents annual grassland carrying capacity (the number of sheep per unit area); ES is grassland ESV per unit area ($/ha). A grassland should be classified into conservation, moderately productive and conservation sector when ICG is less than 0.25, from 0.25 to 0.75, and larger than 0.75 respectively (Guo et al., 2006).

2.6.2. Emergy-based ICG index

An emergy-based ICG index (ICG′) is developed to provide grassland classification management from biophysical perspective. In particular, the carrying capacity for the selected area is quantified by the local renewable resources in emergy terms as the modified ecological footprint approach proposed by Zhao et al. (2005). Its formula is:

$$\mathrm{ICG}^{'} = \frac{\mathrm{MAX}(R)}{\mathrm{MAX}(R) + \mathrm{ESV}} \tag{21}$$

where $\mathrm{ICG}^{'}$ means emergy based ICG; MAX(R) represents the emergy of renewable resources per unit area (sej/m^2/y), indicating the carrying capacity of local grasslands; ESV is the local grassland ESV (sej/m^2/y). The measurements of MAX(R) and ESV can be found in Eqs. (1)–(16). Because NPP, carbon sequestration, soil building and groundwater recharge are driven by renewable resources, i.e. MAX(R), therefore, ESV here is the sum of indirect and existing services.

2.6.3. Non-monetary benefit-cost analysis

Grassland ESV costs in this study are quantified by the emergy supporting the generation of local renewable resources, i.e. MAX(R). Air, soil purification and climate regulation are the benefits derived from grassland ES, evaluated using the decline in human health losses and ecosystem quality degradation. The benefit-cost ratio (BCR) can be calculated as:

$$\mathrm{BCR}_i = \frac{\mathrm{MAX}(R)}{\mathrm{ESV}_i} \tag{22}$$

where BCR_i and ESV_i are the BCR and valuation of ecosystem service i.

2.7. Case study: China's grassland ecosystems

Grassland is the largest terrestrial ecosystem in China. Mainland China has 3.94E + 08 ha of grassland, contributing 40% and 13% to China's and world's grassland area respectively (EBCAY, 2015; Han et al., 2018). However, approximately 22% of China's grasslands are degraded (Bao et al., 1998) and nearly 90% of grasslands in North China are degraded to different extent (Nan, 2010), while degraded areas still increasing annually (Feng et al., 2015). Therefore, the sustainability improvement of China's grassland ES is highly urgent. An example of full calculation process and whole data sources are detailed in supporting information (S1 and S2 respectively).

3. Results

3.1. The spatial distribution of grassland ESV

Fig. 3 shows the spatial distribution of China's grassland ESV. Generally, the grassland ESV in northern and western China are larger than that in southern China. In parallel, western and southern China have larger grassland ESV per unit area than that in northern China. Specifically, Tibet has the largest grassland ESV (1.72E + 23 sej/y), followed by Inner Mongolia (3.29E + 22 sej/y), Qinghai (2.49E + 22 sej/y) and Xinjiang (1.84E + 22 sej/y) so on. This is consistent with their larger grassland areas than other provinces. Steppe ecosystems contribute most to their larger grassland ESV, followed by meadow ecosystems, except for Qinghai province with meadow as the largest one, followed by steppe. While Shanghai has the smallest grassland ESV (5.20E + 18 sej/y), followed by Tianjin (1.75E + 19 sej/y), Hainan (1.91E + 19sej/y) and Jiangsu (1.98E + 19sej/y).

With respect to ESV per unit area, Tibet also ranks first with the value of 8.01E + 11sej/m^2/y, followed by Yunnan, Guizhou, Ningxia and so on. Conversely, Gansu, Henan, Shandong, Hebei, Shaanxi and Inner Mongolia have a relatively smaller grassland ESV per unit area. This indicates the larger grassland area of Inner Mongolia is the cause of its larger grassland ESV.

3.2. The spatial distribution of different grassland ES

Fig. 4 shows the spatial distribution of China's grassland value of different ES types. NPP in China is concentrated in southwest China (including Yunnan-Kweichow Plateau, Sichuan and Tibetan Plateau), contributing 46% to China's total grassland NPP. Grasslands in these areas as well as in Ningxia, Xinjiang and Gansu, account for 83% of carbon sequestration in China. The remaining provinces in China just provide 17% of total carbon sequestration. Consequently, grasslands in western China account more than 80% for the total carbon sequestration of China's grasslands. With respect to soil building, Yunnan has the largest service (5.38E + 10 sej/m^2/y), followed by Guizhou (3.70E + 10 sej/m^2/y) and Sichuan (2.83E + 10 sej/m^2/y) province.

Fig. 4 indicates Tibet and Northern Shaanxi have a relative higher soil building service (2.04E + 10 and 1.88E + 10 sej/m^2/y

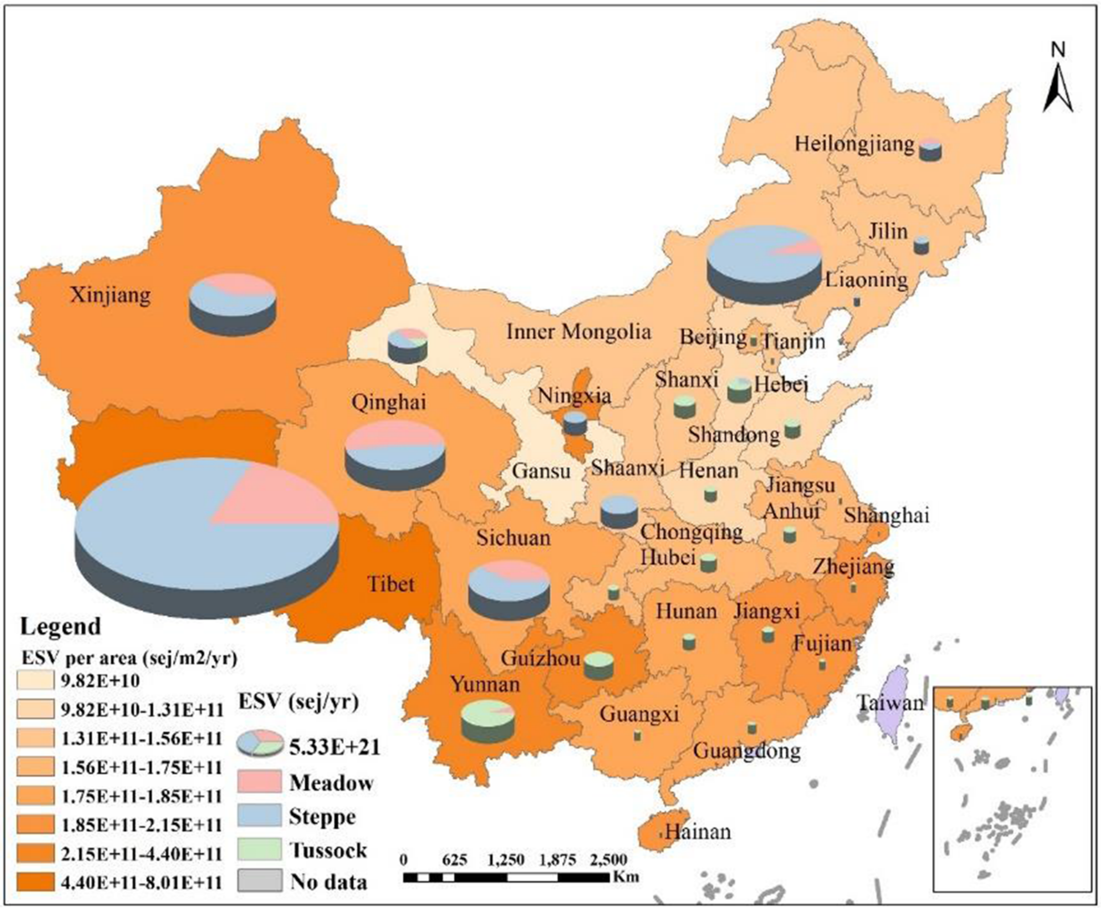


Fig. 3. The spatial distribution of grassland ESV in 2010.

respectively). Compared to NPP, carbon sequestration and soil building, groundwater recharge service of China's grasslands has different distribution characteristics. Eastern and central China, in aggregate, has larger groundwater recharge service than that in western China. Specifically, though Hainan has the second smallest grassland area, it owns the largest groundwater recharge service per unit area, which is 2.62E + 10 sej/m^2/y. Other provinces in eastern and central China, including Jiangxi, Fujian, Zhejiang, Hunan, Guangdong and so on, also belong to regions with relative higher groundwater recharge services per unit area.

The important areas of air and soil purification are mainly distributed in provinces with higher emergy per capita, such as Beijing, Qinghai, Xinjiang, Tibet, Tianjin, Shanghai and so on (Lin et al., 2018). This is because the air and soil purification capacity of the same grassland type are the same in this study. As to soil retention, western and central China provide a higher soil retention service. Instead, Tibet, Xinjiang, Qinghai, Gansu and Sichuan provinces just account for 14% to China's soil retention service, though their grasslands areas cover 64% of China's grasslands areas. Microclimate regulation service mainly concentrates in southern and southeast coastal provinces. Specifically, Guangdong, Guangxi, Fujian, Jiangxi, Zhejiang, Hunan, Hainan, Anhui, Guizhou, these nine provinces provide 34% microclimate regulation services to China. While their grasslands areas only account for 1.23% to China's grasslands. Northern China, especially in Xinjiang, Inner Mongolia, Tibet, Ningxia and Qinghai, have less microclimate regulation service due to their less precipitation and evapotranspiration.

Climate regulation service is more relevant in Tibetan Plateau (including Qinghai (1.18E + 10 sej/m^2/y) and Tibet (1.08E + 10 sej/m^2/y)), the Tianshan Mountains, Kunlun Mountains (e.g. Xinjiang (1.08E + 10 sej/m^2/y)) and Inner Mongolia grassland (6.14E + 09 sej/m^2/y). Eastern China, including Beijing, Tianjin and Shanghai, contribute 14% to China's climate regulation, while their grasslands areas only account for 0.07% to China's grasslands. This fact is related to their higher emergy per capita.

3.3. Emergy-based ICG (ICG′) and China's grassland classification management

Table 1 shows that 27% of China's grasslands belong to intensively productively sector, and 82% of grasslands in North China are divided into intensively and moderately productive sector, which are consistent with the previous research results, i.e. approximately 22% of China's grasslands are degraded (Bao et al., 1998) and nearly 90% of grasslands in North China are degraded to different extent (Nan, 2010). MPS provinces account for 55% of total grasslands areas, indicating the great potential degradation, and urgent need for grassland ecosystems restoration and conservation policies. The grasslands area of MPS and IPS provinces in North China contribute 90% to the total MPS and IPS grassland ecosystems, which means grasslands protection pressure in North China is larger than that of in South China. This is partly because grasslands area in North China is much larger than that of in South China.

As to provincial scale, Fig. 5(a) indicates that most western provinces belong to moderately productive sector, except for Tibet, classified into productive sector. Northeast, Inner Mongolia, Guangdong and north China (except for Hebei) are classified into conservation sector.

China's steppe ecosystems (Fig. 5(b)) have similar ICG′ distribution characteristics to China's meadow ecosystem, with productive sector only in Tibet and most moderately productive sector in western

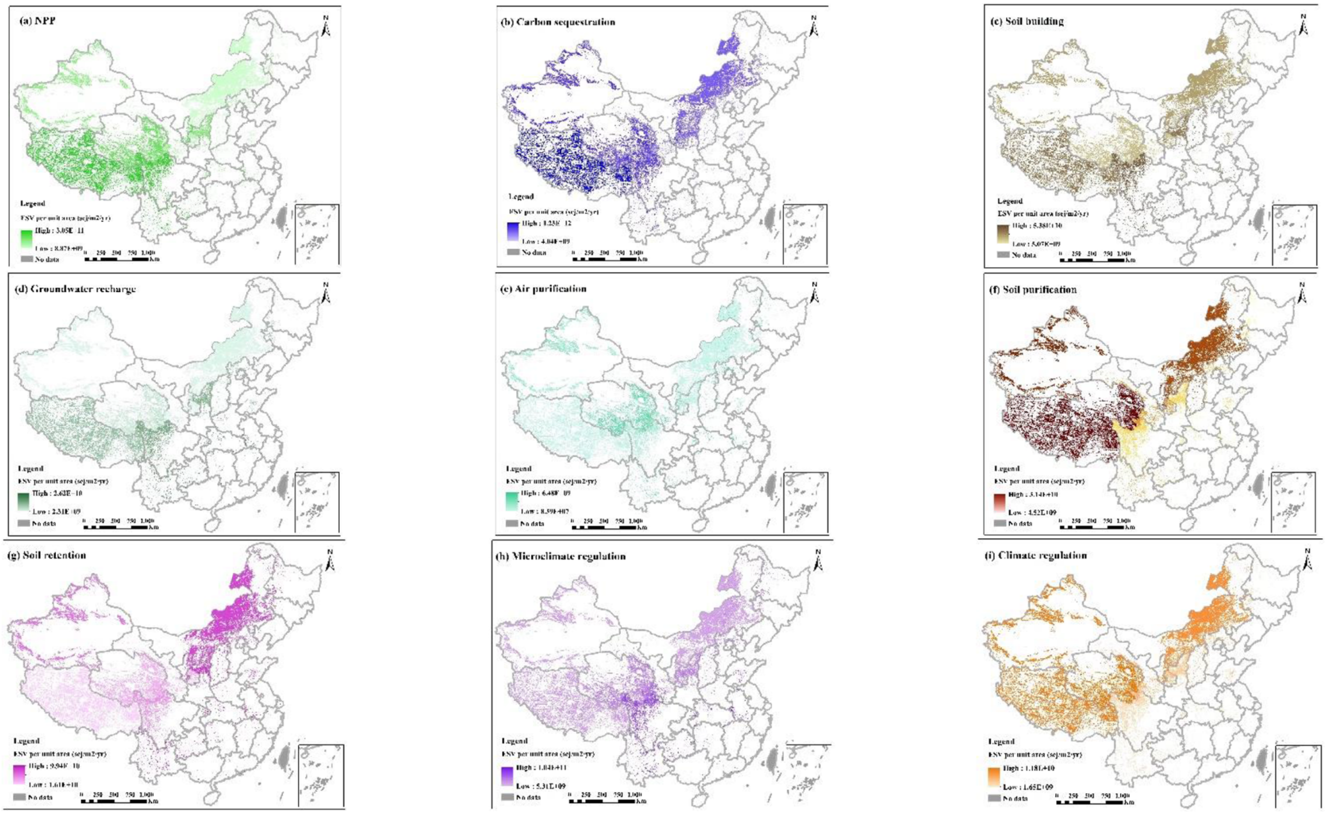


Fig. 4. The spatial analysis of China's different grassland ecosystem service in 2010 ((a) NPP; (b) Carbon sequestration; (c) Soil building; (d) Groundwater recharge; (e) Air purification; (f) Soil purification; (g) Soil retention; (h) Microclimate regulation; (i) Climate regulation).

provinces (except for Gansu included in conservation sector) and Inner Mongolia. The rest of provinces with steppe ecosystems belong to conservation sector.

Fig. 5(c) shows that most China's tussock ecosystems are categorized into conservation sector, except from Tibet (classified as productive sector), Xinjiang, Sichuan, Yunnan, Guizhou, Jiangxi and Hainan provinces, which belong to moderately productive sector. These indicates that provinces classified into conservation sector should not be used for grazing. Instead, grasslands protection policies should be implemented to prevent a further degradation of such ecosystems. The production in grasslands, applicable to moderately productive sector, needs an appropriate management to keep a balance between production and ES, implying a sustainable utilization within the grasslands carrying capacity (Liu et al., 2018).

Tibet is classified as the only productive province. In fact, its emergy derived from renewable resources is much higher than its other services, originating from its much higher elevation. Qinghai-Tibet plateau ecological barrier, national key ecological functional area and national banned development area are located in Qinghai-Tibet Plateau, especially in the north plateau. This fact indicates that Tibet needs to be protected for ecological benefits. Therefore, using an emergy-based ICG to determine the classification management of grasslands is not appropriate for special areas, such as high elevation regions with fragile ecological states.

On the other hand, Tibet and other Western and Northern provinces (i.e. Inner Mongolia, Xinjiang, Qinghai, Sichuan and so on), belong to IPS and MPS provinces respectively (Table 1 and Fig. 5) with grazing production, leading to their various grasslands deterioration degree. Among them, Tibet has the relatively great degrading pressure due to the largest IPS grassland area. The provinces with large MPS areas, including Inner Mongolia, Xinjiang, Qinghai, Sichuan, Yunnan, Gansu, etc., also have great degradation pressure. These are consistent with the results that study hot areas of grasslands degradation are mainly distributed in most regions in Inner Mongolia, Xinjiang, Qinghai, Tibet and other areas (Hu et al., 2017).

These indicate the IPS and MPS provinces based on ICG evaluation own production or grazing capacity as well as potential grasslands degradation stress, especially in areas with fragile ecological environment. Grassland carrying capacity and ecosystem services vary with grassland coverage and productivity, consequently the value of ICG and the corresponding management classification vary, which bring difficulties to decision-makers (Liu et al., 2018). That means temporal and dynamic ICG values are more practical and informative for policy design.

3.4. BCR of China's grassland ES

The bar graphs in Fig. 5 show the BCR of China's grassland ecosystems. In particular, the blue bar, i.e. NPP, is evaluated using MAX (R). Therefore, higher bars than NPP one represent larger benefits larger than costs.

For China's meadow ecosystem, most provinces' BCR are less than 1, except for Inner Mongolia and Xinjiang, having a BCR value related to soil purification of 1.98 and 1.03 respectively. China's steppe ecosystems have similar characteristics. In particular, Inner Mongolia and Xinjiang have BCR value larger than 1, i.e. 1.61 and 1.11 respectively.

Steppe ecosystems in the other provinces are featured with benefits less than their costs. In the case tussocks, there are four provinces with the BCR of soil purification larger than 1, including Beijing (1.52), Tianjin (1.38), Inner Mongolia (1.61) and Xinjiang (1.27). At national scale, the BCR values of China's grassland are less than 1. This may depend on the fact that benefits are relatively slow variables compared to annual renewable resources inputs.

Table 1
The grasslands area and the ratio of different sectors.

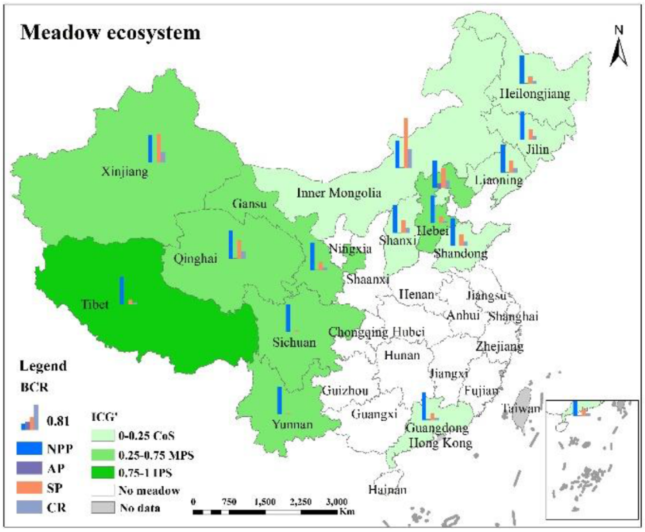
Provinces	Area(km^2)				Ratio
	Meadow ecosystem	Steppe ecosystem	Tussock ecosystem	Total [i]	
Beijing	18		834		
Tianjin			176		
Hebei	328	4032	10820	328	
Shanxi	140	8	12136		
Inner Mongolia	25807	403616	88	403616	
Liaoning	91	692	42		
Jilin	4	5448	219		
Heilongjiang	5590	4727			
Shanghai			52		
Jiangsu			170		
Zhejiang			382		
Anhui			5060		
Fujian			537		
Jiangxi			2060	2060	
Shandong	289		6797		
Henan			3456		
Hubei			4428		
Hunan			2530		
Guangdong	233		841		
Guangxi			556		
Hainan			107	107	
Chongqing			2107		
Sichuan	39855	64060	378	104293	
Guizhou			7656	7656	
Yunnan	1510	176	18843	20529	
Shaanxi		41420	157		
Gansu	16626	36649	5846	16626	
Qinghai		117527	102494	117527	
Ningxia		9542		9542	
Xinjiang	86527	129495	105	216127	
Tibet	97310	343923	27	441260	
Total [a]	274328	1161315	188904	1624547	
CoS	32172	92976	159728	284876	18%[b]
MPS	144846	724416	29176	898438	55%[c]
IPS	97310	343923	27	441260	27%[d]
Total grasslands area in North China	232730	1097079	143197	1473006	
CoS in North China [h]	31939	92976	143065	267980	18%[e]
MPS in North China	103481	660180	105	763766	52%[f]
IPS in North China	97310	343923	27	441260	30%[g]

Note: a means the total grasslands area of 31 provinces in China; b, c and d indicate the ratio of CoS, MPS and IPS provinces to the total grasslands area respectively; e, f and g mean the ratio of CoS, MPS and IPS provinces in North China to the total grasslands area in North China respectively; h represents North China here including Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shandong, Henan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang and Tibet according to the geographical dividing line between northern and southern China. i means the total area with green background is the sum of MPS and IPS area in each province. Land use data source: Xu et al. (2018).

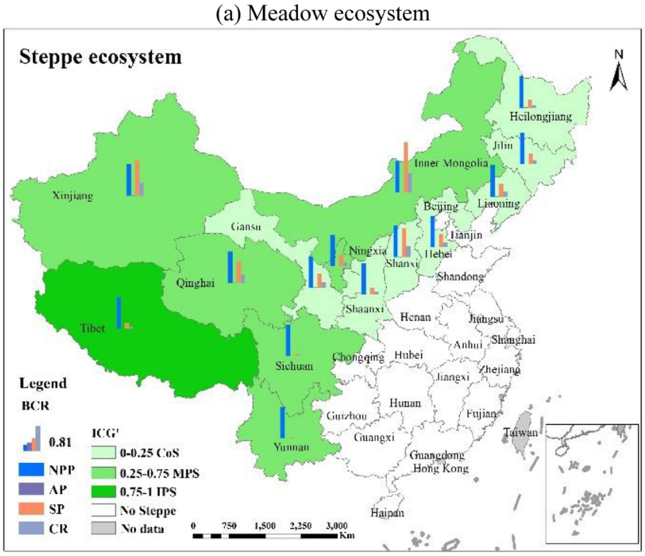
4. Discussions

4.1. Ecosystems' purification services and degradation

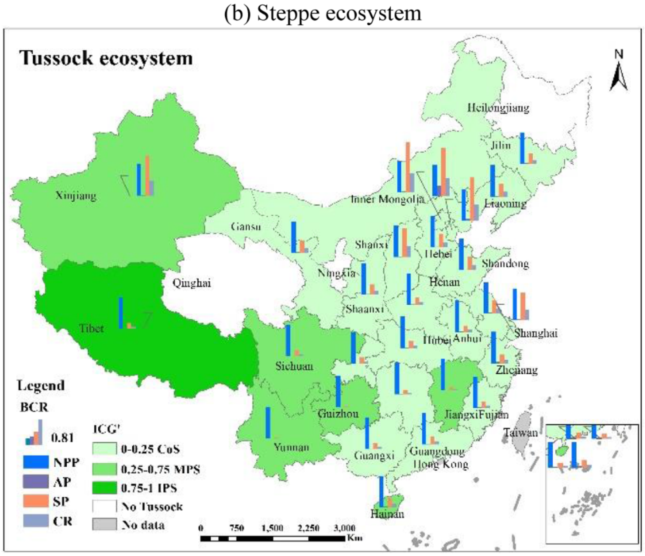
In this study, air and soil purification services are estimated based on their purification capacity. Grassland ecosystem itself has certain stability, in long term. However, pollutants accumulate in ecosystems, gradually changing the physical and chemical properties of soil, plant composition, biomass and microbial species, and, ultimately, leading to ecosystems degradation and decline in ES (Day et al., 2004).



(a) Meadow ecosystem



(b) Steppe ecosystem



(c) Tussock ecosystem

Fig. 5. The benefit-cost ratio and index of classification grassland management in China (BCR: Benefit-cost ratio; AP: Air purification; SP: Soil purification; CR: Climate regulation; ICG': Index of classification grassland management; CoS: Conservation sector; MPS: Moderately productive sector; IPS: Intensively productively sector).

Studies evaluating the dynamic influence of pollutants accumulation on ecosystem purification capacity are urgently needed. Yet, to our best knowledge, only are few studies focus on the impacts of pollutants accumulation on grasslands purification functions. Conversely, current studies are mainly focused on aquatic ecosystems, especially wetland ecosystems (Day et al., 2004; Breaux et al., 2005; Yang et al., 2006; Fink and Mitsch, 2007). These studies already indicate that pollutants exert a relevant influence on water purification service. For example, some artificial wetlands are not stable at the early construction stage. Then, during the operation process, wetland ecosystems gradually become stable and their sewage treatment ability is more efficient, differently from natural wetlands (Yang et al., 2006). These studies already provided several insights for further application on grasslands which will be developed in the future.

4.2. Emergy-based ICG and sustainable grassland management

In this study, the ratio of carrying capacity to the sum of carrying capacity and ES, expressed in emergy terms, is evaluated to provide insights for grassland classification management. This study provides a preliminary ICG′ esteem for year 2010. Collecting further data, the dynamic ICG′ in long term should be monitored. In fact, using an average carrying capacity and ESV for one year may lead to opt for an unsustainable solution, like grasslands overgrazing, especially in some fragile areas. Moreover, most China's grasslands are considered less productive. Thus, overgrazing is currently facilitated to meet the increasing demand for livestock products (Liu et al., 2018). Consequently, their carrying capacity (Zheng et al., 2018) as well as ability to withstand natural disasters, are further degraded. In fact, though China's grasslands area is 1.9 times that of forests, its conservation investment only accounts for 0.4% of that in forest ecosystems (Zheng et al., 2018). Therefore, more funds are needed for China's grasslands conservation, restoration and grazing restriction.

At global scale, grassland ecosystems play a significant role. However, 49.2% of global grasslands are degrading (Gang et al., 2014), associated with overgrazing, global warming and drought. The overutilization of grasslands is a worldwide issue needing prompt attention. Yet, little efforts have been made to preserve global grasslands (Dai et al., 2016). This contrasts with the extension of grasslands, covering a larger area than agriculture and wetland ecosystems (respectively 3.2E + 09, 1.4E + 09 and 0.6E + 09 ha) (Zheng et al., 2018). Moreover, grasslands are heavily exploited for livestock production, due to their high economic and social value. This leads to a general neglecting to their ecological functions and benefits, which would imply the fact that grasslands ESV are essential for sustainability.

4.3. The limitations of this study

Due to the unavailability of an index to measure biodiversity contribution to global biodiversity, biodiversity contribution is not assessed in this study. This might cause an underestimate of grassland ESV. This service should be assessed to make the present evaluation more accurate. Due to the lack of data on global average carbon sequestration per unit area in subtypes of grasslands, the global average carbon sequestrated by grasslands is applied to evaluate the climate regulation service. Having these data, this service could be evaluated more accurately.

On the other hand, emergy-based ICG to classify grassland management may be not suitable for all ecosystems, especially for unique areas, such as Qinghai-Tibet Plateau, having a much higher elevation than the rest of China. This means that more local characteristics should be considered and integrated while developing specific ecosystems management and conservation practices.

5. Conclusions

This study provides a coherent non-monetary accounting method for grassland ESV based on emergy, which was previously missing in the literature. This approach includes the application of a grassland ecosystems classification, a classification of different ES and the development of specific ESV accounting techniques. Grasslands ICG′ and BCR are also developed and evaluated to give some potential indicators for more informed management and conservation actions.

The developed case study shows that grassland ESV in northern and western China are larger than that in southern China. Conversely, western and southern China have larger grassland ESV per unit area than that in northern China. In addition, most grasslands in China are classified into moderately productive and conservation sectors. This indicates the need of urgent actions to protect China's grasslands. Benefits from grasslands ES are smaller than the cost in China's most provinces. Though some limitations still exist, this study is a first step to develop a data-informed and coherent management and planning approach to China's grasslands.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2020.101073.

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