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Research article

Spatial heterogeneity of carrying capacity on the Tibetan Plateau: An ecosystem service approach

Lijing Wang [a], Stephen Polasky [b], Yi Xiao [a], Lingqiao Kong [a], Lingxiao Ying [a], Hua Zheng [a], Zhiyun Ouyang [a,*]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 100085, Beijing, China

[b] Department of Applied Economics, University of Minnesota, St. Paul, MN, 55108, USA

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ABSTRACT

In ecology, carrying capacity is typically defined as the maximum number of organisms of a particular species that can be supported indefinitely in a given environment. However, this way of defining carrying capacity has been hard to apply in regional sustainability and management. Here, we propose that carrying capacity is the ability of ecosystems to sustainably provide maximum ecosystem services without damaging the ecosystem in a given region. That is, carrying capacity is multidimensional. We apply this approach to evaluate carrying capacity based on the ecosystem service provision, including ecosystem processes and functions such as soil conservation, carbon sequestration and water purification, and constituents of human well-being such as grassland productivity and water retention on the Tibetan Plateau. The results showed that carrying capacity of water retention, water purification, soil conservation, grassland forage production and carbon sequestration were estimated at 267.80 billion m^3, 12.93 million tons, 34.24 billion tons, 97.70 million SU and 0.16 billion tons. Overall, grassland forage production is severely overloaded, with a loading ratio of 1.50. The loading ratios of water retention and water purification are 0.05 and 0.02, loading ratio of soil conservation is 0.80, loading ratio of carbon sequestration is 0.83, and all of them are not overloaded. However, soil conservation and carbon sequestration were severely overloaded in 10 and 47 counties, respectively. The overloading varies with carrying capacity and loading ratios in different counties. 108 and 54 counties are severely overloaded and overloaded respectively, and 34 counties are not overloaded.

1. Introduction

Carrying capacity is an important concept that bridges ecology and policy making. The classical definition of carrying capacity is the maximum number of organisms of a particular species that can be supported indefinitely in a given environment (Hixon, 2008), including animal population size, species richness and the total human population (Benton, 2001; del Monte-Luna et al., 2004; Pearl and Reed, 1920; Sayre, 2008; Walker and Valentine, 1984). The historical application of carrying capacity has continued to inform its importance in conservation biology, rangeland and wildlife management, aquaculture, and fisheries biology today (Chapman and Byron, 2018; Thomson, 1886). Overall, these studies have contributed to the ecosystem management (Cropp and Norbury, 2019; Rees and Wackernagel, 1992; Wackernagel et al., 2002).

However, efforts to parametrize and measure carrying capacity in the field have proven problematic for the many and varied definitions of carrying capacity (Hixon, 2008). Meanwhile, some scholars noted that the more built up the environment is, the more difficult it becomes to apply the concept of carrying capacity for the development of science and technology. And they stated that carrying capacity has been “largely abandoned” in the social and policy sciences (Council, 2014; Monte-Luna et al., 2004; Mote et al., 2020).

Ecosystem services provide a new perspective on carrying capacity. Ecosystem services are the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life (Daily, 1997; Daily et al., 2000). In other words, humans benefit from functioning ecosystems (Costanza, 2024). Currently, a substantial number of scholars have analyzed the supply and demand of provisioning, regulating, and cultural ecosystem services across global, regional, and local scales (Aziz et al., 2025; Kashef et al., 2025; Tian et al., 2025). These studies have played a critical role in

* Corresponding author.
E-mail address: zyouyang@rcees.ac.cn (Z. Ouyang).

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advancing our understanding of the multifaceted value of ecosystem services (González-García et al., 2020). However, ecosystem service is not an anthropocentric concept, ecosystem processes and functions do not only benefit humans; other organisms also gain from them, even though they do not define them as we do (Costanza, 2024). Therefore, carrying capacity should focus not only on human benefits but also on the ecosystem itself, in this sense, carrying capacity is multidimensional.

Here, we redefine carrying capacity by introducing the concept of ecosystem services and develop a new framework to quantitatively evaluate it. Based on indicators of ecosystem damage and the linkages between ecosystems and human well-being, key ecosystem services are obtained, including regulating services to assess whether the ecosystem is damaged and provisioning services for human well-being. Meanwhile, the loading ratio of carrying capacity is classified.

We illustrate the application of the carrying capacity framework through a case study of Tibetan Plateau, China, a region rich in endowments of ecosystems. The Tibetan Plateau is one of the hotspots for global biodiversity conservation and is the most unique eco-geographical unit in the world(Myers et al., 2000). Known as the "Asian Water Tower", it plays an important role in providing ecosystem services. Meanwhile, as an underdeveloped region, the Tibetan Plateau has nonetheless experienced rapid economic development since 2000.

The purpose of this study is to provide a new understanding and develop a simple framework for carrying capacity that is link to ecosystem services, and to classify the levels of loading ratio on the Tibetan Plateau. We hope the study can provide a useful reference for the sustainable development on the Tibetan Plateau and for regional sustainability policy making.

2. Methods

We propose that carrying capacity is the ability of ecosystems to sustainably provide maximum ecosystem services without damaging the ecosystem in a given region.

2.1. The study area of Tibetan plateau in China

The Tibetan Plateau is located in the central Asia (25°59′30″ N-40°1′0″ N, 67°40′37″ E−104°40′57″ E). Its total area is about 2.78 million km^2, and it is known as the "Roof and World", with an average altitude of more than 4400 m. In winter and summer, the temperature is below −7 °C and above 15 °C, respectively. The pattern of precipitation also varies both spatially and temporally across the plateau, decreasing from the southeast to the northwest, with very low levels in winter and much higher levels in summer. The plateau is home to approximately 36 million people, with over 90 % of the population living in the south-eastern region (Qi et al., 2020). The dominant ecosystems are grassland, bare land, forest, shrub and desert, which together account for about 91 % of the total area. Grasslands are mainly found in the northwestern part of the plateau, while forests and croplands are concentrated in the southeastern region. The Tibetan Plateau is also the source of the Mekong, Yangtze, and Yellow Rivers (Fig. 1).

2.2. Data sources

(1) The ecosystem pattern (resolution 90 m) was sourced from the Qinghai-Tibet Plateau Ecosystem Data Integration Platform (https://www.gscloud.cn/qtp/qtpecosys/dataset/dataset_detail/7b22d9b28c0d4c138d1825fddbed0124) relating to the periods 2000–2010 and 2010–2020.
(2) Net Primary Production (NPP) were from the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/zh-hans/data/37d61044-9802-4d00-96a1-ff331454f265).
(3) The CO_2 emission data is from the Carbon Emission Accounts & Datasets (https://www.ceads.net/data/county/). Impute the missing counties according to the changes and proportions of GDP and population of provinces, cities and counties from 2000 to 2020.
(4) Water pollutants are sourced from National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/zh-hans/data/ffce7736-e8b7-4811-ace4-f80f0daae20a).

Statistical analyses were performed and reported using Excel 2019, and ArcGIS 10.7.

2.3. The framework for carrying capacity

We developed a framework based on the ecosystem damage indicators and the linkages between ecosystem and human well-being (Table 1). Different regions have distinct key ecosystem services that

Fig. 1. The elevation and rivers on the Tibetan Plateau.

help ensure global or regional sustainability.

In this study, soil erosion, climate change and water pollution are considered main indicators of ecosystem damage on the Tibetan Plateau. They correspond to soil conservation, carbon sequestration and water purification respectively. Their loads are water erosion at light level, CO_2 emissions and water pollutants emissions. Their ecological significances are soil conservation that prevent soil erosion at light level, carbon sequestration that can maintain stable CO_2 concentration in the atmosphere, and water pollutants decomposition that prevent excessive pollutant concentration.

Grassland forage production and water retention are representative indicators of the linkages between ecosystem and human well-being on the Tibetan Plateau. Their load are livestock (cattle, yak, sheep, goat, horse, donkeys, mules and camels) and water withdrawal, respectively. Their ecological significances are to meet the forage needs of livestock for grassland forage production and to meet the water needs of residents for water retention (Liu et al., 2022; Sun et al., 2020).

Based on the carrying capacity and their loads, we evaluate the loading ratios of five selected ecosystem services on the Tibetan Plateau. Finally, the loading ratios of the five ecosystem services are classified into 3 categories (Fig. 2). If the load for an ecosystem service doesn't exceeds its supply, it is considered not overloaded. If the load for an ecosystem service exceeds its supply but less than 1.5 times its supply, it is considered overloaded. If the load for an ecosystem service exceeds its 1.5 times its supply, it is considered severely overloaded.

2.4. Methods of carrying capacity quantification

Based on the constituents of human well-being, the five ecosystem services are obtained.

2.4.1. Carrying capacity

(1) Carrying capacity of grassland forage production

Quantification of grassland forage production used different categories of grassland in county scale.

$$GFP = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} (G_{ij} \cdot U_j)}{F \cdot D}$$

where GFP is the total amount of livestock that can be feed by the grassland forage production, sheep unit (SU). G_{ij} is the annual grass yield (standard hay) of grassland type j in county i (kg). U_j is the utilization rate of grassland type j (%), F is the feed intake per SU per day, which is 1.8 kg forage (standard hay) per SU (Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2015). D is 365 days.

$$G_{ij} = \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{NPP_{ij} \cdot A_{ij}}{1000 \times S_{ij}(1 + SG_{ij})}$$

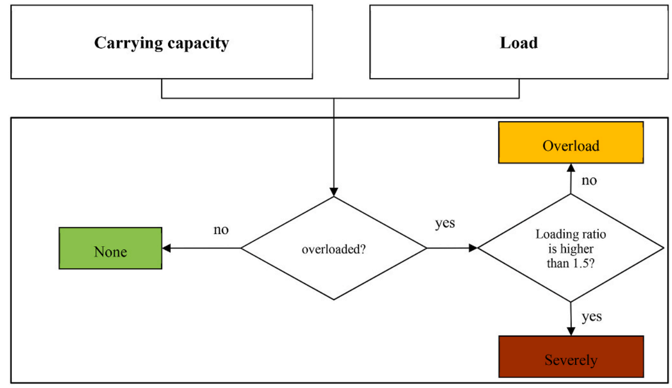

Fig. 2. The evaluation of carrying capacity.

where NPP_{ij} is NPP of grassland j in county i (g C m^{-2}·a^{-1}), A_{ij} is the area of grassland j in county i (km^2), S_{ij} is the conversion coefficient between grassland biomass and NPP of grassland j in county i (Wang and Wen, 1996), and SG_{ij} is the ratio coefficient between underground and aboveground biomass of grassland j in county i (Piao et al., 2004).

(2) Carrying capacity of carbon sequestration

Carrying capacity of carbon sequestration refers to the total amount of carbon sequestration in the ecosystem annually.

$$CS_{CO_2} = \frac{M_{CO_2} \times NEP}{M_C}$$

where $CSCC_{CO_2}$ is the amount carbon sequestration in the ecosystem (t CO_2/a), $\frac{M_{CO_2}}{M_C} = \frac{44}{12}$ is converted from C to CO_2 coefficient; NEP is net ecosystem productivity (t·C/a).

Among them, NEP is obtained by its conversion coefficient with NPP, and NEP is calculated according to NPP:

$$NEP = \frac{\alpha \cdot NPP \cdot M_{C_6}}{M_{C_6H_{10}O_5}}$$

where NEP is net ecosystem productivity (t C/a); α is the conversion coefficient of NEP and NPP; NPP is net primary productivity (t dry matter/a); $\frac{M_{C_6}}{M_{C_6H_{10}O_5}} = \frac{72}{162}$ is the coefficient of conversion of dry matter to C.

(3) Carrying capacity of water retention

We estimate carrying capacity of water retention by using the following model, which was revised from the Integrated Valuation of Ecosystem Services and Tradeoffs model:

Table 1
Carrying capacity based on the linkages between ecosystem and human well-being.

Constituents of well-being			Ecosystem services	Carrying capacity	Load	Significance
Goals	Contents	Indicators				
Basic material for good life	Forage	Forage	Grassland productivity	Forage supply	Forage consumption of livestock	Forage supply that can meet the forage consumption of livestock
	Water resource	Water resource	Water retention	Water retention capacity	Annual water withdrawal for production and living	Water retention capacity that can meet the water resource consumption
Security	Disasters	Soil erosion	Soil conservation	Soil conservation capacity	Soil erosion at light level	Soil conservation capacity that can prevent water erosion at light level
	Climate change	Global warming	Carbon sequestration	Annual carbon sequestration capacity	Annual CO_2 emission	Annual carbon sink that can maintain CO_2 concentration stable in the atmosphere
Health	Pollutant purification	Clean water	Water purification	Decomposition capacity of water pollutants	Annual water pollutants emission	Decomposition capacity of water pollutants that can prevent excessive concentration of water pollutants

$$WR = \sum_{i=1}^{j} (P_i - R_i - ET_i) \cdot A_i$$

where WR is total water retention (m^3), P_i is precipitation (mm), R_i is storm runoff, ET_i is evapotranspiration (mm), and A_i is the area of the ecosystem (km^2) (Kareiva et al., 2011; Sharp et al., 2016).

Runoff coefficient values were estimated by (Ouyang et al., 2016):

$$R = P \cdot a_k$$

where R is the runoff (mm), P is the precipitation (mm), a_k is the runoff coefficient.

(4) Carrying capacity of soil conservation

Carrying capacity of soil conservation refers to the soil retained by the ecosystems within a certain period.

Soil conservation was calculated using the Universal Soil Loss Equation, and the model can be expressed as:

$$SC = P_i - E_i = R \cdot K \cdot LS \cdot (1 - C)$$

where SC represents the soil conservation ($t \cdot hm^{-1} \cdot a^{-1}$), P_i and E_i represent potential soil erosion and actual soil erosion in county i, respectively, R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} a^{-1}), K is the soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}), LS is the topographic factor, and C is the vegetation cover factor(Ouyang et al., 2016).

(5) Carrying capacity of water purification

The total amount of carrying capacity of water purification for pollutant from ecosystems in a region is given by

$$QW = \sum_{i}^{n} A_i \cdot QW_i$$

QW_i represent the capacity of ecosystem i to absorb or filter water pollutant. A_i is the area of ecosystems. The ecosystems include wetlands, lakes, and rivers. We selected chemical oxygen demand (COD) as the representative indicator of water purification to account for the amount of pollutants purified by ecosystems (Ouyang et al., 2016, 2020).

2.4.2. Load in 2020

(1) Grassland forage production load

Grassland forage production load refers to the total livestock annually.

$$GFPL = \sum_{j=1}^{n} (L_{ij} \cdot C_j)$$

where L_{ij} is livestock j in county i, (SU). C_j is the conversion coefficient between livestock and sheep unit.

Livestock include cattle, yak, sheep, goat, horse, donkeys, mules and camels. We derived the data from the Qinghai, Tibet, Xinjiang, Gansu, Sichuan, Yunnan Statistical Yearbook and China Statistical Yearbook (Zhang, 2022).

(2) Carbon sequestration load

Carbon sequestration load refers to the amount of carbon that the ecosystems need to store each year to avoid increases in atmosphere CO_2 level caused by human activities.

CO_2 emissions are considered the load for carbon sequestration. The CO_2 emission data were obtained from the China's carbon accounting database (https://www.ceads.net.cn/), using county-level data with an annual time resolution. Since approximately 23 % of global carbon sequestration occurs in oceans, this study focuses on the remaining 77 % stored by terrestrial ecosystems (Friedlingstein et al., 2020).

(3) Water retention load

Water retention load is the water demand of human activities annually.

$$L_i = D_i \cdot HP_i + \sum_{j=1}^{n} E_{ij}$$

where L_i is the load of water retention in county i. D_i is per capita water demand for water in county i. E_{ij} is water withdrawal of j industry in county i (i.e. the primary, secondary, and tertiary sectors of economy).

The data comes from the statistics of water consumption for human activities in the statistical yearbooks of relevant provinces, cities and counties on the Tibetan Plateau (Gansu, 2020; Qinghai, 2020; Sichuan, 2020; Xinjiang, 2020; Xizang, 2020; Yunnan, 2020).

(4) Soil conservation load

$$L_i = P_i - S_0$$

For soil conservation load, L_{ij} is the soil conservation that the ecosystems can prevent soil erosion (water erosion) at light level in county i. P_i is the potential soil erosion in county i. S_0 is light soil erosion (water erosion) and is also the judgment criteria of soil loss (China, 2008).

(5) Water purification load

$$L_i = \sum_{j=1}^{n} E_{ij}$$

For water purification load, L_i is the amount of water purification that the ecosystems need to achieve to avoid the increase of water pollutants concentration in the wetland caused by human activities annually. E_{ij} are water pollutants of j category source in county i (i.e. three main industries and residents). COD emission is regarded as the load of water purification.

2.4.3. The loading ratio

$$R_{ij} = \frac{L_{ij}}{CC_{ij}}$$

where R_{ij} is the loading ratio in county j of carrying capacity i, L_{ij} is the load of carrying capacity i in county j, CC_i is the carrying capacity i in county j.

2.4.4. Identification of overload level of carrying capacity

Overload level of each carrying capacity is identified by:

$$T_{ij} = \begin{cases} \textit{None}\ R_{ijt} \le V_i \\ \textit{Overload}\ 1.5V_i \ge R_{ijt} > V_i \\ \textit{Severe overload}\ R_{ijt} > 1.5V_i \end{cases}$$

T_{ij} is overload level of carrying capacity of i in county j. V_i is the standard for determining whether carrying capacity i is overloaded.

For grassland forage production, water retention, soil conservation and water purification, $V_i = 1$.

For carbon sequestration, $V_i = 1.30$ is used because ocean carbon sequestration accounts for 23 % of the global total, while terrestrial ecosystem account for the remaining 77 %. Thus, the standard for determining $V_i = 1.30$ is derived from $R_j = \frac{L_j}{0.77\, CC_j} = \frac{1.30\, L_j}{CC_j}$, where R_j is loading ratio in county j, L_j is carbon emissions in county j, and CC_j is carbon sequestration in county j.

The comprehensive overload of carrying capacity in county scale was identified based on the highest overload of the combination of five ecosystem services.

Comprehensive overload of carrying capacity:

$$T_j = \max(T_{ij})$$

where T_i is overload level in county j.

3. Results

3.1. Carrying capacity, loading ratio and change on the Tibetan plateau

We selected five ecosystem services to evaluate the carrying capacity of the Tibetan Plateau, including grassland forage production, carbon sequestration, water retention, soil conservation and water purification (Figs. 3 and 4).

In 2020, the carrying capacity of grassland forage production was 94.88 million sheep units, while the grassland livestock was 142.37 million sheep units. Overall, the carrying capacity of grassland forage production was severely overloaded, with a loading ratio of 1.5. However, the loading ratio decreased by 0.18 over the preceding twenty years because the carrying capacity of grassland forage production increased by 12.78 % due to the climate becoming warmer and wetter (Yin et al., 2015), and grazing density was reduced as well. The loading ratio was highly heterogenous across counties, 84 counties (43.37 %) were severely overloaded, 57 counties (29.59 %) were overloaded, and 53 counties (27.04 %) were not overloaded. Most of severely overloaded counties were located in the eastern and southern Tibetan Plateau (Fig. 3).

The carrying capacity of carbon sequestration was 143.36 million tons, while the carbon sequestration load reached 118.54 million tons. Overall, the carrying capacity of carbon sequestration was not overloaded, with a loading ratio of 0.83 in 2020. The carrying capacity of carbon sequestration increased by 5.47 % for the warmer and wetter climate, but the loading ratio was still increased by 0.6 over the preceding twenty years because carbon sequestration load increased by 291.69 %. The loading ratio was highly heterogenous across counties, 7 counties (3.57 %) were overloaded, 47 counties (23.98 %) were severely

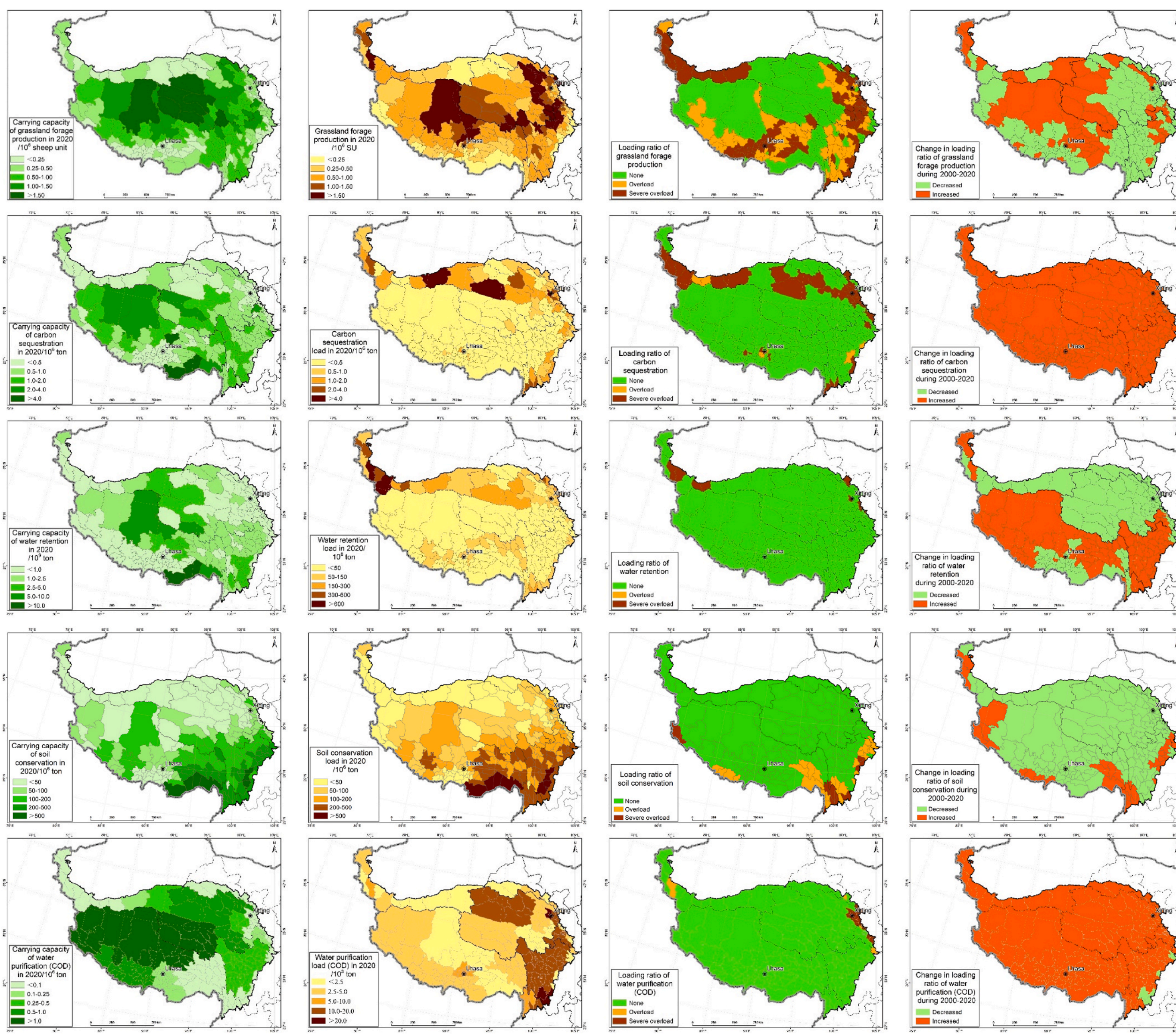

Fig. 3. The spatial distribution of the carrying capacity of grassland forage production, carbon sequestration, water retention, soil conservation and water purification, theirs load and theirs loading ratio in 2020 and change in loading ratio during 2000–2020.

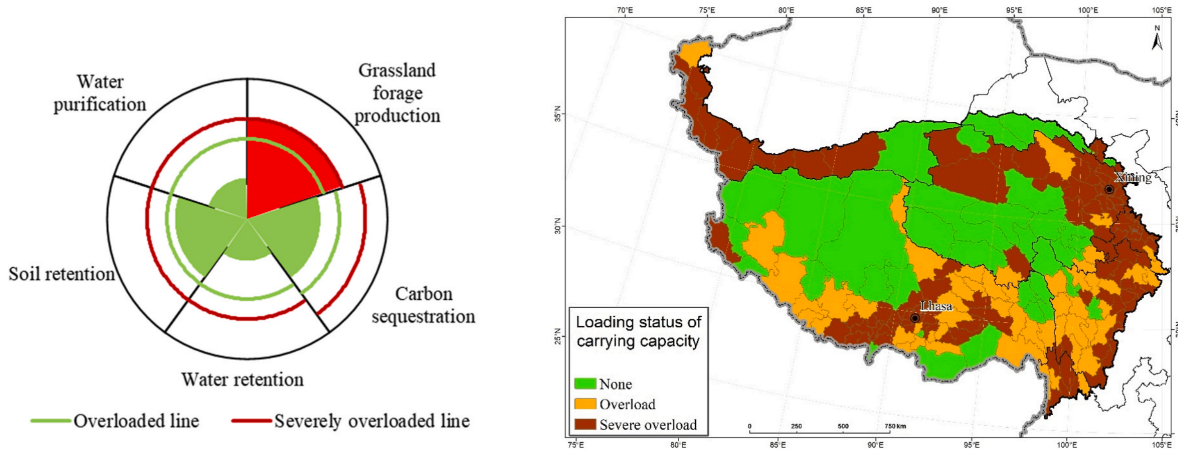

Fig. 4. The loading ratio and spatial pattern of carrying capacity in 2020.

overloaded, and 142 counties (72.45 %) were not overloaded. Most of the severely overloaded counties were located in the northern Tibetan Plateau (Fig. 3).

The carrying capacity of water retention was 239.82 billion tons, while the water retention load was 12.99 billion tons. Overall, the carrying capacity of water retention was not overloaded, with a loading ratio of 0.05 in 2020. The carrying capacity of water retention and water retention load increased by 1.86 % and 6.35 %, respectively, and its loading ratio increased by 0.002 over the preceding twenty years. In total, 13 counties (6.63 %) were severely overloaded, and 183 counties (93.37 %) were not overloaded and no counties were classified as overloaded. Most of the severely overloaded counties were located in the northern Tibetan Plateau (Fig. 3).

The carrying capacity of soil conservation was 28.21 billion tons, while the soil conservation load was 22.54 billion tons. Overall, the carrying capacity of soil conservation was not overloaded, with a loading ratio of 0.80 in 2020. Meanwhile, its loading ratio decreased by 0.09 because the carrying capacity of soil conservation increased by 12.78 % due to the ecosystem conservation policy and climate change. The loading ratio was highly heterogenous across counties, 10 counties (5.10 %) were severely overloaded, 27 counties (13.78 %) were overloaded, and 159 counties (81.12 %) were not overloaded. Most of severely overloaded counties were located in southeastern Tibetan Plateau (Fig. 3).

The carrying capacity of water purification (COD) was 12.93 million tons, while the water purification load was 0.27 million tons. Overall, the carrying capacity of water purification was not overloaded, with a loading ratio of 0.02 in 2020. The carrying capacity of water purification increased by 5.21 %, but its loading ratio increased by 0.01 because water purification load increased by 124.93 % over the preceding twenty years. A total of 16 counties (8.16 %) were severely overloaded, 4 counties (2.04 %) were overloaded, and 176 counties (89.80 %) were not overloaded. Most of severely overloaded and overloaded counties were located inn the northeastern Tibetan Plateau (Fig. 3).

3.2. *Carrying capacity across five ecosystem services*

We superimposed the loading ratios of five ecosystem services (Fig. 4). There were 162 counites (82.65 %) with at least one ecosystem service overloaded, 108 counties (55.10 %) with at least one ecosystem service severely overloaded, and 5 counties (2.55 %) with severely overloaded for four ecosystem services. There were only 34 (17.35 %) counties without overloading in any of the five ecosystem services. The counties without overloading were concentrated in central Tibetan Plateau, while the counties with severe overloading were located in the northern and southern Tibetan Plateau.

There are 110 counties without overloading in water retention, carbon sequestration, soil conservation and water purification (Table 2). The percentages of counties with none overload, overloading and severe overloading were 17.35 %, 27.55 %, and 55.10 %, respectively (Fig. 4). The counties without overloading were concentrated in the central Tibetan Plateau, the counties with overloading were located in the southern Tibetan Plateau, and the counties with severe overloading were located in the northern and southern Tibetan Plateau.

4. Discussion

4.1. *The concept and framework for carrying capacity*

The classical carrying capacity refers to the maximum population size of a species that the environment can sustain indefinitely, to which it is able to provide an appropriate supply of food, water, habitat, and other natural resources (Hixon, 2008). However, as demonstrated by previous research, this way that defined concept of carrying capacity has limited utility in addressing the complexities of human populations and

Table 2
The loading ratio of five ecosystem services of carrying capacity.

	None	Overloaded	Severely overloaded
GFP		49	50
CS		6	11
WR			
SC	8	18	6
WP		3	
GFP + CS		1	13
GFP + WR			2
GFP + SC		8	2
GFP + WP			1
CS + SC			1
CS + WP			5
WR + SC			8
WR + WP			5
SC + WP	5	1	
GFP + CS + WR	1		6
GFP + CS + SC			1
GFP + CS + WP			5
GFP + WR + SC	2		
GFP + WR + WP	1		
CS + WR + SC	1		
CS + WR + WP	19		
WR + SC + WP	21		
GFP + CS + WR + WP	11		5
GFP + WR + SC + WP	4		
CS + WR + SC + WP	76		
GFP + CS + WR + SC + WP	34		

Note: GFP is grassland forage production. WR is water retention. SC is soil conservation. CS is carbon sequestration. WP is water purification.

sustainability challenges (Council, 2014). This concept is particularly difficult to apply to natural populations because its simplifying assumptions of independent limiting factors and population size being directly proportional to whatever factor is most limiting (Liebig, 1843).

Our study shows that incorporating ecosystem services offers a new perspective on carrying capacity. Unlike traditional approaches that focus solely on human benefits, we highlight the interdependence of humans and ecosystems in a given region, which benefits not only people but also other organisms (Costanza, 2024). This integrated perspective allows carrying capacity to be re-envisioned as encompassing both human well-being and ecosystem health. Meanwhile, the human demand for ecosystem products includes not only material products, such as food and water, but also non-material products, especially regulating services (Pereira et al., 2024), such as pollination, soil conservation, carbon sequestration and flood mitigation, as well as cultural services like nature-based recreation and education. From an ecological perspective, sustainability means that ecosystems can continuously provide services that support human well-being. Therefore, carrying capacity can be defined as the ability of ecosystems to sustainably provide maximum ecosystem services without damaging the ecosystem in a given region. Therefore, carrying capacity is multidimensional, reflecting the relationship between ecosystem services and human well-being (Kluger and Filgueira, 2021).

From a global sustainability perspective, every region needs to contribute to ecosystem services rather than cause ecological problems. The carrying capacity of a region is constrained by the ecosystem services that are in the shortest supply. The factors that constrain carrying capacity may be any ecosystem service, reflecting the variability in limiting factors across regions.

The framework for evaluating carrying capacity and its overload can be based on ecosystem damage and the linkages between ecosystem and human well-being. Here, the threshold of carrying capacity is defined as the maximum ecosystem services supplied by ecosystems in a region, representing the maximum potential use by social and economic system indefinitely. Advances in ecosystem services provide evaluation methods make it possible to assess carrying capacity at local, national, regional, and global scales (Daily, 1997; Nations et al., 2021; Ouyang et al., 2020; Sharp et al., 2016). For key regulating services, such as soil conservation, the load is defined based on preventing soil erosion at light level. For provisioning services, their loads are defined, as before, based on supply-demand (Cohen, 1995; Wei et al., 2019).

Introducing ecosystem services into carrying capacity evaluation provides a useful tool for promoting regional sustainability and management. Adaptive policies and ecosystem manage approaches can be designed to enhance the services in shortest supply, or reduce the use of the ecosystem services. For example, reduction of livestock for grassland forage production, improving carbon storage and reduction of carbon emissions for carbon sequestration.

4.2. Practical utility in the Tibetan plateau

There is considerable debate regarding the carrying capacity of local food production. The food production carrying capacity is useful in global Sustainable Development Goal (Nations, 2015), but it is remain controversial at the regional scale due to issues of trading, allocation and storage. Therefore, grassland forage production has been used as a proxy for food production. This is because meat consumption accounts for a large proportion of local diets, which is a typical feature of pastoral regions (Wang et al., 2021). We found that livestock didn't overgraze in the northern Tibetan Plateau, consistent with previous studies (Xi et al., 2023).

The Tibetan Plateau is not overloaded in terms of carbon sequestration as a whole. Carbon sequestration increased by 5.47 % due to ecosystem conservation and restoration programs, such as Grain for Green, Grassland Conservation and Natural Forest Protection Program (Lu et al., 2018; Ouyang et al., 2016). However, the growth rate of carbon sequestration load far exceeds that of carbon sequestration. The carbon sequestration load in the periphery counties accounted for 64.11 % of the total on the Tibetan Plateau and remained overloaded throughout the study period, particularly in Qinghai province (Wo et al., 2023). Previous studies reported that carbon sequestration on the Tibetan Plateau ranges from approximately 0.10 to 0.22 billion tons, which is consistent with our findings (Meng et al., 2023; Zeng et al., 2023). Over the same period, gross domestic product on the Tibetan Plateau increased by 14.35 % annual, which was faster than the national average growth rate of 12.28 % (National Bureau of Statistics, 2021).

In the framework, carrying capacity is converted into a comparable loading ratio. The general outcome of carrying capacity assessment is the maximum human population or animal population size (Hurlbert and Stegen, 2014; Stokstad, 2005). When regulating services are included, all ecosystem services are uniformly transformed into loading ratio, ensuring that the results remain comparable. On this basis, the comprehensive carrying capacity of the Tibetan Plateau was visually presented. There are still 34 counties without overloading across all carrying capacity, while counties with severely overloading accounted for 55.10 %.

The framework makes it possible to evaluate carrying capacity in other regions. The results from the Tibetan Plateau demonstrate that it is feasible to evaluate carrying capacity using available data and methods. Therefore, the tractable approach to evaluating carrying capacity is applicable not only on Tibetan Plateau but also across China and in other regions.

4.3. Limitations

Although the framework for carrying capacity includes many aspects of human well-being and corresponding ecosystem services, it remains incomplete. Due to the complexity of rainstorm precipitation and flood formation process, the load and overload of flood mitigation related to flood disasters couldn't be effectively evaluated at a large scale. In addition, cultural services have not yet been evaluated within the framework, requiring a deeper understanding of the relationship between ecosystems and human well-being.

5. Conclusion

This study redefines carrying capacity from an ecosystem services perspective defining it as the ability of ecosystems to sustainably provide maximum ecosystem services without damaging the ecosystem in a given region. We apply this approach to evaluate the carrying capacity and load of the Tibetan Plateau, focusing soil conservation, carbon sequestration, water purification, water retention, and grassland forage production. We also calculated the loading ratios of these services to determine whether their loads exceeded their carrying capacities.

The results show that, overall, grassland forage production is severely overloaded with a loading ratio of 1.50. Water retention, water purification, soil conservation and carbon sequestration are not overloaded. However, soil conservation and carbon sequestration were severely overloaded in 10 and 47 counties, respectively. The overloading varies with carrying capacity and loading ratios in different counties. In total, 108 counties are severely overloaded, 54 counties are overloaded, and 34 counties are not overloaded.

CRediT authorship contribution statement

Lijing Wang: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Stephen Polasky:** Writing – review & editing, Writing – original draft, Investigation. **Yi Xiao:** Data curation. **Lingqiao Kong:** Data curation. **Lingxiao Ying:** Validation, Methodology. **Hua Zheng:** Data curation. **Zhiyun Ouyang:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no competing interest.

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Data availability

Data will be made available on request.

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