J. Mt. Sci. (2019) 16(7): 1702-1714 e-mail: jms@imde.ac.cn http://jms.imde.ac.cn
https://doi.org/10.1007/s11629-018-5148-2

Quantitative evaluation of Tibet's resource and environmental carrying capacity

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Citation: Wang L , Liu H (2019) Quantitative evaluation of Tibet's resource and environmental carrying capacity . Journal of Mountain Science 16(7). https://doi.org/10.1007/s11629-018-5148-2

Abstract: This study identifies the carrying state and value of Tibet's resource and environmental carrying capacity. A new theoretical framework is proposed for exploring the resource and environmental carrying capacity based on two perspectives of "growth limit" and "stability of Human-Earth relationship system". On this basis, an ideal growth model that accords with the "short board" effect is established to predict the population limitation. Analytical results show that the holistic state of resource and environmental carrying capacity in Tibet is in jeopardy. From 2010 to 2016, Tibet's carrying state continued to decline, moreover, the negative forces still overwhelm the positive forces. Although the resource reserves still have room for more population, the environmental capacity and ecological capacity have been overloaded. Meanwhile, the Human-Earth relationship system is in an unstable stage. Three scenarios that respond to different socioeconomic developments are implemented to predict the population limitation of resource and environmental carrying capacity in Tibet; thus, authors argue that Tibet should keep its population size within 4 million around 2025. This research will provide reference for sustainable development and resources and environmental conservation in Tibet.

Keywords: Population limitation; Resources carrying capacity; Environmental carrying capacity; Short board effect; Tibet

Received: 31-Jul-2018
1st Revision: 08-Nov-2018
2nd Revision: 10-May-2019
Accepted: 28-May-2019

Introduction

As an engineering mechanics concept, carrying capacity originally means "the maximum load" of an object without any damage. Subsequently, it was defined in the field of Ecology as "The maximum amount of livestock that the grassland can support without any damage" (Hawden and Palmer 1922). With the outbreak of food shortages and environmental degradation in worldwide, people realized the importance of the balance of Human-Earth relationship, the concept of carrying capacity expanded into the field of sustainable development of Human-Earth relationship system (Wang et al. 2007). According to several significant studies relating to resource and environmental carrying capacity (Meadows et al.1972; Cohen 1995;

Costanza 2006) that clarified the importance of the environment and the relationship between resources and population (Feng et al. 2017), a dynamically bidirectional relationship was found between regional resources and environmental carrying capacity and socioeconomic development. Thereby, researchers have devoted to making clear that whether the areas can support more population or should restrict the development. Several early and creative theories and methods, such as System Dynamics method, Ecological Footprint method, Energy Analysis, and the UNESCO & Food and Agriculture Organization (FAO) method (UNESCO and FAO 1985; Karnopp and Rosenberg 1990; Rees 1992; Odum 1995), have boosted to find the answers (Fischer and Sun 2001; Haberl et al. 2001; Neto et al.2006; Li and Jin 2009; Zeng et al. 2011; Dalerum 2014; Ye et al. 2016).

Among the rest, Tibet has long come into researchers' sight due to its specific natural surroundings, and the local government also hoping to know Tibet's carrying limitation to take reasonable planning and management. Therefore, many useful experiments have been carried out for evaluating the resources and environmental carrying capacity in Tibet. Most of them reached a similar conclusion that the carrying pressure in Tibet has increased as the ecological carrying capacity has showed a decreasing trend (Zhang et al. 2001; Liu et al. 2005; Xu et al. 2007; Zeng 2007; Hu and Zhang 2010; Zhong et al. 2010; An and Cheng 2014; Zhao et al. 2015; Zhao et al. 2015). For example, a study on Shannan Region of Tibet found that its average annual rate of ecological degradation was 0.86% (1965-2004), and the loads of partial areas were twice than their own capacity (Zhong et al. 2010). Meanwhile, grassland is the single-element research hotspot in Tibet's resource and environmental carrying capacity filed as it occupies seventy percent of Tibet's land. Researches at different periods all warned that Tibet has an overloaded trend in grassland carrying capacity (Su 1995; Zhao 2007; Wongsaenmai et al. 2008; Zhao et al. 2015; Xu 2014; Liang 2017). Besides, researchers also did studies in water and land resources carrying capacity (Wang et al.2014; Zhao et al. 2015; Gao et al.2018) and resource and environmental carrying capacity in sub-regions of Tibet (Xu et al. 2007; Hu 2010). To sum up, those discussions in Tibet mainly focus on ecological carrying capacity; the carry capacity of single element, such as grassland, water and land resources; or resource and environmental carrying capacity in Tibet's sub-regions. Yet there is no conclusion in terms of comprehensive resource and environmental carrying capacity in Tibet, and the same problem existed in such research. Likewise, authoritative demographic projections (Lutz et al. 2001; Lutz et al. 2003), which focused on demographic factors, are isolated from resource and environmental carrying capacity studies; thus, leading many assessments of resource and environmental carrying capacity to a less valid in practice (Qi 2005; Feng et al. 2017). Some scholars even suggested giving up the term "carrying capacity" because of the ambiguous affecting factors and the normal concept it contains (Lindberg et al. 1997; Buckley 1999).

However, in recent years, a growing scientific consensus was that although regional resource and environmental carrying capacity dynamically changed in different development periods, overwhelmingly, there must be a limit value of resource and environmental carrying capacity in a specific region as the space and resources were finite in the region. Especially, this limitation is vital for Tibet. The first reason is that the extreme and vulnerable regions unsuitable for human living occupy most part of Tibet, which makes it impossible for unfettered development. Another reason is that if let the unrestricted human activities continually destroy Tibet's narrow populated surroundings, the residents will have nowhere to live. In addition, as a relatively sealing cyclical system, Tibet cannot accommodate an excess of external resources support on a large scale. For all these reasons, it is our responsibility to comprehensively evaluate Tibet's carrying state under the current intensity of human activities and then propose a reasonable population size.

To investigate the state of Tibet's resource and environmental carrying capacity and the population limitation, firstly, this study creates a "pressure-support", "destructiveness-resilience" and "degradation-promotion" ("PS-DR-DP") hexagon interactive model, considering both "growth limit" principle and the stability of Human-Earth relationship system. Then, on this basis, authors build an ideal growth model under the perspective of "short board" effect that is designed to predict the population limitation of Tibet. Finally, those questions mentioned above are addressed in these novel ways. In this work, we evaluated the holistic load-carrying state and population limitation in Tibet that have not been made in the previous research field of resource and environmental carrying capacity. Our research represented a novel way to integrate Human-Earth interactions within a dynamic and comprehensive framework, not only provides a reference for Tibet's development planning, but also proposes new ideas and methods for quantitatively assessing the largest population of regional resource and environmental carrying capacity. We think it would help to enrich the related theoretical system and applied research.

1 Materials and Methods

1.1 Theoretical framework

Carrying Capacity is defined as that population at any moment in time which can be indefinitely sustained at a given standard of living. It is not a threshold and can be enhanced by appropriate national development using physical and human resources. Sociocultural factors can both enhance and diminish carrying capacity" (UNESCO and FAO 1985). On the other hand, the environmental capacity is indirectly described in the "growth limit" study of biological populations as "the amounts limit of biological population because of the limited food in a specific environment" (Verhulst 1838). Meanwhile, authors think the dual concepts of "growth limit" and "short board" should be used to define stability in the context of the Human-Earth system as a research prerequisite while previous researches did not. Therefore, this study defines the regional resource and environmental carrying capacity as the point at which "the regional population will reach its limit in a specific condition when the resource use is 'fulfilling' and 'most efficiency' under a stable Human-Earth relationship system". It includes three parts: resources support capacity, environmental capacity and risk-disaster resisting ability. Specifically, resources support capacity refers to the largest population supported by available resources those depended on the current technology. Environmental capacity is the abilities of water, soil and atmosphere to accommodate pollutants. For example, if the fresh water, the soil environment and the air quality all drop to the least level for agricultural production and human health, and then the regional population will reach the ceiling. Similarly, the largest population protected from a major disaster shows the risk-disaster resisting ability.

Generally, the natural backgrounds determine the rudimentary carrying capacity of the region, and then socioeconomic progress provides the region more resources through improving the use efficiency. Simultaneously, depending on the high technology, humans enhance the ability of environmental purification and improve the ability to prevent disasters. However, at the same time, the consumptions of resources continue soaring and the environmental problems become more serious, even the major disasters probability increases. In short, the production and consumption in regional carrying capacity are in a unity of opposites.

The "pressure-state-response" and the "driving force-pressure-state-impact-response" models are main approaches in regional resource and environmental carrying capacity study. The former depended on subjective judgments and empirical models; therefore, it cannot work well in the context of complex feedback system. Indeed, the latter can be utilized to improve the former via comprehensive Human-Earth relationships, emphasized the "limit of growth", however, it just expressed a traditional "responsive" environmental protection concept. Both did not encapsulate urgently needed early warning-oriented evaluation processes. Furthermore, both the openness and dynamic natures of Human-Earth system were more-or-less ignored in previous researches.

In order to make up for these shortcomings and dynamically express the offset effect between production and consumption in regional carrying capacity, we advance three pairs of interactive forces named "pressure-support", "destructiveness-resilience" and "degradation-promotion", and construct the "PS-DR-DP" hexagon theoretical model based on the concept of "growth limit" and the Human-Earth relationship stability system (Wang et al. 2019). These six forces are divided into two categories: negative forces and positive forces. The negative forces include pressure, destructiveness and degradation. Support, resilience and promotion together represent the positive forces. Then the dynamic changes of the hexagon shape and area caused by those interactive forces are used to illustrate the stability of Human-Earth relationship system and regional carrying state. For further explanation, authors build a simulated diagram to visualize the warning evaluation mechanism (Figure 1), which reflects the full loading state and perfect state (Figure 1). The full loading state means that the region is overloaded and is going to collapse the stable structure of Human-Earth system. Likewise, the perfect state means that the regional population is kept in a reasonable range that is lower than the limitation of carrying capacity, while the Human-Earth system remaining stable.

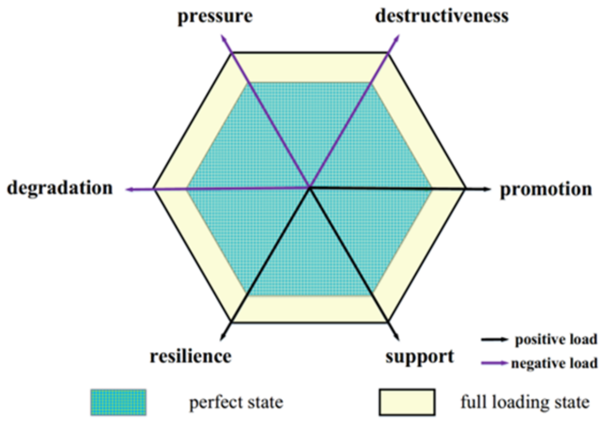

Figure 1 Carrying state model of resource and environmental carrying capacity. (**Note:** the scope of "full loading state" covers the range of "perfect state".)

1.2 Methods and evaluation systems

1.2.1 Rating standards of resource and environmental carrying capacity

Although resource and environmental carrying capacity is limited by natural factors, socioeconomic progresses can enhance or diminish resource and environmental carrying capacity in the same region under specific conditions. Wherein the urbanization process provides the fundamental impetus for changes in regional carrying capacity; a generally higher urbanization level is therefore reflected in a stronger carrying capacity. If the urbanization level is too high that negatively impacts the regional carrying capacity, however, the change of the regional resource and environmental carrying capacity will impede the urbanization process and even to collapse the Human-Earth relationship system. In order to quantitatively reveal this bidirectional degree, therefore, this study refers to the "threshold value of three stage urbanization" developed in the "China Modernization Report (2013)-Urban Modernization Study" (He 2014) while also taking the turning point of counter urbanization in developed countries into account. As a result, the developmental stages of resource and environmental carrying capacity can be shown in Table 1, which corresponding to the stability of Human-Earth relationship system (Wang et al. 2019).

1.2.2 Population projection model of limitation of resource and environmental carrying capacity

The key target of this study is to determine Tibet's largest population size under current economic development level based on its resource and environmental carrying capacity. Generally, Tibet is a relatively sealing cyclical system, because the extreme geographical conditions and fragile ecology always be the "short board" to restrict Tibet's development. Therefore, the law of diminishing returns is suitable to evaluate the population limitation of Tibet. Then considering the bilateral interaction relationship between regional carrying capacity and socioeconomic development as well as the limited space and resources of Tibet, this study sets the expectancy of carrying state as the dependent variable while the

Table 1 The developmental stages of resource and environmental carrying capacity

Rank	Mean contribution value	Status of the Human-Earth relationship system
I	≤0.30	Balance load at lower level with an approximate stable state
II	0.30～0.70	An unstable state caused by the high speed increasing
III	0.70～0.85	An ideal carrying capacity of an approximate stable state
Ⅳ	≥0.85	A full loaded state with the system collapsing

Note: The mean contribution value is the average value of positive and negative contributions.

development index is the independent variable. Next, inspired by the basic idea of a domain expert (Fan et al. 2017), authors redraw a restricted relationship model that has only one turning point as shown in Figure 2. Also, as a comparison, authors take both the constraints and the openness in regional resource and environmental carrying capacity into account, and then plot a corresponding diagram as shown in Figure 3.

In these figures, E(c) is short for the "expectancy of carrying state", and E(c)* is the largest value corresponding to the turning point. TP $_{(1,\ 2,\ \text{and}\ 3...n)}$ are short for the turning point in different periods, and E(c)*$_{(1,\ 2\ \text{and}\ 3...n)}$ are the corresponding expectations.

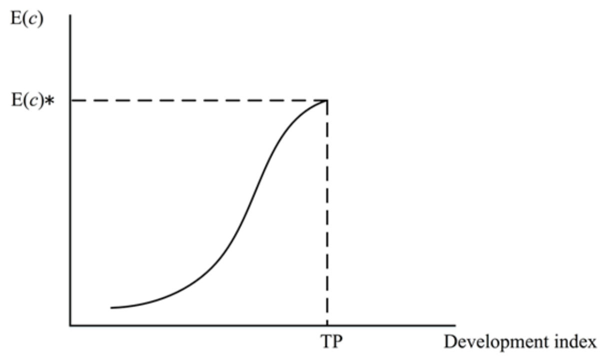

Figure 2 The relational model under the principle of "short board".

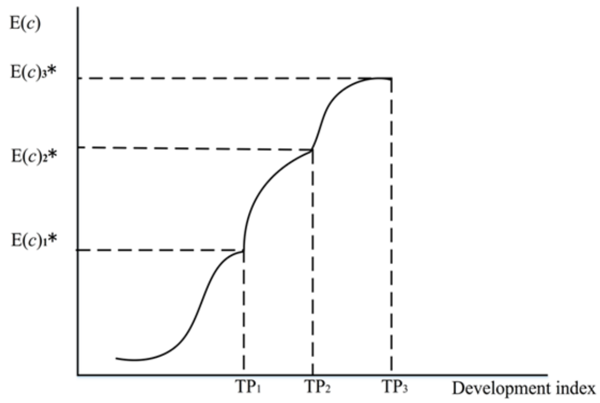

Figure 3 The relational model under a condition with little restriction.

1.2.3 Calculation methods of contribution value and carrying state

In order to calculate the contribution value that reflects the stability of Human-Earth relationship system, this study borrows the idea of the "entire-array-polygon" method (Wu et al. 2005) and perfects the mathematical expression in Eq. 1. This approach supposes the presence of N standardization indexes, and then it sets the zero point as the origin and takes one (the largest standard value) as the radius to form a central N polygon. This means that each variable value is distributed between the zero point and vertexes such that value points link up and form an irregular N polygon. Thus, N indexes can generate (N-1)!/2 irregular N polygons according to the multiplication principle of classified arrangement, and the ratio between the irregular N polygonal average area and the central N polygonal area is the contribution value of each component of carrying capacity.

However, it is not enough to set the contribution values as the only criteria, for the influencing factors are strongly interacting with each other. In order to supplement this feature, this study defines that the carrying state is equal to the ratio between the positive contribution values to the negative contribution values that is shown by Eq. 2. Namely, if the ratio is bigger than one, and then the region is in a good carrying condition, and the bigger ratio means the better carrying capacity. Other values can be used as warnings of danger; thus:

$$C = \frac{\sum_{i<j}^{i,j}(k_i^m+1)\left(k_j^m+1\right)}{N\left(N-1\right)} \quad (1)$$

and

$$S = \frac{\sum_{i=1}^{i} C_i^p}{\sum_{j=1}^{j} C_j^n} \quad (2)$$

In Eq. 1, C is the carrying capacity contribution value of subentry, N is the index number, k_i^m and k_j^m refer to the i and the j variable value in the m index system, respectively. In Eq. 2, S is the state of carrying capacity, C_i^p is the i positive contribution value, and C_j^n is its negative counterpart.

1.2.4 Algorithmic method of population limitation

There is a specific mathematical relationship between the regional resource and environmental carrying capacity and the development index. It is found that as the agglomeration of population, the consumption of resources, environment and ecology increase. In contrast, people's gathering also activate the productivity to meet the living needs and protect the surroundings. Obviously, the consumptions and the productions interact with each other and hold a non-linear relation. Thus, this study takes the square root of ratio between consumption rate and the productivity as the independent variable that responded to the development index. As known to all, an increasing population means more consumption of resources, and previous researches (Sveikauskas 1975; Ciccone and Hall 1996) have proved that a higher economic density will pose more agglomerative effects and increase the productivity. Clearly, in a certain region, the change of GDP is equal to the alteration of economic density. For these reasons, this study proposes that the annual growth rate of resident population stands for the consumption rate, and the yearly GDP growth rate is the productivity, which use P_r and G_r for short, respectively. As a result, this study builds Eq. 3 and Eq. 4, which corresponding to the restricted relationship model.

$$E(C) = -C_i^p\omega^2 + C_j^n\omega + \beta_0 \tag{3}$$

$$\omega=\sqrt{P_r/G_r} \tag{4}$$

$$\omega^*=C_j^n/2C_i^p \tag{5}$$

In these equations, E(C) is the expectancy of carrying state, C_i^p is the i positive contribution value, and C_j^n is its negative counterpart; β_0 is a start point of carrying state. ω is the independent variable, as explained in Eq. 4. In addition, the calculus has proved that ω^* (Eq. 5) is the specific variable value that responds to the biggest expectancy.

1.2.5 Evaluation index system

In this study, three evaluation index systems are designed to help measuring the contribution value and the carrying state. First of all, following the basic rules of index selecting, this research takes two significant index systems (Fan et al. 2017; General Office of the Central Committee of the Communist Party of China, General Office of the State Councill of the People's Republic of China 2017) as the primary references; including land resources (pressure index), water resources (amount of consumption), environment (exceeding pollutants) and ecology (ecological health). Then, three scientific and workable index systems are constructed which correspond to three pairs of interactive forces respectively. By applying the "PS-DR-DP" theoretical model, the consumption and stock of water, land and energy are responded with "fulfilling" state, while 'power consumption per unit of GDP' and 'whole-society productivity' are used to reflect the degree of the "most efficiency" (Table 2). Similarly, the indexes in Table 3 and Table 4 synthetically assess the status of environment and ecological health.

1.3 Data sources and processing

1.3.1 Data sources

Most data in this article derive from China Statistical Yearbook (2010, 2017) and Tibet Statistical Yearbook (2010, 2017). Several data of energy are obtained from China Energy Statistical Yearbook (2010, 2017). The data of desertification are from *A Bulletin of Status Quo of Desertification and Sandification in China (the fourth and the fifth)*. A Bulletin of Soil and Water Conservation in China (2010, 2016) offer the soil erosion data. Based on the original material (Qin et al. 2009), authors figure out the available land area by using the land resource calculation method that is stipulated in *Tibet's Major Function Oriented Zoning*, likewise, the available grassland data are provided by another reference (Yang 2003). Finally, these raw data were standardized by the Min-max method.

1.3.2 Correlation test on indicators

This research performs a correlation analysis in order to completely avoid (where possible) and mitigate reductions in subjective influence when selecting indicators for inclusion in our index system. It uses SPSS to test the bivariate correlations between those interacted forces by referring to Pearson correlation coefficient (Stigler and Stephen 1989; Karl 2006), a statistic that is used to reflect the linear correlation of two variables, stipulated that a larger absolute value of coefficient showed a stronger correlation. Analytical results in Table 5 show a weak linear correlation between pressure and support, and the same situation occurs between destructiveness and resilience as well as degeneration and promotion. Specifically, the former two pairs of forces show a

Table 2 The evaluation index system of pressure and support

Force	Influencing factor	Index	NO.
Pressure	Livestock	Main livestock (standard sheep) (10^4)	K^1_1
	Water	Total water consumption (10^8 m^3)	K^1_2
	Land	Annual decrease of cultivated area (km^2)	K^1_3
		Building area (km^2)	K^1_4
	Energy	Total urban liquefied petroleum gas supply (ton)	K^1_5
		Electricity consumption (hundred million kw·h)	K^1_6
		Power consumption per unit of GDP (kw·h /10^4 yuan)	K^1_7
	Population	Resident population at year-end (10^4)	K^1_8
		GDP (10^8 yuan)	K^1_9
Support	Resources support	Available grassland area（10^4 hm^2）	K^1_{10}
		Total water resources (10^8 m^3)	K^1_{11}
		Food production (10^4 ton)	K^1_{12}
		Available land area (km^2)	K^1_{13}
		Crude oil production (ton)	K^1_{14}
		Total electrical generation (10^8 kw·h)	K^1_{15}
	Social and economic support	Whole-society productivity (yuan /per capita)	K^1_{16}
		Urban per capita disposable income (yuan)	K^1_{17}
		Rural per capita disposable income (yuan)	K^1_{18}

Note: k_i^1 is the variable in the evaluation index system of pressure and support.

Table 3 The evaluation index system of destructiveness and resilience

Force	Influencing factor	Index	NO.
Destructiveness	Atmospheric environment	Sulfur dioxide emission (10^4 ton)	K^2_1
	Water environment	Wastewater discharge (10^7 ton)	K^2_2
	Soil environment	Industrial solid waste output (10^4 ton)	K^2_3
	Major disaster	Amount of natural disaster victims (10^4)	K^2_4
		Direct economic loss of geological disasters (10^7 yuan)	K^2_5
Resilience	Pollutant treatment	The investment in treatment of environmental pollution (10^7 yuan)	K^2_6
		Disposal of industrial solid waste (10^4 ton)	K^2_7
		Sewage treatment (10^4 ton)	K^2_8
	Prevention and cure	Amount of health professionals (10^4)	K^2_9
		Investment in geological disaster prevention (10^7 yuan)	K^2_{10}

Note: k_i^2 is the variable in the evaluation index system of destructiveness and resilience.

Table 4 The evaluation index system of degradation and promotion

Force	Influencing factor	Index	NO.
Degradation	Desertification	Desertification area (km^2)	K^3_1
	Forest and grassland degradation	Forest calamity area (km^2)	K^3_2
		Grassland damage area (km^2)	K^3_3
	Water and soil erosion	Scope of responsibility for soil erosion control (km^2)	K^3_4
Promotion	Protection and governance	Planting grassland increased area (km^2)	K^3_5
		Prevention area of forest calamity (km^2)	K^3_6
		Prevention area of grassland damage (km^2)	K^3_7
		Recovery area of water and soil erosion (km^2)	K^3_8

Note: k_i^3 is the variable of the evaluation index system of degradation and promotion.

negative interaction, for they are symbiotic and together consume the same resources. Promotion mainly aims to ease the ecological degeneration that has been existed before artificial destruction, thus, the last pair of forces positively correlate with each other. To sum up, these represent that the preliminary work in this study has weakened the problem of multicollinearity between those independent factors.

Table 5 The bivariate linear correlation results of each pair of interaction forces. PC*= Pearson correlation' Des#= Destructiveness; Deg^= Degradation

Dataset 1		Pressure	Support
Pressure	PC*	1	-0.289
	Sig. (2-tailed)		0.451
	N	9	9
Dataset 2		Des#	Resilience
Des#	PC*	1	-0.163
	Sig. (2-tailed)		0.793
	N	5	5
Dataset 3		Deg^	Promotion
Deg^	PC*	1	0.243
	Sig. (2-tailed)		0.757
	N	4	4

Note: N is the number of samples, and the predetermined significance level (Sig) is 0.05.

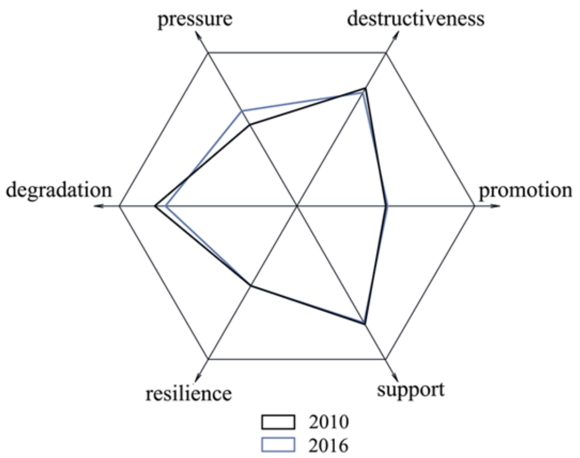

Figure 4 The state of resource and environmental carrying capacity in Tibet (2010 and 2016).

2 Results

2.1 Changes of carrying state

Over the recent decade, especially since 2010, Tibet's economy has achieved rapid development and people's material living standards have been constantly improved. However, we must take harmonious Human-Earth relationship into account first and should regard the ecological protection as the prerequisite in Tibet. Based on previous works (June 2003; Goldstein et al. 2010; Zhang and Deng 2016), authors continue to search the specific answer to this considerable issue. Concretely, in order to give a true reflection of Tibet's development and renew people's cognition of Tibet's resource and environmental carrying capacity, this study selects the most intense period of human activities in recent years (2010-2016) to find the state changes of Tibet's resource and environmental carrying capacity. The analytical results are shown in Table 6 and Figure 4.

2.1.1 Overall responses

Table 6 shows a negative change in Tibet's carrying state between 2010 and 2016. Firstly, from 2010 to 2016, Tibet's carrying state continuously declined, as the carrying state was 0.8580 in 2010, and then it dropped to 0.8371 in 2016. Secondly, in 2010 and 2016, the mean contribution values were separately 0.6500 and 0.6553, they both stayed in an unstable state under the high increase of economic strength. Thirdly, at the aspects of environmental capacity and risk-disaster resisting ability, across both 2010 and 2016, ecological degradation was still severe, and the environmental destruction was no less grim. Worse still, the forces of promotion and resilience fell far behind them. Fourthly, in terms of resources capacity, support surpassed pressure, which drove the society and economy to develop further. To be specific, contrast to 2010, pressure grew fast in 2016 with large other negative forces as usual, while promotion and resilience almost showed no change, which caused an increasing gap between the positive forces and the negative forces. In addition, the corresponding carrying state maps show that Tibet was in a shock growth period although it did not exceed the warning range. In brief, these analysis results warn us that Tibet's carrying state of resource and environmental carrying capacity walked in a precarious line during 2010 to 2016.

2.1.2 Developing trend of resources support capacity

Table 6 The change of carrying state in Tibet in 2010 and 2016. MCV=Mean contribution value.

Year	Pressure	Support	Destructiveness	Resilience	Degradation	Promotion	Carrying state	MCV
2010	0.5265	0.7721	0.7731	0.5246	0.7993	0.5043	0.8580	0.6500
2016	0.6237	0.7594	0.7396	0.5225	0.7769	0.5097	0.8371	0.6553
Changes	0.0972	-0.0127	-0.0335	-0.0021	-0.0224	0.0054	-0.0209	0.0053

Notes: The data in this table is reserved for the original data to 4 decimal places.

Analyses of pressure and support show an asymmetric relationship between the consumption and the production of resources in Tibet. From 2010 to 2016, the growth of Tibet's resources pressure was faster than other forces (Table 6). Although it has abundant resources, there is no fluke for Tibet to develop worry-freely. For instance, combined with the previous researches (Shi and Mao 1999; Sun 2005; Han 2011) and our findings, authors find that the most abundant water reserves in Tibet even have little advantage. Moreover, during 2010 to 2016, pressure increased about 19 percent while the corresponding support decreased about two percent. Consequently, Pressure will overwhelm support within ten years if Tibet keeps the current developmental trend.

2.1.3 Changes of environmental capacity

Although the destructive force reduced under a better governance, the overall environmental capacity continued declining during 2010 to 2016. Because destructiveness was much bigger than resilience, even worse, resilience had a slight decrease. This situation may ascribe to a weak technological level and people's lack of enough attention to environmental pollution. For instance, Tibet's industrial added value increased over twice in 2016 than that of 2010, but the investment in treating environmental pollution did not keep the same pace with it. Another evidence is that the industrial wastes discharge was much more than its corresponding treatment, and this gap will become greater in that way. To conclude, Tibet still faces a serious situation in environmental protection.

2.1.4 Differences in degradation and promotion

In terms of ecology, analyses show that the force of degradation was larger than any other interactive forces although it decreased from 2010 to 2016. Moreover, it is worth mentioning that only promotion increased among all positive forces. Although the increase of promotion was small, it demonstrated people's efforts to protect ecology. However, the hyper-slow increase of promotion did little in reversing the less good situation of Tibet's carrying state of resource and environmental carrying capacity at present. In conclusion, the high degradation cannot accommodate to a large-scale development, and this situation will be a normal in a long term. After all, for Tibet, a top priority is to keep an eye on any tiny harm that maybe lead to severe consequences to the surroundings.

2.2 Responses of environment, ecology and resource to population limitation of Tibet resource and environmental carrying capacity

According to the design of the "PS-DR-DP" theoretical model, the ideal ratio between C_j^n and C_i^p is equal to one. Applying this assumption into Eq. 5, authors find the perfect value of ω^* is 0.5, so the ratio between P_r and G_r is better not over 0.25. Based on the "short board" principle, authors assume that the expected values of carrying capacity have reached the peak in 2010 and 2016, so authors calculate the hypothetic value of ω^* corresponding to each pair of interactive forces, respectively. Results in Table 7 show that the values of ω^* that, between destructiveness and resilience, and between degradation and promotion, were both over 0.5, which means that Tibet's ecology and environment were both severely overloaded; simultaneously, the value of ω^* that, between pressure and support, was lower than 0.5, showing that the resources support capacity has a spare capacity.

2.2.1 Reflections of environment and ecology

According to the analyses, the most obvious thing is that the current economic and the technical strength mismatched the pressure of population, especially in terms of destructiveness and resilience, degradation and promotion. It is quite clear that the conflicts between those two pairs of interactive forces dominated Tibet's resource and environmental carrying capacity. However, the ecological fragility in Tibet is innate and the situation could not change on a large scale under a foreseeable technical condition (Zheng 1996). This

Table 7 The hypothetic values of ω^* in 2010 and 2016.

Hypothetic ω^*	Pressure and support	Destructiveness and resilience	Degradation and promotion
In 2010	0.3410	0.7368	0.7925
In 2016	0.4107	0.7078	0.7621

Notes : ω^* is the specific variable value that responds to the biggest expectancy.

plight impedes researchers to calculate the explicit answer of Tibet's limitation of population. For another, authors find that the serious pollution problem in Tibet had a close relationship with the weak environmental awareness. Thereby, this influencing factor may mutate, which obstructs us to calculate an exact change of environmental capacity by misapplying the law of diminishing returns. For these reasons, authors will not predict the limit of environmental and ecological capacity in this study.

2.2.2 Performance of Resource support

Basically, the resources support has a relatively regular and smooth change process. It is unlike the environmental capacity that can be changed soon by using high technology or restrictive planning to reduce the pollutants. Moreover, it is not as almost be determined by the natural conditions as the ecological capacity does. Therefore, it is suitable to apply the law of diminishing returns in resources support capacity. As a corroboration of this conclusion, authors find that the actual values of ω of resources support were 0.3315 and 0.4071 in 2010 and 2016, respectively, which rightly echoes with the preceding hypothetic ω^* in Table 7. Meanwhile, those results also mean that Tibet can carry more population in terms of the resources support. Thus, according to the previous settings, authors regard the contribution values of 2016 as the origin on the condition that the change trend of pressure and support both keep the current speed. As a result, these two corresponding curves (2016 – 2025) are shown in Figure 5.

It can be seen from Figure 5 that the pressure will exceed the support around 2025, especially in 2023, pressure will nearly equal to the support, which corresponding to the maximum setting value of ω. Therefore, three scenarios are set up in Table 8 to test Tibet's limitation of carrying capacity at that critical time with considering the economic development trend of Tibet.

Analytical results show that in terms of pressure and support, Tibet can carry a population of up to 4 million and a minimum of 3.7 million around 2025. These predictive values are compatible with a recognized population forecast of Tibet, which thought Tibet's lowest population would be 3.6921 million and the largest population would reach to 4.1964 million by 2030 (Guo and Cao 2006). Furthermore, Tibet's yearly population growth rate was close to two percent and the yearly GDP growth rate was about 11 percent during 2014 to 2017, coincidentally, closing to the high setting in the scenarios. Therefore, this situation denotes that the soaring demands of population is tightly pressing against Tibet's socioeconomic strength, which maybe explain that why Tibet has difficulty in handling other problems such as environmental pollutants. Consequently, it warns Tibet to control both the size and the increasing rate of population.

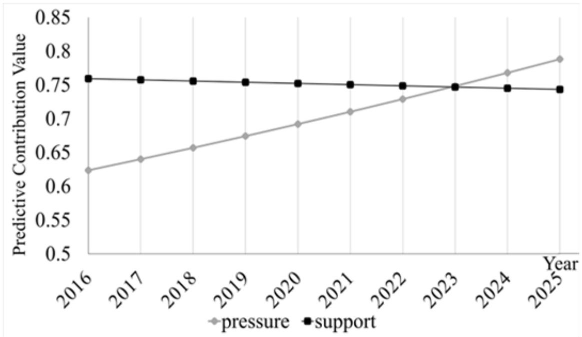

Figure 5 The predictive contribution value of pressure and support during 2016 to 2025.

Table 8 Tibet's possible population size limit in 2023

Scenarios	G_r (%)	P_r (%)	Limit population (×10⁶)
High setting	10	2.5	3.9291
Middle setting	8	2	3.9099
Low setting	6	1.5	3.6665

Notes: *Gr* stands for the annual growth rate of resident population; *Pr* stands for the yearly GDP growth rate.

3 Discussion

This study concludes the holistic carrying capacity of Tibet is getting worse consistent with early findings (Zha and Luo 2002; Zeng 2007), and the population increase has placed increasing stress on Tibet's natural resources and surroundings. Indeed, it has been grown a scientific consensus about the anthropogenic decline of Tibet's load, and researchers thought the most blame is the decline of ecological carrying capacity. However, if Tibet's ecological carrying capacity has been overloaded, why the system did not collapse? What is the most important factor in determining Tibet's population limitation?

The answer to which factor determines the limit of population size has been always controversy. For instance, if authors set “short board” effect as the unique standard, and then most portions of Tibet should prohibit human activities for protecting ecology, which may severely hinder the indispensable development. Likewise, if people consider “growth limit” only, the scarcest or the most restrictive factor will be the Sword of Damocles that people must worry about whether humans can, or not, withstand the consequences of system collapse. In this research, from three interrelated perspectives, which are growth limit, stability of Human-Earth relationship system and short board effect, authors finally calculate the population limitation based on resources support. The premise is that the forces of destructiveness and degradation are decreasing, and authors assume that this positive change will continue. Overwhelmingly, the most fundamental condition is that this research operates Tibet as a closed cyclical system in terms of resource and environmental carrying capacity studies. As the analytical results denote that there is no room for more population because ecology and environment are both severely overloaded; meanwhile, only the resources support has a spare capacity. Thus, those conclusions of population limitation are based on Tibet’s finite resources. However, if Tibet’s environmental destruction and ecological degradation continue to deteriorate, it will have no way to set resources support as the restriction. For these reasons, the effects of technical progress to improve environment capacity and risk-disaster resisting ability require a further research. Similarly, although authors have innovatively built the "PS-DR-DP" hexagonal theoretical model to dynamically evaluate and simulate the state of resource and environmental carrying capacity, it cannot test the stability of the carrying state. Therefore，authors have to delve into this issue in the next stage.

4 Conclusion

To evaluate the carrying state and population limitation of resource and environmental carrying capacity in Tibet, this paper creatively builds the carrying capacity limit formula that in line with the law of diminishing returns, correspondingly, authors modify the critical carrying model. Then, authors evaluate the overall carrying state of resource and environmental carrying capacity in Tibet and calculate the largest population of Tibet in 2025 for the first time in the field of Tibet’s resource and environmental carrying capacity study. The analytical results show the following signs.

(1) The resource and environmental carrying capacity of Tibet is at stake while there is room for maneuver as the decline of negative forces show a promising trend. However, the corresponding positive forces are something of a disappointment. Thus, effective measures should be implemented to prevent the resource and environmental carrying capacity of Tibet from dropping into a worse situation.

(2) From 2010 to 2016, resources support capacity fell at the fastest rate, which led the situation of resource and environmental carrying capacity to further danger. The over-shrinking environmental capacity is the key artificial reason for the inferior resource and environmental carrying capacity, and the weak risk-disaster resisting ability bears the principal responsibility for Tibet’s overloaded trend.

(3) According to the situation of resource and environmental carrying capacity, Tibet’s population limitation could be 3.93 million, 3.91 million and 3.67 million in 2023, respectively, under three different socioeconomic development scenarios. Based on the trend of socioeconomic development and population growth in Tibet, authors suggest that Tibet should restrict its population within four million around 2025. The overloaded environmental capacity and risk-disaster resisting ability requires further supervision.

A further conclusion from this study is that the increase of human demands indeed dominates the Tibet’s population size on the aspect of resources support capacity. As an evidence of extensive development in Tibet, the pressure on resources increased nearly twice than the growth of population, suggesting that Tibet need an economical use of resources as well as a control of population. Meanwhile, authors find that Tibet’s natural growth rate of population is about one percent while the rate of population growth reaches two percent, which may provide perspective for Tibet to take a macro-control measure of population.

Acknowledgements

This study was supported by the Specific Project of National Key Research and Development Program of China (Grants No.2016YFC0503506) and the Strategy Priority Research Program of Chinese Academy of Sciences (Grants No. XDA20010103).

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