Emergy Footprint Analysis of Gannan Tibet an Autonomous Prefecture Ecological Economic Systems

Hua Liu, Yu-mei Wei and Xin Jin

Abstract Emergy footprint theory combines emergy analysis with conventional ecological footprint theory. In this paper, using emergy footprint theory, we calculated some emergy indices to evaluate and analyze the ecological economic system of Gannan Tibetan Autonomous Prefecture in Gansu province. In addition, we offer advices on how to improve its sustainable development.

Keywords Ecological footprint · Emergy footprint · Gannan Tibetan Autonomous Prefecture · Sustainable development

1 Introduction

In recent years, China has found itself confronted with a series of contradictions among natural resources, environment, and the economy. Issues such as population growth, resources depression, and environment deterioration have made sustainability a critical issue [1]. To make sustainability a reality, we must measure where we are now and how much further we can go. In the new methods of valuation, measurement of sustainability has gone from qualitative analysis to quantitative analysis. Ecosystems provide a wide variety of valuable goods and services [2]. Goods and services, in turn, must be quantified and measured on a common scale. Quantifying the value of ecosystem services has become an important vehicle for assuring social recognition and acceptance of the public management of ecosystems [3, 4].

H. Liu · X. Jin
School of Mathematics and Computer Science, Northwest University for Nationalities, Lanzhou 730124, China
e-mail: 7783360@qq.com

Y. Wei (✉)
Experimental Center, Northwest University for Nationalities, Lanzhou 730124, China
e-mail: 649118046@qq.com

B.-Y. Cao et al. (eds.), *Ecosystem Assessment and Fuzzy Systems Management*, Advances in Intelligent Systems and Computing 254, DOI: 10.1007/978-3-319-03449-2_6,

Gansu is the habitat of several minority nationalities. These are two autonomous prefectures (Gannan Tibetan Autonomous Prefecture and Linxia Hui Autonomous Prefecture) and five autonomous counties (Subei Mongolian Autonomous County, Aksay Kazak Autonomous County, Sunan Yugur Autonomous County, Tianzhu Tibetan Autonomous County, and Zhangjiachuan Hui Autonomous County). The ecological environment aggravation of minority nationality regions has seriously hindered the development of Gansu in recent years. Gannan Tibetan Autonomous Prefecture is located in the southern part of Gansu Province (100°46′–104°44′E, 33°06′–36°10′N), with a total land area of 40,201 km^2 and population 680,800. The location is at the eastern margin of the Qinghai–Tibet Plateau, in the upper reaches of Yangtze River and the Yellow River. With the Loess Plateau and Minshan Mountain forming a complex boundary, Gannan exhibits a diverse ecosystem. Gannan Tibetan Autonomous Prefecture experienced economic rapid development after 2000, but on the other hand, its natural ecosystem has deteriorated. This unreasonable economic growth increased the likelihood of ecological disasters in the region. The sustainability of Gannan's ecological economic systems directly affects the ecological security of the minority nationality regions in Gansu Province. In short, quantitative analysis and evaluation of Gannan's ecological economic systems are conducive to the sustainable development of Gansu Province as well as the Yellow River and the Yangtze River Basin.

The aim of this chapter is to demonstrate a new sustainable development index for emergy footprint and emergy capacity from calculations combining the emergy analyses with the ecological footprint model and the concept of basic sustainability.

The chapter will be structured in three parts:

1. introduction to ecological footprint and emergy theory,
2. introduction to emergy footprint,
3. calculations to emergy capacity and emergy footprint in the Gannan region.

2 Introduction to Ecological Footprint and Emergy Theory

2.1 The Ecological Footprint Methodology

Ecological footprint was developed by Wackernagel and Rees in 1996. Ecological footprint model is a biophysical assessment device to quantitatively estimate a region's sustainability. The Ecological footprint for a particular population is defined as the total 'area of productive land and water ecosystems required to produce the resources that the population consumes and assimilate the wastes that the population produces, wherever on Earth that land and water may be located' [5, 6]. Ecological footprint calculations are based on two simple assumptions; first, that we can keep track of most of the resources we use and many of the wastes we generate; second, that most of these resources and waste flows can be converted to a corresponding biological productive area.

Ecological capacity is defined the as the locally available carrying capacity. Ecological footprint methodology uses a common measurement unit to express ecological footprint and ecological capacity in terms of a biological productive area with the global average productivity, utilizing the ‘equivalence factor’ and ‘yield factor.’ So the areas are expressed in standardized ‘global hectares’ [7]. Therefore, ecological footprint and ecological capacity become directly comparable with each other across the globe. As the ecological footprint and ecological capacity are both measured in the same units, they can be compared directly.

Ecological footprint is estimated by the Eq. (1):

$$\mathrm{EF} = N \times \mathrm{ef} = N \times \sum_{i=1}^{n} (aa_i \times r_i) = N \times \sum_{i=1}^{n} \left(\frac{c_i}{p_i} \times r_i \right) \tag{1}$$

Ecological capacity is estimated by the Eq. (2):

$$\mathrm{EC} = N \times \mathrm{ec} = N \times \sum_{j=1}^{n} \left(a_j \times r_j \times y_j \right) \tag{2}$$

EF is the total ecological footprint; N is population size; ef is average per capita footprint; i are the kinds of natural resources or consumption items (for example, energy, food, or forest products production and consumption); a_j is the corresponding areas of No. j resources or consumption items per capita; c_i is the amount or production of No. i resource per capita; p_i is average annual productivity or yield of No. i resource; r_j is equivalence factor; y_j is yield factor. In the analysis of ecological footprint, six main categories of ecologically productive area are distinguished: crop land, pasture, forest, water area, built-up, and energy land.

If the ecological footprint of a region is larger than the ecological capacity, the region runs an ecological deficit. If the ecological capacity of a region is larger than ecological footprint, the region runs an ecological remainder.

2.2 Emergy Theory

Natural systems and economic systems are all tied to energy flow. Traditional energy analysis, however, has been criticized in many aspects. One is that various energy types, including materials and services, cannot be compared or totaled only by energy quantity. Emergy theory is a new method to evaluate natural capital and ecosystem services. Emergy analysis has been developed over the past 25 years by Odum [8]. Emergy (spelled with an ‘m’) is defined as the energy of one type required in transformations to generate a flow and storage. In this account, solar emergy is used. Solar emergy of a flow or storage is the solar energy required to generate that flow or storage. Its units are solar emergy emjoules (abbreviation: sej). The total emergy of an item can be expressed as Eq. (3):

$$\text{emergy} = \text{available energy of item} \times \text{transformity} \tag{3}$$

The transformity is defined as the amount of emergy of one type required directly and indirectly to generate a unit of energy of another type. It is the emergy per unit energy in units of emjoules per Joule that constitutes the ratio of emergy to available energy. The units of transformity are solar emjoules/Joule, abbreviated sej/J or solar emjoules/g (sej/g).

Emergy measures both the work of nature and that of humans in generating products and services, as a science-based evaluation system that represents both natural values and economic values with a simple, universal unit. As the products and services are both measured in the same units, they can be compared directly.

3 Emergy Footprint and Calculation of Gannan

3.1 Emergy Footprint and Emergy Capacity

Emergy footprint has been developed by Zhao et al. [9]. Emergy footprint methodology is a new method of ecological footprint calculation, based on the emergy analysis. The translation of human demand of natural resources and the supply of natural services into understandable and quantifiable concepts are the main objective of this new method. First, amounts of human consumption corresponding to six categories of ecological productive areas and amounts of natural supply are calculated. Next, these amounts are translated into common unit emergy through the emergy analysis. Finally, in this new method, the emergy footprint and emergy capacity is derived by dividing the emergy amounts by the Emergy Density. Emergy density is the emergy amount per unit time of a region; the following two Eqs. (4) and (5) are used to calculate the emergy density:

$$P_{\mathrm{e}} = \frac{\text{total emergy of the earth}}{\text{areas of the earth}} = \frac{1.583 \times 10^{25}\,\mathrm{sej}}{5.1 \times 10^{10}\,\mathrm{hm}^2} = 3.104 \times 10^{14}\left(\mathrm{sej\,hm}^{-2}\right) \quad (4)$$

$$P_{\mathrm{g}} = \frac{\text{total emergy of Gannan}}{\text{areas of Gannan}} = \frac{6.99 \times 10^{21}\,\mathrm{sej}}{4.0201 \times 10^{6}\,\mathrm{hm}^2} = 1.74 \times 10^{15}\left(\mathrm{sej\,hm}^{-2}\right) \quad (5)$$

P_{e} is the earth emergy density. The total emergy amount 1.583×10^{25} sej of the earth in 1 year is taken from [10]. The total emergy amount of the earth is the sum of the emergy of solar insolation, deep earth heat, and tidal energy.

P_{g} is the emergy density of Gannan. In calculation of the total emergy of Gannan, five kinds of renewable resources emergy are considered: sun, wind, chemical energy in rain, geo-potential energy in rain, and earth cycle energy. As shown in Table 1, the maximum item of emergy amount is regarded as the total emergy of Gannan to avoid the duplicate calculation.

Table 1 Calculations for emergy capacity in the Gannan (2010)

Item	Raw data (J)	Transformity (sej/J)	Total emergy (sej)	Emergy per cap (sej/cap)	Emergy capacity per cap (hm^2/cap)
Population of Gannan: 680,800; earth emergy density P_e *= 3.104E+1014*					
Sun	2.25E+20	1	2.25E+20	3.30E+14	1.07E+00
Wind	5.68E+18	6.23E+02	3.54E+21	5.20E+15	1.68E+01
Rain geo-potential	7.86E+17	8.89E+03	6.99E+21	1.03E+16	3.31E+01
Rain chemical	1.32E+17	1.54E+04	2.03E+21	2.99E+15	9.63E+00
Earth cycle	4.50E+16	2.90E+04	1.31E+21	1.92E+15	6.18E+00
Total emergy of Gannan (the maximum item)			6.99E+21		
Emergy capacity in the Gannan					3.31E+01

Emergy footprint of Gannan is estimated by the Eq. (6):

$$\mathrm{EF}' = N \times \mathrm{ef}' = N \times \sum_{i=1}^{n} a_i = N \times \sum_{i=1}^{n} \frac{c_i'}{p_g} \tag{6}$$

EF′ is the total emergy footprint; N is population size; ef′ is average per capita emergy footprint; i are the kinds of natural resources or consumption items (for example, energy, food, or forest products production and consumption); a_i is the corresponding emergy footprint of No. i resources or consumption items per capita; c_i' is the emergy amount or production of No. i resource per capita (sej); P_g is the emergy density of Gannan.

Emergy capacity of Gannan is estimated by the Eq. (7):

$$ec' = \frac{e}{P_e} \tag{7}$$

where ec′ is the emergy capacity per capita; e is the renewable resources of emergy amount per capita (sej) in Gannan; P_e is the earth emergy density.

The concept of ecological budget is defined as the sum of emergy capacity minus emergy footprint. If the ecological budget is negative, it is often interpreted as an ecological 'overshoot.' That is, 'ecological deficit' in which human consumption exceeds the carrying capacity in a given region, meaning the region is unsustainable. In a reverse situation where the ecological budget is positive and human consumption is within the carrying capacity, the state is called an 'ecological surplus,' meaning the region is sustainable.

3.2 Calculation of Gannan

To calculate the emergy footprints and the emergy capacity in Gannan Tibetan Autonomous Prefecture for 2001–2010, the method of emergy footprint was used. Table 1 shows the emergy capacity of Gannan in 2010. In order to avoid duplicate

Table 2 Calculations for emergy footprint in the Gannan (2010)

Item	Raw data (J)	Transformity (sej/J)	Total emergy (sej)	Emergy per cap (sej/cap)	Emergy footprint per cap (hm^2/cap)	Land types
Emergy footprint per capita			2.48E+22	3.65E+16	2.10E+01	
Biological resources			5.24E+21	7.69E+15	4.42E+00	
Wheat	1.38E+15	6.80E+04	9.38E+19	1.38E+14	7.93E−02	Arable land
Cereal	8.15E+12	3.59E+04	2.93E+17	4.30E+11	2.47E−04	Arable land
Beans	4.35E+12	3.59E+04	1.56E+17	2.29E+11	1.32E−04	Arable land
Tubers	9.70E+12	3.59E+04	3.48E+17	5.12E+11	2.94E−04	Arable land
Corn	5.35E+10	3.59E+04	1.92E+15	2.82E+09	4.57E−07	Arable land
Vegetables	3.15E+13	5.81E+04	1.83E+18	2.69E+12	1.55E−03	Arable land
Chinese medicine	3.89E+14	2.00E+05	7.78E+19	1.14E+14	6.57E−02	Arable land
Oil-bearing crops	7.82E+14	6.90E+05	5.40E+20	7.93E+14	4.56E−01	Arable land
Fruits	2.86E+13	5.30E+04	1.52E+18	2.23E+12	1.28E−03	Forest
Forestry	1.84E+13	2.00E+05	3.68E+18	5.41E+12	3.11E−03	Forest
Meats	4.75E+14	3.17E+06	1.51E+21	2.21E+15	1.27E+00	Pasture
Milks	1.67E+15	1.70E+06	2.84E+21	4.17E+15	2.40E+00	Pasture
Wools	3.92E+13	4.40E+06	1.72E+20	2.53E+14	1.46E−01	Pasture
Fishery	4.75E+11	2.00E+06	9.50E+17	1.40E+12	8.03E−04	Water area
Energy resources			1.96E+22	2.88E+16	1.66E+01	
Electric	1.01E+17	1.59E+05	1.61E+22	2.36E+16	1.36E+01	Water area
Coal	8.92E+16	3.98E+04	3.55E+21	5.21E+15	3.00E+00	Fossil land

calculation, the maximum item of emergy amount is regarded as the total available emergy. This amount is divided by the amount of population in the region being measured, equaling the amount of e in Eq. (7) the emergy supply of natural resources per capita. And then, the amount of e is divided by the earth emergy density P_e. We get the emergy capacity per capita (ec′). The calculation method for 2001–2009 is same as 2010.

The emergy capacity (ec') of Gannan was 33.1 hm^2/cap. As proposed by [11], at least 12 % of the earth's carrying capacity is available for biodiversity protection. Emergy capacity is reduced by 12 % for biodiversity protection. With 12 % set aside for biodiversity protection, the emergy capacity of Gannan dropped from 33.1 hm^2/cap down to 29.1 hm^2/cap.

Tables 2 and 3 show the emergy footprint of Gannan in 2010. The actual consumption amounts of two kinds of natural resources (biological resources and energy resources) are calculated, respectively, and these amounts are translated into the common units' emergy. These emergy amounts are divided by the population to get the c_i' in Eq. (6). The amount of c_i' is divided by the region emergy density of Gannan

Table 3 Ecological footprints summary in the Gannan (2010)

Emergy footprint per capita		Emergy capacity per capita	
Land types	Total (hm^2/cap)	Category	Total (hm^2/cap)
Arable land	6.03E−01	Renewable resources	3.31E+01
Forest	4.39E−03		
Pasture	3.82E+00		
Water	8.03E−04	12 % for biodiversity	3.97E+00
Built-up area	1.36E+01		
Fossil energy	3.00E+00		
Total	2.10E+01	Total	2.91E+01

Table 4 Ecological footprints and emergy capacity in the Gannan for 2001–2010

Year	Emergy footprint per capita (sej/cap)	Emergy capacity per capita (sej/cap)	Ecological budget
2001	18.0	29.72	11.72
2002	17.9	29.45	11.55
2003	18.2	29.45	11.25
2004	16.7	29.05	12.35
2005	18.6	29.20	10.60
2006	18.8	28.78	9.98
2007	19.0	28.64	9.64
2008	20.2	29.17	8.97
2009	20.4	29.16	8.76
2010	21.0	29.14	8.14

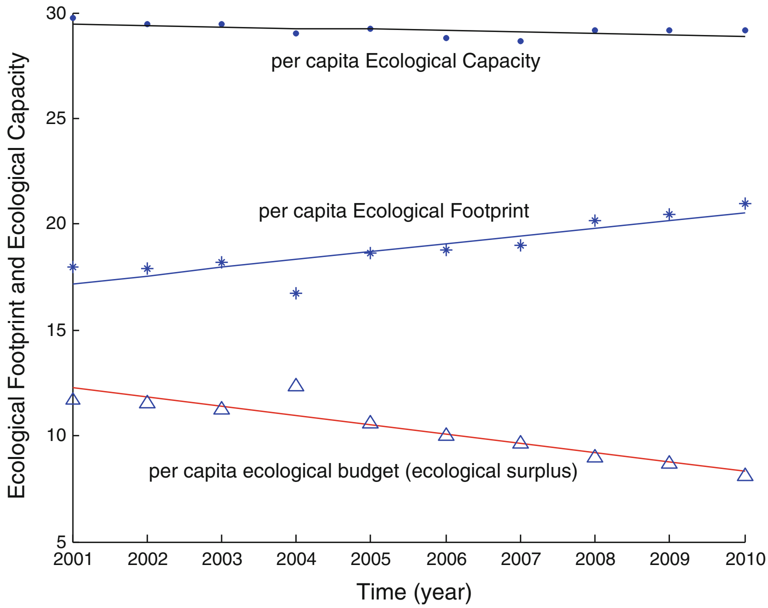

Fig. 1 Ecological footprints and emergy capacity in the Gannan for 2001–2010

P_g to get the footprint, and all the footprints are added together to get the ecological footprint per capita. The calculation method for 2001–2009 is same as 2010.

As Table 2 and Table 3 show the ecological emergy footprint of Gannan in 2010 was 21.0 hm^2/cap. The emergy capacity of Gannan was 29.1 hm^2/cap. We can draw this conclusion: the emergy capacity of Gannan is larger than the emergy footprint. Consequently, the ecological surplus was 8.131 hm^2/cap. It meant the region is sustainable in 2010.

The ecological footprint of Gannan was calculated using existing data for long periods of time: 2001–2010. Table 4 and Fig. 1 analyze development trend of Gannan's per capita ecological footprint and ecological capacity and ecological budget 2001–2010. As Fig. 1 shows, the ecological footprints of Gannan increases and the emergy capacity and ecological budget (ecological surplus) of Gannan decrease.

4 Conclusion

The aim of this paper is aim to demonstrate a new sustainable development index for emergy footprint and emergy capacity from calculations combining the emergy analyses with the ecological footprint model and the concept of basic sustainability. The per capita ecological footprint and per capita emergy capacity of Gannan from 2001 to 2010 was calculated. Results showed that the per capita emergy capacity in Gannan decreases and the ecological budget (ecological surplus) dropped from 11.72 hm^2 in 2001 to 8.14 hm^2, whereas the per capita emergy footprint increased from 18 to 21 hm^2 during the same time period. The results indicate that Gannan has been running an ecological surplus, but the surplus has been decreasing every year and if we do not care about it, Gannan will be ecological deficit in the future.

As Table 3 shows, the order of bio-productive land types size was: Built-up area>Pasture>Fossil energy>Arable land>Forest>Water. That meant the lion's share of the emergy footprint was built-up area. The proportion of bio-productive land types in emergy footprint was not reasonable. Owing to the unreasonable structure of ecological economic systems of Gannan, advice was offered to the government of Gannan Tibetan Autonomous Prefecture that people of Gannan devote major efforts to developing agriculture, forestry and stock raising, touring agriculture, and farm product processing. At the same time, people must decrease built-up area from now on. These measures should prove beneficial to the economy of the ecological economic systems of Gannan.

Ecosystems are quite complex and often poorly understood [12]. The dynamic and complexity of ecosystems make it likely that the measures of the value of ecosystem services will continue to be partial and incomplete. It demonstrates the need for much additional interdisciplinary research that can make significant contributions to the valuation of ecosystem services [13].

Acknowledgments Thanks to the support by National Natural Science Foundation of China (No. 31260098), Natural Science Foundation of Gansu Province (No. 1208RJYA037) and Program for Scientific Research Innovation Team of Northwest University for Nationalities.

References

1. Zhao, S., Li, Z.Z., Li, W.L.: A modified method of ecological footprint calculation and its application. Ecol. Model. **185**, 65–75 (2005)
2. Costanza, R, d'Arge, R., de Groot, R.S., Faber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van der Belt, M.: The value of the world's ecosystem services and natural capital. Nature **387**, 253–260 (1997)
3. Daily, G.C.: Introduction: what are ecosystem services. In: Daily, G.C. (ed.) Nature's Services: Societal Dependence on Natural Ecosystems, pp. 1–10. Island Press, Washington, DC (1997)
4. Wilson, M.A., Carpenter, S.: Economic valuation of freshwater ecosystem services in the United States: 1971–1997. Ecol. Appl. **9**(3), 772–783 (1999)
5. Rees, W.E.: Eco-footprint analysis: merits and brickbats. Ecol. Econ. **32**(3), 371–374 (2000)
6. Wackernagel, M., Onisto, L., Bello, P., Linares, A.C., Falfan, I.S.L., Garcia, J.M., Guerrero, A.I.S., Guerrero, M.G.S.: National natural capital accounting with the ecological footprint concept. Ecol. Econ. **29**, 375–390 (1999)
7. Wackernagel, M, Schulz, N.B, Deumling, D., et al.: Tracking the ecological overshoot of the human economy. Proc. National Acad. Sci. **99**(14), 9266–9271 (2002)
8. Odum, H.T.: Emergy evaluation. In: Ulgiati, S., Brown, M.T., Giampietro, M., Herendeen, R.A., Mayumi, K. (eds.) Advances in Energy Studies. Energy Flows in Ecology and Economy, pp. 99–111. MUSIS, Roma (1998)
9. Zhao, S., Li, Z.Z, Li, W.L.: A modified method of ecological footprint calculation and its application. Ecol. Model. **185**, 65–75 (2005)
10. Odum, H.T., Brown, M.T., Williams, S.B.: Handbook of Emergy Evaluations Folios 1–4. Center for Environmental Policy. University of Florida, Gainesville FL (2000)
11. WCED, World Commission on Environment and Development, Our Common Future. Oxford University Press, Oxford (1987)
12. Liu, H., Li, Z.Z., Gao, M., Dai, H.W., Liu, Z.G.: Dynamic complexities in a host-parasitoid model with Allee effect for the host and parasitoid aggregation. Ecol. Complexity **6**(3), 337–345 (2009)
13. Zhao, S., Wu, C.W., Hong, H.S., Wang, W.P.: The theoretical model for quantifying the value of ecosystem services. J. Biotechnol. **136S**, S766–S767 (2008)