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The Dynamic Analysis and Comparison of Emergy Ecological Footprint for the Qinghai–Tibet Plateau: A Case Study of Qinghai Province and Tibet

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Received: 14 August 2019; Accepted: 5 October 2019; Published: 11 October 2019



Abstract: The Qinghai–Tibet Plateau is experiencing rapid urbanization and ecological degradation, which have led to unsustainable development. It is urgent to conduct a scientifically rigorous study to evaluate its sustainability. Emergy ecological footprint (EEF) is a new modification of ecological footprint based on ecological thermodynamics. This study applied a modified EEF model and three indicators to analyze the sustainability using data collected from Tibet and Qinghai Province during 1995 to 2014. The grey model (GM) was applied to simulate and predict the ecological status of Qinghai and Tibet. Results showed that: (1) the emergy ecological footprint and ecological deficit of Qinghai province increased in general from 1995 to 2014, while Tibet was still sustainable during this period despite the fact that its ecological surplus decreased; (2) the three sustainability indicators indicate that Qinghai and Tibet are moving away from sustainability; (3) the ecological deficit of Qinghai will keep increasing and the ecological surplus of Tibet will keep decreasing from 2015 to 2024. Finally, several suggestions were proposed to protect the local environment and restore ecological functions in these regions.

Keywords: emergy ecological footprint; emergy carrying capacity; sustainability indicators; grey model

1. Introduction

Sustainability, which can be expressed as “the capacity to endure” [1], has become a worldwide goal of environmental development. Sustainability is crucial for a region’s policy-making. All human activities depend on the planet’s natural capital, which can be defined as a stock of materials including ecosystem, minerals, forests, biodiversity, and so on, to provide ecological services and natural resources [2]. Humans have had significant effects on the earth, associated with population growth and economic development. Currently, many conflicts have become more notable among natural resources, environment, and economy, and there are increasing risks of ecosystem quality degradation and tipping the biosphere into a state where it would be very difficult or even impossible to support the human civilization [3]. Therefore, studies should focus on the coordination between environmental protection and economic development. In addition, the conflict between short-term development and long-term welfare must be taken into account [4]. Since the early 1970s, many reports such as “The Limits to Growth”, “Our Common Future”, and “State of the World” have warned that the unlimited growth of the human population and consumption would lead to unsustainability [5,6]. In recent years,

environmental deterioration has still been getting worse. The detrimental effect of human behavior on the biosphere is also coming to the surface [7,8]. To achieve long-term sustainability, the human consumption of resources cannot exceed the environmental carrying capacity to maintain sustainability. It is necessary to measure the consumption of human needs and the region's carrying capacity to estimate how much further we can go.

Ecological footprint (EF) was initiated as a policy and planning tool for sustainability [9], and has become an emerging ecological economics method to evaluate sustainable development quantitatively. EF of any defined population (from an individual to the population of a city or country) is the area of biologically productive land and water appropriated exclusively to produce the resources used and the waste generated by the population. Carrying capacity is the number of individuals of a given species that a given habitat can support without being permanently damaged [10]. As the ecological footprint and carrying capacity are measured in the same unit, they can be compared in order to assess the state of regional sustainable development. If the ecological footprint of a region is larger than the carrying capacity, the region experiences an ecological deficit; if the carrying capacity is larger than the ecological footprint, the region is an ecological reminder.

Currently, EF has been widely adopted to evaluate the sustainability of different scales, for instance national [11,12], regional [13–15], city [16,17], and campus [18], and of different systems (e.g., agricultural [19], grassland [20], tourism [21], industry [22,23], and biogas systems [24]). However, there are some obvious, inherent flaws in EF [25,26]. First, the 'equivalence factor' and 'yield factor' are based on the global productivity and international standard, failing to reflect the complexity of the ecological functions and the temporal differences of the natural environment. Second, the conventional method does not distinguish the renewable and nonrenewable land uses. In addition, it does not consider the land with low biological productivity. To remedy these deficiencies, many scholars have combined EF with other methods, such as the input–output analysis [27,28], the thermodynamic method [29], emergy accounting [4,30], and embodied exergy [31]. In these studies, emergy accounting was proven to complement the EF and overcome some limitations of the EF.

Emergy (spelled with an "m"), originated by Odum in the late 1980s, is defined as available energy previously used up directly or indirectly in the process of producing a product or service [32,33]. It is measured in solar equivalent joules and its unit is sej (solar equivalent joules). More detailed information about emergy analysis can be found in [34–36].

Zhao et al. (2005) [37] proposed an emergy ecological footprint method (EEF) by integrating emergy analysis into the conventional ecological footprint model. This method provided insight to evaluate the resource consumption and the impact on the environment through the method of tracking emergy flows in ecosystems. In recent years, many researchers have introduced this new method to evaluate the sustainable development [24,30,38–40].

The Qinghai–Tibet Plateau (QTP), known as the world's third pole, holds the largest typical alpine meadow ecosystem and provides a unique environment for a wide variety of alpine species. However, due to climate change and increasing grazing pressures, the QTP is faced with severe problems on sustainable development. For example, nearly 40% of the QTP's grassland has experienced fragmentation and decreased in grassland coverage [41], or degraded to desert or "black soil beach" [42]. This degradation could further affect the ecosystems of surrounding areas and threaten the livelihood of nearly 40% of the population of China. As the QTP covers wide areas, different regions are significantly different in economy and environment, so it is not reasonable to evaluate the overall sustainability of the QTP. The objective of this article is to evaluate the long-term sustainability of the QTP through a modified emergy ecological footprint model. Qinghai Province and the Tibet Autonomous Region are taken as the study areas because they are two main regions in the QTP. Moreover, three evaluation indicators were proposed to analyze the sustainability of Qinghai and Tibet. Finally, the future sustainable status was predicted with the grey model. Several suggestions considering the local realities were proposed to protect local environment and restore ecological functions. Results of this study are expected to contribute to the sustainable development of the QTP.

2. Materials and Methods

2.1. Study Area Overview

Location of the study area are shown in Figure 1.

Qinghai Province ($89^{\circ}24'–103^{\circ}04'$ E, $31^{\circ}36'–39^{\circ}12'$ N) is located in the northeast of the Qinghai–Tibet Plateau. The total area of Qinghai is more than 7.2×10^9 hm² (hectare) with a total population of 5.98 million in 2017. The average elevation is over 3500 m a.s.l, with the altitude elevation stretching from 1650 m to 6860 m a.s.l. Qinghai has a typical plateau continental climate. The annual mean temperature is 5–8 °C and the annual total precipitation is about 300 mm, both varying a lot among different areas [43]. Qinghai has experienced rapid economic growth since the implementation of China's Western Development policy. The annual increase rate of GDP was up to 20% since 2000. Qinghai is a multi-ethnic populated area, the population of minorities accounts for more than 40% of the total population.

Tibet ($78^{\circ}25'–99^{\circ}06'$ E, $26^{\circ}50'–36^{\circ}53'$ N) is located in the southwest of the Qinghai–Tibet Plateau. It covers about 1.23×10^{12} hm² with a total population of 3.37 million. The average elevation is above 4000 m, with a range from 1000 m in the southeast to 5000 m in the northwest. The annual mean temperature is 2.8–11.9 °C and annual total precipitation is 74.8–901.5 mm [44]. There are many rare species in Tibet, such as the Tibetan antelope, yak, yew, and so on [45]. Tibet is abundant in natural resources, such as water, forests, and minerals.

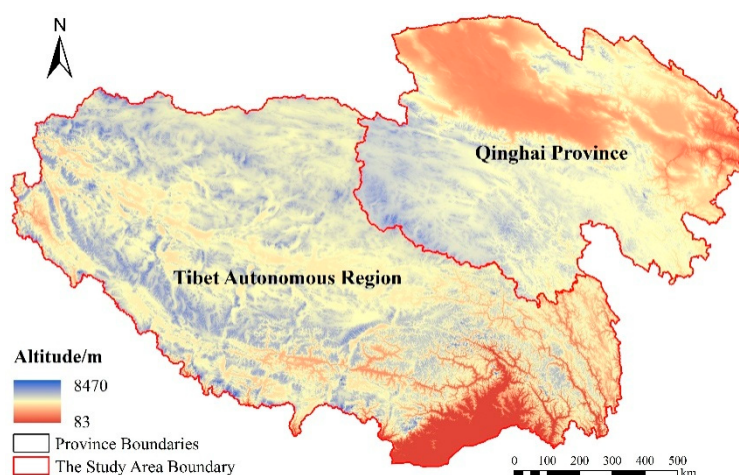


Figure 1. Location of the study area.

2.2. Data Source and Processing

Original socioeconomic data, such as population, agricultural production, industrial production, total waste of industry, and gross domestic product (GDP) data, were retrieved from the “Qinghai Statistical Yearbook” and the “Tibet Statistical Yearbook” for 1995–2014.

The emergy conversion coefficient and transformity used to calculate the unit emergy value (UEV) for all products and five renewable resources were collected from published literature [4,34,46–50]. Detailed data and data sources on five renewable resources and consumption items are listed in Tables 1 and 2. The emergy conversion coefficient is defined as the amount of emergy per unit product or service contained. Transformity, the most widely used unit of emergy value (expressed in sej/J or sej/g), is defined as the amount of solar emergy required to produce a unit of available energy at the output. It measures the process efficiency—the lower the transformity, the more efficient the conversion [51]. Solar emergy of a flow or a storage is the solar emergy used directly or indirectly to generate that flow or storage. Its unit is solar emergy emjoules (abbreviation: sej) [34].

Table 1. Emergy ecological footprint of Qinghai in 2014.

Category	Items	Basic Data	Unit	Emergy Conversion Coefficient	Unit	Transformity	Unit	EEF (hm ²)	Eef (hm ² /cap)
Cropland	Grain	631,800	t	1.62E+10	J/t	8.30E+04	sej/J	1.35E+06	0.2322
	Wheat	348,600	t	1.57E+10	J/t	6.80E+04	sej/J	5.94E+05	0.1017
	Hulless barley	94,400	t	1.62E+10	J/t	8.30E+04	sej/J	2.02E+05	0.0347
	Beans	56,800	t	1.85E+10	J/t	6.90E+05	sej/J	1.16E+06	0.1982
	Oil plants	315,100	t	2.55E+10	J/t	6.90E+05	sej/J	8.84E+06	1.5156
	Melons	12,500	t	2.46E+09	J/t	8.30E+04	sej/J	4.07E+03	0.0007
	Vegetables	1,585,846	t	2.50E+09	J/t	2.70E+04	sej/J	1.71E+05	0.0293
	Tobacco	150	t	1.43E+09	J/t	8.49E+04	sej/J	2.90E+01	0.0000
	Corns	188,800	t	1.65E+10	J/t	2.70E+04	sej/J	1.34E+05	0.0230
	Potatoes	359,500	t	4.20E+09	J/t	8.30E+04	sej/J	2.00E+05	0.0343
	Sugur beets	980	t	2.68E+09	J/t	8.40E+04	sej/J	3.52E+02	0.0001
Grassland	Meat	334,100	t	4.60E+09	J/t	4.00E+06	sej/J	9.80E+06	1.6798
	Milk	312,600	t	2.90E+09	J/t	2.00E+06	sej/J	2.89E+06	0.4956
	Cotton	20,718	t	4.60E+09	J/t	4.40E+06	sej/J	6.69E+05	0.1146
	Eggs	21,800	t	5.50E+09	J/t	2.00E+06	sej/J	3.82E+05	0.0656
	Honey	1533	t	2.95E+09	J/t	8.40E+04	sej/J	6.06E+02	0.0001
Forestry	Walnuts	358	t	2.65E+09	J/t	6.90E+05	sej/J	1.04E+03	0.0002
	Pepper	130	t	3.86E+10	J/t	6.90E+05	sej/J	5.52E+03	0.0009
	Woods	5000	t	1.57E+10	J/t	4.40E+04	sej/J	5.51E+03	0.0009
	Fruits	13,249	t	3.30E+09	J/t	5.30E+05	sej/J	3.70E+04	0.0063
Water areas	Fishery	9037	t	5.50E+09	J/t	2.00E+06	sej/J	1.59E+05	0.03
Fossil land	Chemical fertilizer	1886.4	t	-	-	1.60E+15	sej/t	4.81E+03	0.0008
	Plastic film	7045.86	t	-	-	3.80E+14	sej/t	4.27E+03	0.0007
Built-up land	Waste water	2.30E+08	t	5.00E+06	J/t	8.60E+05	sej/J	1.58E+06	0.2704
	Waste gas	2.71E+08	t	2.40E+06	J/t	4.80E+04	sej/J	4.98E+04	0.0085
	Solid waste	1.24E+08	t	6.90E+08	J/t	1.80E+06	sej/J	2.46E+08	42.1803
	Electricity	3.14E+10	Kw·h	3.60E+06	J/kW·h	1.60E+05	sej/J	2.88E+07	4.9384
Total								3.03E+08	51.96

Table 2. Emergy ecological footprint of Tibet in 2014.

Category	Items	Basic Data	Unit	Emergy Conversion Coefficient	Unit	Transformity	Unit	EEF (hm ²)	Eef (hm ² /cap)
Cropland	Grain	4663	t	1.62E+10	J/t	8.30E+04	sej/J	1.00E+04	0.0031
	Wheat	237,252	t	1.57E+10	J/t	6.80E+04	sej/J	4.04E+05	0.1272
	Hulless barley	680,542	t	1.62E+10	J/t	8.30E+04	sej/J	1.46E+06	0.4596
	Beans	22,107	t	1.85E+10	J/t	6.90E+05	sej/J	4.50E+05	0.1417
	Other grains	35,173	t	1.62E+10	J/t	8.30E+04	sej/J	7.54E+04	0.0238
	Oil plants	63,433	t	2.55E+10	J/t	6.90E+05	sej/J	1.78E+06	0.5606
	Peanuts	338	t	2.55E+10	J/t	6.90E+05	sej/J	9.49E+03	0.0030
	Vegetables	682,132	t	2.50E+09	J/t	2.70E+04	sej/J	7.34E+04	0.0231
	Green feeds	355,752	t	1.43E+09	J/t	8.49E+04	sej/J	6.89E+04	0.0217
Grassland	Meat	286,200	t	4.60E+09	J/t	4.00E+06	sej/J	8.40E+06	2.6437
	Milk	340,600	t	2.90E+09	J/t	2.00E+06	sej/J	3.15E+06	0.9922

Table 2. Cont.

Category	Items	Basic Data	Unit	Emergy Conversion Coefficient	Unit	Transformity	Unit	EEF (hm ²)	Eef (hm ² /cap)
Forestry	Fruits	12,553	t	3.30E+09	J/t	5.30E+05	sej/J	3.50E+04	0.0110
	Tea	54	t	1.43E+10	J/t	2.00E+05	sej/J	2.46E+02	0.0001
	Matsutake	80	t	9.35E+09	J/t	2.70E+04	sej/J	3.22E+01	0.0000
	Mushroom	506	t	9.35E+09	J/t	2.70E+04	sej/J	2.04E+02	0.0001
	Walnuts	4352	t	2.65E+09	J/t	6.90E+05	sej/J	1.27E+04	0.0040
	Pepper	137	t	3.86E+10	J/t	6.90E+05	sej/J	5.82E+03	0.0018
	Woods	74,250	t	1.57E+10	J/t	4.40E+04	sej/J	8.18E+04	0.0258
	Bamboo	11,072	t	1.57E+10	J/t	4.40E+04	sej/J	1.22E+04	0.0038
Fossil land	Chemical Fertilizer	1012	t	-	-	1.60E+15	sej/t	2.58E+03	0.0008
	Plastic film	1724	t	-	-	3.80E+14	sej/t	1.04E+03	0.0003
Built-up land	Waste water	4.31E+06	t	5.00E+06	J/t	8.60E+05	sej/J	2.96E+04	0.0093
	Waste gas	2.19E+07	t	2.40E+06	J/t	4.80E+04	sej/J	4.03E+03	0.0013
	Solid waste	3.83E+06	t	6.90E+08	J/t	1.80E+06	sej/J	7.59E+06	2.3891
	Electricity	3.22E+09	kW·h	3.60E+06	J/kW·h	1.60E+05	sej/J	2.96E+06	0.9323
Total								2.66E+07	8.38

Solar radiation emergy was estimated from a 30 m resolution digital elevation model (DEM) using the Area Solar Radiation tool of the ESRI ArcGIS10.4 software. The DEM was downloaded from the Geospatial Data Cloud website (<http://www.gscloud.cn/>). Both precipitation data and wind speed data were based on climate data from the 154 meteorological stations located in the Qinghai–Tibet Plateau and its surrounding areas. The climate data were downloaded from the National Meteorological Information Center (<http://data.cma.cn/>) and were interpolated by ANUSPLIN software. More detailed information about ANUSPLIN software can be found in [52,53].

2.3. A Modified Emergy Ecological Footprint Method

The method used here followed the emergy ecological footprint model proposed by Zhao et al. (2005) [37]. The emergy ecological footprint of a region could be calculated based on the following three steps:

- (1) Estimate the amounts of human consumption corresponding to six categories of ecologically productive areas and the amounts of natural supply.
- (2) Translate these amounts into emergy unit through the emergy analysis.
- (3) Derive the ecological footprint and carrying capacity by dividing the emergy amounts by the emergy density, which refers to the amount of emergy that each unit area uses.

However, some improvements were proposed in this paper. The improvements are reflected in the following ways: (1) The emergy ecological footprint was used to assess the influence of regional population and economic changes on the environment and resources. In other words, instead of using consumption data, we used regional biological resources productivity and emergy to estimate the ecological footprint of human population growth and economic development. The conventional EEF is a global concept, in which the world is regarded as a self-sufficient, closed system where human consumption equals to the economic yield that humans produce, hence human consumption can be used as an ecological footprint to indicate the human impact on the entire world. However, the fact is that the world is an open system because of imports and exports, thus human consumption can't reflect the regional ecological impact [54]. The real ecological footprint produced by human is not the consumption of the products and resources in the area, but the sum of economic activities and resources extracted within the area. (2) The region emergy density (6.27×10^{10} sej/m²·a) was adopted to calculate the emergy ecological footprint and the emergy carrying capacity of Qinghai and Tibet from 1995 to 2014, and a comparative analysis was made between these two regions. RED is the emergy

amount per unit time of a region ($\text{sej}/\text{m}^2\cdot\text{a}$). It not only can reflect the true supply capacity and human consumption in an area, but also can be used to estimate regional patterns in carrying capacity and ecological footprint. (3) The total waste data of industry, including waste gas, waste water, and solid waste, were incorporated into the EEF calculation.

2.3.1. Emery Ecological Footprint

The emery ecological footprint is calculated by the following equation:

$$EEF = EEF_1 + EEF_2 + EEF_3 + EEF_4 + EEF_5 + EEF_6 = \sum \frac{UEV_i \times f_i}{RED} \quad (1)$$

$$RED = \frac{\text{total emery of a region}}{\text{areas of the region}} \quad (2)$$

$$eef = \frac{EEF}{N} \quad (3)$$

where EEF is total emery ecological footprint (hm^2); EEF_1 to EEF_6 are the emery ecological footprints of six land-use categories (hm^2), including cropland, grassland, forestry, water areas, fossil land, and built-up land; UEV_i represents the amount of the emery required to produce the i^{th} product or service (sej/g , sej/J , $\text{sej}/\text{\$}$); f_i is the amount of the i^{th} product or resource (g , J or $\text{\$}$); RED is region emery density ($\text{sej}/\text{m}^2\cdot\text{a}$); N is the size of population in a region; eef is emery ecological footprint per capita (hm^2/cap).

When calculating the total emery of a region, we considered five types of renewable resources: solar radiation emery, rain chemical emery, rain geopotential emery, wind emery, and earth rotation emery [50]. Referring to emery theory, if the emery is of the same properties, only the maximum value will be included. Therefore, the total emery of a region equals to the sum of the maximum value from the first four renewable resources and earth rotation emery [55]. The equation is as follows:

$$RE = SA \times AR \times RD \times G \quad (4)$$

$$RP = SA \times AR \times RD \times H \times g \quad (5)$$

$$WE = SA \times AD \times k \times WS^3 \times (362.25 \times 24 \times 3600\text{s}) \quad (6)$$

$$EF = SA \times HF \quad (7)$$

where RE is rain chemical emery (J); SA is the area of the study area (m^2); AR is the annual precipitation ($\text{m}\cdot\text{yr}^{-1}$); RD is rain density ($1 \times 10^3 \text{ kg}\cdot\text{m}^{-3}$); G is Gibbs free energy ($4.94 \times 10^3 \text{ J}\cdot\text{kg}^{-1}$); RP is rain geopotential emery (J); H is the average difference between altitude and clouds (m); g is gravitational acceleration ($9.8 \text{ m}\cdot\text{s}^{-2}$); WE is wind emery (J); AD is the air density ($1.23 \text{ kg}\cdot\text{m}^{-3}$); k is the residence coefficient (10^{-3}); WS is average wind speed ($\text{m}\cdot\text{s}^{-1}$); EF is earth rotation emery (J); HF is heat flux ($1 \times 10^6 \text{ J}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$). The above formulas derived from [4,56,57].

2.3.2. Emery Carrying Capacity (ECC)

The natural resources for society can be separated into renewable and nonrenewable resources. Carrying capacity is not sustainable unless it is based on the use of resources in a renewable way, so only renewable resources would be taken into account when calculating the emery carrying capacity.

Moreover, 12% of the biodiversity conservation area was deducted from the emergy carrying capacity. The following equation is used to estimate the emergy carrying capacity.

$$eec = \frac{e}{RED} \times 0.88 \quad (8)$$

where eec is emergy carrying capacity per capita (hm^2); e is the renewable resources emergy per capita (sej); RED is the region emery density ($\text{sej}/\text{m}^2 \cdot \text{a}$).

2.4. Sustainability Evaluation Indicators

2.4.1. Ecological Footprint Index (EFI)

Ecological footprint index, proposed by WU (2005) [58], refers to the percentage reserved for future sustainable development ability of the region. It is calculated by the following equation:

$$EFI = \frac{ECC - EEF}{EEC} \times 100\% \quad (9)$$

where EFI is ecological footprint index.

When $EFI = 0$, it indicates that the region is in the critical point for sustainability and unsustainability. When $EFI > 0$, it indicates that the region is in sustainable development status; that is to say, there is a margin of carrying capacity to support the growth of regional ecological footprint; the greater its value, the stronger its sustainability. When $EFI < 0$, it indicates that the region is in unsustainable development status; that is to say, the carrying capacity is insufficient to support the growth of regional ecological footprint; the smaller the value, the stronger its unsustainability.

2.4.2. Ecological Footprint Intensity Per Ten Thousand Yuan GDP (EFG)

The ecological footprint per ten thousand yuan GDP refers to the amount of the ecological footprint to produce ten thousand yuan GDP in a certain region. In other words, it reflects the rate of resource utilization of this region. The greater value of EFG indicates lower productivity of biologically productive land [59].

$$EFG = \frac{\text{Regional } EEF}{\text{Regional GDP}} \quad (10)$$

2.4.3. Development Capacity (DC)

The development capacity is closely related to ecosystem diversity. The DC of a region can be obtained based on Ulanowicz's formula of growth and development. The following equation is used to estimate DC [60].

$$DC = eef \times EFDI \quad (11)$$

$$EFDI = - \sum (P_i \times \ln P_i) \quad (12)$$

where DC is the index of development capacity; eef is emergy ecological footprint per capita; $EFDI$ is ecological footprint diversity index; P_i is the ratio of the i^{th} emergy ecological footprint per capita of the bioproductive land category to the total EEF .

$$P_i = \frac{\text{eef of a certain land category}}{EEF} \quad (13)$$

2.5. Sustainability Predication

In this paper, we used the grey model (GM) to predict the future sustainability of Qinghai and Tibet from 2015 to 2020. Among all the prediction tools, the grey model is the most widely accepted

with a certain degree of accuracy despite it being simple [61]. It is a time series forecasting model, which means it is a first-order univariable forecasting model. It can predict system developing trends with limited information [62] and has been widely used as a prediction tool in many fields, such as CO₂ emission [63], electricity consumption [64], and stock price [65]. The GM (1,1) model is the most widely used model. The first '1' in GM(1,1) means there is only one variable in the model, the second '1' means the first order grey differential equation is used to construct the model [66]. The steps of GM (1,1) are as follows:

Step 1: Calculate the ecological surplus of the study area and line as a primitive sequence:

$$X^{(0)} = \{x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n)\}, (n = 1, 2, 3, \dots, n) \quad (14)$$

where $X^{(0)}$ is primitive sequence; $x^{(0)}(n)$ is primitive data; n is the number of the data.

Step 2: Take accumulated generating operation (AGO) on $X^{(0)}$:

$$X^{(1)} = \{x^{(1)}(1), x^{(1)}(2), \dots, x^{(1)}(n)\}, (n = 1, 2, 3, \dots, n) \quad (15)$$

where $X^{(1)}(k) = \sum_{i=1}^k x^{(0)}(i)$ ($k = 1, 2, 3 \dots, n$). $X^{(1)}(k)$ is the accumulation generating operation of $X^{(0)}(k)$ denoted as 1-AGO.

Step 3: Establish a first order grey differential equation:

$$\frac{dX^{(1)}}{dt} + aX^{(1)} = \mu \quad (16)$$

where a is developing coefficient, μ represents grey input.

Step 4: Use the ordinary least square method to estimate $[a, \mu]^T$ using the following equation:

$$[a, \mu]^T = (B^T B)^{-1} B^T Y \quad (17)$$

where

$$Y = [X_1^{(0)}(2), X_1^{(0)}(3) \dots X_1^{(0)}(n)]^T \quad (18)$$

$$B = \begin{bmatrix} -\frac{1}{2}[X_1^{(1)}(2) + X_1^{(1)}(1)] & 1 \\ -\frac{1}{2}[X_1^{(1)}(3) + X_1^{(1)}(2)] & 1 \\ \vdots & \vdots \\ -\frac{1}{2}[X_1^{(1)}(n) + X_1^{(1)}(n-1)] & 1 \end{bmatrix} \quad (19)$$

Step 5: Obtain the grey prediction equation:

$$\hat{X}^{(1)}(k+1) = [X^{(0)}(1) - \frac{\mu}{a}] \times e^{-ak} + \frac{\mu}{a}, (k = 1, 2, \dots, n) \quad (20)$$

where $\hat{X}^{(1)}(k+1)$ is the basic grey predicting value of $X^{(1)}(k+1)$.

Step 6: Take inverse accumulated generating operation (IAGO) on $X^{(1)}$:

$$\hat{X}^{(0)}(k+1) = \hat{X}^{(1)}(k+1) - \hat{X}^{(1)}(k), (k = 1, 2, \dots, n) \quad (21)$$

where $\hat{X}^{(0)}(k+1)$ is the basic grey predicting value of $X^{(0)}(k+1)$.

Step 7: Test the efficiency of the grey forecasting model:

$$PE(k)(\%) = \frac{x^{(0)}(k) - \hat{x}^{(0)}(k)}{x^{(0)}(k)} \quad (22)$$

$$MAPE(k)(\%) = \frac{1}{n} \sum_{k=1}^n \left| \frac{x^{(0)}(k) - \hat{x}^{(0)}(k)}{x^{(0)}(k)} \right| \quad (23)$$

where $PE(k)$ and $MAPE(k)$ are the shortage of percentage error and mean absolute percentage error respectively, both of which are used to compare original sequence and simulative sequence. The proposed forecasting model yields plausible prediction values when the MAPE is low [60]. MAPE for GM(1,1) accuracy is shown in Table 3.

Table 3. MAPE for model evaluation [64].

MAPE (%)	Forecasting Power
>50	Weak and inaccurate forecasting
20–50	Reasonable forecasting
10–20	Good forecasting
<10	Highly accurate forecasting

3. Results

3.1. Analysis of Emergy Ecological Footprint

3.1.1. Analysis of Composition of EEF

The account of the study area's EEF is shown in Tables 1 and 2 (taking 2014 for an example). Qinghai's EEF consists of six categories: cropland, with 11 products; grassland, with five products; forestry, with four products; water areas, with one product; fossil land, with two products; and built-up land, with four products. As shown in Table 2, the emergy ecological footprint (eef) of cropland (eef_1) was 2.17 hm²/cap, the *eef* of grassland (eef_2) was 2.36 hm²/cap, the *eef* of forestry (eef_3) was 0.01 hm²/cap, the *eef* of water areas (eef_4) was 0.03 hm³/cap, the *eef* of fossil land (eef_5) was almost zero, the *eef* of built-up land (eef_6) was 47.40 hm²/cap. Thus the *eef* of Qinghai in 2014 was 51.96 hm²/cap. Among the six land-use categories, the built-up land produced the most emergy ecological footprint. The contribution of the built-up land to the total *eef* was 91.22%, followed by grassland (4.54%), cropland (4.18%), water areas (0.06%), and fossil land (0). Table 2 reflects that rapid urbanization consumes a lot of resources and has a significant effect on local environment.

Tibet's EEF consists of five categories: cropland, including 10 products; grassland, including two products; forestry, including eight products; fossil land, including two products; and built-up land, including four products. The total *eef* of Tibet was 8.38 hm²/cap. Among the six categories, grassland contributed 43.44% to the total *eef* and built-up land contributed 39.74% to the total *eef* in 2014.

Comparing Tables 2 and 3, we can find that the eef_6 of Qinghai was more than 14 times as much as that of the Tibet, but the eef_2 of Qinghai was about 64.84% of that of Tibet, indicating that urbanization in Qinghai develops much faster than that in Tibet. The economic development in Qinghai mainly depends on rapid urbanization, particularly industrialization; while Tibet mainly depends on animal husbandry as well as urbanization.

3.1.2. Analysis of Trends of *ecc* and *eef*

Generally, the *ecc* of both Qinghai and Tibet showed a downward trend from 1995 to 2014, but the *eef* showed an upward trend during this twenty-year period. The *eef* of Qinghai Province increased from 7.29 hm² in 1995 to 39.9 hm² in 2014, reaching the maximum value (43.63 hm²) in 2013 (Figure 2). The *ecc* of Qinghai decreased from 12.27 hm² in 1995 to 11.36 hm² in 2014. We can observe from

Figure 2 that the *eef* exceeded the *ecc* since 2004, which reveals that Qinghai experienced an expanding energy ecological deficit beginning in 2004.

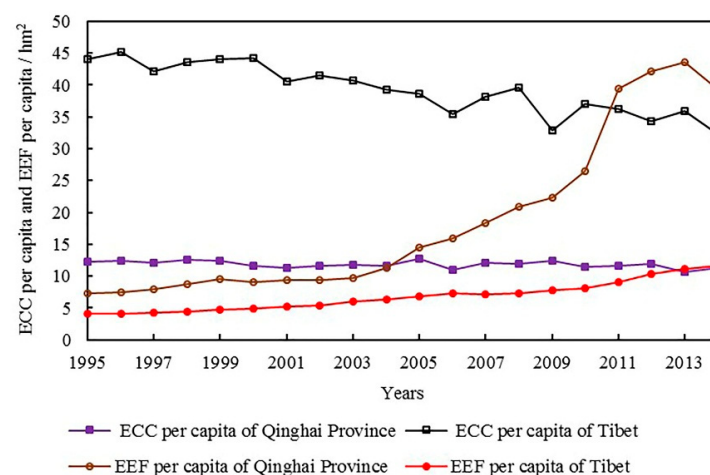


Figure 2. Energy ecological footprint per capita and energy carrying capacity per capita of Qinghai and Tibet.

The *eef* of Tibet increased from 4.04 hm^2 to 11.7 hm^2 during 1995–2014, with an increase rate of 189.60%. However, the *eef* of Tibet was still within the *ecc*, which had an average of 39.28 hm^2 . Thus Tibet was still sustainable. It can be observed from Figure 2 that the *ecc* of Tibet was about four times as much as that of Qinghai Province, but the *eef* of Tibet was much less than that of Qinghai, especially after 2004, indicating that environment of Qinghai is less sustainable than that of Tibet, but its economic development and human activities have more impact on local environment and resources. As a result, Qinghai became unsustainable since 2004, while Tibet was still sustainable.

3.2. Analysis of Sustainability Indicators

3.2.1. Ecological Footprint Index (EFI)

The EFI of Qinghai and Tibet declined from 1995 to 2014 (as shown in Figure 3). The EFI of Tibet decreased gradually during 1995–2004, dropping from 90.85% to 63.63%, which means that Tibet was still at a high level of sustainability. EFI of Qinghai fluctuated between 2005–2013, with values greater than zero from 1995 to 2004, which showed that energy carrying capacity was sufficient to support the growth of regional energy ecological footprint. However, EFI was less than zero from 2005, which indicated that energy carrying capacity was insufficient to support the growth of regional energy ecological footprint.

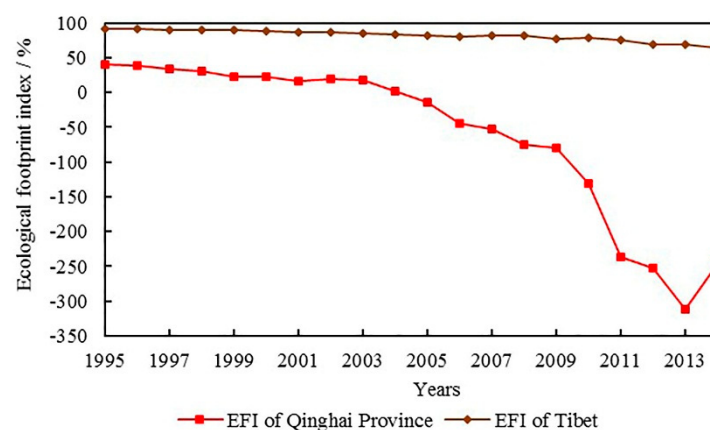


Figure 3. Ecological footprint index of the study area.

3.2.2. Ecological Footprint Intensity Per Ten Thousand Yuan GDP (EFG)

EFG of Qinghai and Tibet showed a downward trend in general from 1995 to 2014 (shown in Figure 4). It revealed that the resource utilization efficiency and the level of economic development of Qinghai and Tibet continuously improved. This result can also prove that both Qinghai and Tibet are devoted to upgrading industry structures, improving energy use efficiency, and increasing capital and technology investment in dealing with pollution. The EFG of Qinghai was much higher than that of Tibet, which indicates that the resource utilization efficiency of Qinghai was higher than Tibet.

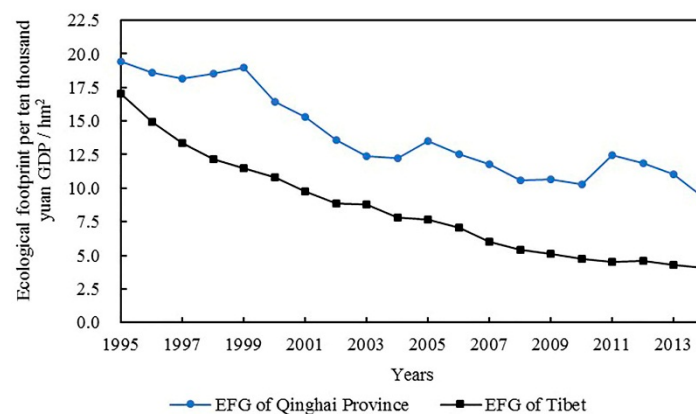


Figure 4. Ecological footprint intensity per ten thousand yuan GDP of the study area.

3.2.3. Development Capacity (DC)

The DC of Qinghai increased from 1995 to 2014 (shown in Figure 5), reached a maximum of 43.43 hm^2/cap in 2013 and declined to 38.17 hm^2/cap in 2014. The annual increase rate of Qinghai's DC (13.67%) is smaller than that of its EEF (22.37%). The DC of Tibet increased from 4.61 hm^2/cap in 1995 to 11.69 hm^2/cap in 2014, with an annual increase rate of 43.47%. This result indicates that the improvement of the DC in Qinghai and Tibet has mainly contributed to the increase in the EEF rather than the increase in the diversity of land types. Moreover, the decreasing rate of diversification of land-use types indicates that both Qinghai and Tibet attempted to balance the distribution among the six land categories from 1995 to 2014, but this distribution is still far away from equilibrium.

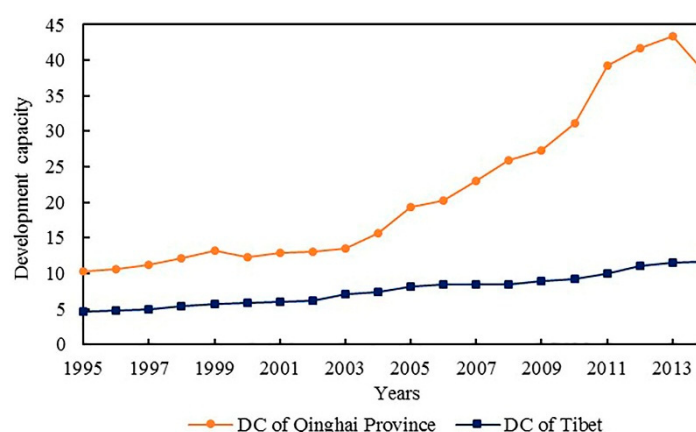


Figure 5. Development capacity of the study area.

3.3. Analysis of Prediction Result

The forecasted values for an ecological surplus of the study area from 1995 to 2014 were shown in Tables 4 and 5. Tables 4 and 5 show the actual ecological surplus per capita, forecasted ecological surplus per capita, percentage error, and mean absolute percentage error obtained by Equations (22)

and (23). Table 4 shows that forecasted data from 1995 to 2004 for average, maximal, and minimal percentage error were 0.03%, 0.39%, and 0.07%. The MAPE for GM (1,1) from 2005 to 2014 was 2.45% for validation data. Furthermore, according to Table 1, the GM (1,1) was adequate to forecast ecological surplus of Qinghai. Table 4 indicates that Qinghai's ecological deficit per capita will rise from 37.93 hm^2/cap in 2014 to 443.08 hm^2/cap in 2024. Qinghai will be seriously unsustainable from 2015 to 2024. Table 5 shows in this twenty-year period, the forecasted data for maximal and minimal percentage error are 11.97% and 0.72%, respectively. The MAPE for GM (1,1) are 0.37% and 1.53%, respectively. So, the GM (1,1) was adequate to forecast ecological surplus of Tibet. Table 6 indicates that Tibet will remain sustainable in 2024, but the ecological surplus per capita will decrease from 23.81 hm^2/cap to 17.38 hm^2/cap in 2024. In other words, Qinghai will hardly be able to meet the requirements of basic sustainability for the fast-growing economy, while Tibet will be able to meet the requirements for local economic development.

Table 4. Ecological surplus for actual value, forecasted value, PE, and MAPE of Qinghai.

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Actual value (hm^2/cap)	4.98	5.20	4.20	3.40	2.75	2.22	1.80	1.45	1.18	0.95
Forecasted value (hm^2/cap)		4.91	4.13	3.83	2.87	2.67	1.93	1.19	1.09	0.24
PE (%)		0.38	0.18	0.20	0.14	−0.11	0.07	−0.39	0.16	−0.36
MAPE (%)					0.05					
	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Actual value (hm^2/cap)	−1.86	−4.94	−6.30	−8.91	−9.89	−15.02	−27.66	−30.18	−33.01	−37.93
Forecasted value (hm^2/cap)		−7.08	−8.91	−11.21	−14.10	−17.75	−22.33	−28.10	−35.36	−44.50
PE (%)		−43.27	−41.36	−25.78	−42.60	−18.15	19.26	6.88	−7.13	−17.32
MAPE (%)					2.45					

Table 5. Ecological surplus for actual value, forecasted value, PE, and MAPE of Tibet.

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Actual value (hm^2/cap)	40.09	41.08	37.86	39.12	39.16	39.31	35.41	36.04	34.63	32.91
Forecasted value (hm^2/cap)		41.96	40.66	39.40	38.18	36.99	35.85	34.74	33.66	32.62
PE (%)		−2.14	−7.40	−0.72	2.50	5.90	−1.24	3.61	2.80	0.88
MAPE (%)					0.37					
	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Actual value (hm^2/cap)	31.74	28.27	30.99	32.27	25.15	28.98	27.26	23.94	24.65	20.47
Forecasted value (hm^2/cap)		31.24	30.05	28.91	27.82	26.76	25.74	24.76	23.82	22.92
PE (%)	−10.51	3.02	10.40	−10.60	7.66	5.57	−3.45	3.35	−11.97	−10.51
MAPE (%)					1.53					

Table 6. The forecast of ecological surplus/deficit of Qinghai Province and Tibet from 2015 to 2024.

Years	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Qinghai	−56.00	−70.47	−88.68	−111.59	−140.42	−176.70	−222.36	−279.81	−352.11	−443.08
Tibet	23.07	22.36	21.66	20.99	20.34	19.71	19.10	18.51	17.94	17.38

4. Discussion

In this study, the model of emergy ecological footprint was modified by using region emergy density to calculate emergy carrying capacity and emergy ecological footprint. This method not only can reflect the true supply capacity of the ecosystem and human resource consumption situation in the study area, but also make the results of carrying capacity and ecological footprint comparable. As a result, the assessment of regional sustainability is more reasonable. In addition, we used the 30 m resolution of the digital elevation model (DEM) to estimate solar radiation emergy. Compared with the method of using the average solar radiation, solar radiation emergy that is calculated by the above method will better reflect the real situation of the study area. Actually, when calculating regional renewable resources, this part of emergy was too small to be included. Instead of using consumption

data, we used regional biological resource productivity and emergy to estimate the ecological footprint of human population growth and economic development, because only the sum of economic activities and resources extracted within the area can reflect the real ecological footprint produced by humans. The eco-economic system is complex, so we simplify the complex system to assess sustainability of the study area. However, this approach does not include data which are difficult to obtain (such as topsoil loss, soil erosion, waste material, and so on), and some data of consumption are not available in each county's statistical yearbooks, which can cause a small amount of deviation between study results and actual conditions. The modified method can increase the reliability of the study results to some extent, but still needs further improvement.

Tables 2 and 3 show that among six land-use categories, built-up land contributed more than half of the total *eef* of Qinghai in 2014; while in Tibet, the contribution of grassland was the largest, with a value greater than 40%. This result indicates that the growth of Qinghai's *eef* is primarily caused by the rapid urbanization, particularly industrialization, because Qinghai is abundant in many resources that provide great convenience for industry development. However, Qinghai's resource utilization efficiency is low due to the backward technology, so a lot of wastes, including waste water, waste gas, and solid waste, which are main proportions of the built-up land category, are produced in the processing of production. Moreover, the proportion of land-use categories reflects that the distribution of the *eef* is far from balanced. As for Tibet, animal husbandry is the main industry and many residents make a living by grazing. Therefore, grassland produced the most emergy ecological footprint. The urbanization in Tibet has developed fast in recent years, but not as fast as that in Qinghai, so the contribution of built-up land to the total *eef* of Tibet is lower than that of Qinghai.

Figures 2 and 3 indicate that the sustainability of Qinghai and Tibet decreased from 1995 to 2014. Qinghai's *ecc* exceeded its *eef* in 2005 and since then EFI of Qinghai has been less than zero. This result is consistent with Wang and Ding (2011) [67] and Liu et al. (2011) [68], both of which indicated that Qinghai's ecological carrying capacity decreased but the ecological footprint increased and Qinghai is already unsustainable (Liu et al., 2011; Wang and Ding, 2011) [67,68]. Tibet's *ecc* was always high enough to cover local *eef* and its EFI was more than 60% in the investigated period. The results are in accordance with An and Chen (2014) [69] and Li et al. (2015) [70], who proved that Tibet's sustainability showed a downward trend, but its carrying capacity was still larger than local ecological footprint. Qinghai is abundant in petroleum, nonferrous metal, natural gas, and so on. More than 72.71% of local industrial enterprises are heavy industrial enterprises, which are highly dependent on local resources and cause serious damage to the environment (Pan and Gai, 2016) [71]. Qinghai is less developed in terms of science and technology, so the resource utilization efficiency was low, resulting in a large amount of resource waste. Many factors, including population growth, urbanization acceleration, economic, social, and industrial development, have resulted in the growing demand and consumption of resources. These are the main factors which led to the increase of *eef* in Qinghai province. Qinghai features a plateau continental climate, the rainfall is about 300 mm a year and varies a lot among different areas [43], so the *ecc* of Qinghai was impossible to support the increasing *eef*. Tibet is one of the most important biological reserves in China. Environmental protection is the primary goal of local economic development. The modern industry in Tibet is backward—up to 2014, there were only 763 industrial enterprises, more than 54.91% of which were light industrial enterprises. Most Tibetans make a living by grazing—the output of animal husbandry accounts for 49.98% of the gross output of farming, forestry, animal husbandry, and fishing. The economic development pattern in Tibet is relatively primitive so the environment was less disturbed. After the implement of “Western Development”, the economy of Tibet began to develop gradually, but Tibet still puts the most effort into protecting the environment because of its momentous ecological status. As a result, the *eef* of Tibet increased at a low speed. Tibet is abundant in rainfall and solar radiation due to its unique location and climate (Zhao et al., 2005) [37], plus with the ecosystem integrity, vast territory areas, and low population density, the local environment shows the features of primeval ecology, so the *ecc* is high enough to maintain local economic activities.

From Figures 4 and 5, we can see that the resource utilization efficiency and economy of the study area were improved from 1995 to 2014. The resource utilization efficiency of Qinghai was lower than that of the Tibet, but Qinghai's economy developed faster. Equation (11) shows that EFG has a positive relationship with EEF but a negative relationship with GDP. Despite the fact that Qinghai's GDP was more than that of Tibet, Qinghai's EEF was almost three times as much as that of Tibet, thus EFG of Qinghai was lower than that of Tibet. However, compared with other developed areas, both Qinghai and Tibet should be improved in further development (Weng et al., 2006; Wei and Wu, 2011; Qin, 2013) [72–74].

Based on the current economic development pattern and growth rate of population, the future sustainability of the study area was forecast by GM (1,1). The prediction results showed that the unsustainability of Qinghai would intensify, and the sustainability of Tibet would continue to decrease from 2015 to 2024. This is probably because the ten-year time frame is too short for Qinghai to reform local development pattern, and the economic growth still depends on the consumption of natural resources. The gap between Qinghai's EEF and ECC becomes larger, and the environment is more unsustainable. As for Tibet, the increase of local population leads to the increase of livestock, which in turn leads to the excessive exploitation of grassland resources (Zhang et al., 2007) [75], so as local grassland vegetation coverage and grass yield will decrease, the grazing capacity will also decline. Moreover, because of the lack of scientific and effective management, Tibet's grassland experiences different degrees of degradation and grassland pests and diseases are getting more serious. Although Tibet is still sustainable at present, the annual reduction rate of ecological surplus will reach 2.70%, which indicates that Tibet is surely to be unsustainable in the near future if the development pattern is not changed.

Policy Implication

In order to achieve sustainable development of the Qinghai–Tibet Plateau, different regions should adopt appropriate policies and measures to develop the local economy.

Resource-based industries have made great contributions to Qinghai's economic growth, but also lead to severe environmental degradation. Since Qinghai plays an important ecological service role to China and the rest of the world (Wang et al., 2015) [76], efforts to promote sustainable development with the balance of economic growth and ecological protection should be made. First, Qinghai should be actively engaged in developing a circular economy that aims to improve resource efficiency by exchanging byproducts and reusing wastes (Geng et al., 2016) [77]. Second, Qinghai can optimize its industrial structure by developing more service-oriented businesses because such businesses consume less materials and produce less impact on the local environment. Qinghai has become one of the most famous tourism destinations because of its abundant landscapes, rare species, and minority culture. The tourism income accounted for 8.77% of Qinghai's GDP in 2014, but there is great potential to further expand it. Besides, it is urgent for Qinghai to make the best use of national policies and regional advantages to import advanced technologies and attract talents. Qinghai can also build up ecological compensation mechanisms to reduce environmentally damaging behaviors and recover the local ecosystem. However, Qinghai is one of the less developed regions in China, which lacks money to further protect local environment. Ecological compensation seems to be an effective method to balance ecological protection and economic growth. Thus, how to determine an appropriate compensation rate is of great importance. In this regard, more research should be made to identify the best compensation rate.

Tibet is an important ecological reserve in China. Protecting the environment should be on its priority list. Considering the decreasing trend of sustainability, Tibet should first continue to carry out the policy of giving rewards and subsidies (GRS) for grassland ecological conservation, which has been implemented by the Chinese government since 2009. The GRS policy encourages herdsmen to determine the number of grazing animals by the size of pasture. If herdsmen cut down the number of livestock, they can get rewards and subsidies from the government. Then the problem of overgrazing

can be solved, the grassland vegetation coverage and grass yield will be increased, and carrying capacity of grassland will be improved (Yang, 2014) [78]. Second, Tibet should make full use of local renewable energy resources, such as hydroenergy, water resources, and geothermal power, to develop the economy because renewable energy can not only help reduce pollution caused by fossil fuel, but also bring more economic and sustainable benefits. Tibet is also well-known for its primary environment, rare species, and Tibetan Buddhism, so developing tourism is a good choice to develop the local economy. Tourism income accounted for 22.15% of the Tibet's GDP in 2014, but there is still a great potential to further expand it. Last but not least, Tibet should increase the resource utilization rate through technological innovation to reduce the waste of resources.

5. Conclusions

As the main components of the QTP, Qinghai and Tibet show a great difference in sustainable status. This study evaluated the emergy ecological footprint and emergy carrying capacity of the study area through an improved emergy ecological footprint method, and applied three indicators (EFI, EFG, and DC) to analyze the sustainability of Qinghai and Tibet for the period of 1995–2014. Results showed that Qinghai had been experiencing an expanding ecological deficit since 2004, but Tibet was still at a high level of sustainability in 2014. The resource utilization efficiency of Qinghai and Tibet has improved, and their levels of economic development have also been increasing. The prediction result of future sustainability indicated that Qinghai will be likely unsustainable, and Tibet will become less sustainable in ten years. Policy suggestions are provided by considering their different economic development conditions. Nonetheless, the eco-economic system was simplified in this study, and some data were either difficult to obtain or unavailable in the statistical yearbook. As a result, there might be a small amount of deviation between study results and actual conditions. The modified method proposed herein can increase the reliability of the results to some extent, but it still needs further improvement.

Author Contributions: Conceptualization, W.L., J.X., and C.L.; data curation, W.W. and Y.S.; formal analysis, W.W.; funding acquisition, W.L. and W.W.; investigation, W.W.; methodology, W.L.; resources, W.W.; software, W.W.; supervision, C.L.; writing—original draft, W.W.; writing—review and editing, W.W. and C.L.

Funding: This paper was partly supported by the National Key Research and Development Program of China (2018YFC0406602), the National Social Science Foundation of China (14CJY010), Key Special Foundation/Project of Science and Technology Department of Qinghai Province (2019-SF-A12), the Fundamental Research Funds for the Central Universities (lzujbky-2016-br05, lzujbky-2019-it03), and the Chinese NSF grant (41471450).

Acknowledgments: We are thankful to all the scientists whose research work was used to perform this assessment on sustainability.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Filipponi, F. Liver transplantation: Is it a sustainable practice? *Dig. Liver Dis. Suppl.* **2011**, *5*, 6–9. [[CrossRef](#)]
2. Costanza, R.; D'Arge, R.; De Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R.V.; Paruelo, J.; et al. The value of the world's ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260. [[CrossRef](#)]
3. Steffen, W.; Richardson, K.; Rockstrom, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; et al. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, 1259855. [[CrossRef](#)] [[PubMed](#)]
4. He, J.; Wan, Y.; Feng, L.; Ai, J.; Wang, Y. An integrated data envelopment analysis and emergy-based ecological footprint methodology in evaluating sustainable development, a case study of Jiangsu Province, China. *Ecol. Indic.* **2016**, *70*, 23–34. [[CrossRef](#)]
5. Meadows, D.H.; Rander, J.; Meadows, D.L. *The Limits to Growth*; Chelsea Green Publishing: London, UK, 2004.
6. Keeble, B.R. The Brundtland Report: 'Our Common Future'. *Med. War* **1988**, *4*, 17–25. [[CrossRef](#)]

7. Niccolucci, V.; Tiezzi, E.; Pulselli, F.M.; Capineri, C. Biocapacity vs Ecological Footprint of world regions: A geopolitical interpretation. *Ecol. Indic.* **2012**, *16*, 23–30. [[CrossRef](#)]
8. Rockström, J.; Steffen, W.; Noone, K.; Persson, A.; Chapin, F.S., III; Lambin, E.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. Planetary boundaries: Exploring the safe operating space for humanity. *Ecol. Soc.* **2009**, *14*. [[CrossRef](#)]
9. Wackernagel, M.; Rees, W.E. *Our Ecological Footprint: Reducing Human Impact on the Earth*; New Society Publishers: Gabriola, BC, Canada, 1996.
10. Rees, W.E. Ecological footprints and appropriated carrying capacity: What urban economics leaves out. *Environ. Urban.* **1992**, *4*, 121–130. [[CrossRef](#)]
11. Galli, A. On the rationale and policy usefulness of ecological footprint accounting: The case of Morocco. *Environ. Sci. Policy* **2015**, *48*, 210–224. [[CrossRef](#)]
12. Gao, J.; Tian, M. Analysis of over-consumption of natural resources and the ecological trade deficit in China based on ecological footprints. *Ecol. Indic.* **2016**, *61*, 899–904. [[CrossRef](#)]
13. Dang, X.; Liu, G.; Xue, S.; Li, P. An ecological footprint and emergy based assessment of an ecological restoration program in the Loess Hilly Region of China. *Ecol. Eng.* **2013**, *61*, 258–267. [[CrossRef](#)]
14. Guo, Y.; Xia, D.; Sun, B.; Wang, X.; Zhang, D.; Li, J. Ecological footprints and development trends in Hefei, China. *Manag. Environ. Qual.* **2018**, *29*, 2–14. [[CrossRef](#)]
15. Nakajima, E.S.; Ortega, E. Carrying capacity using emergy and a new calculation of the ecological footprint. *Ecol. Indic.* **2016**, *60*, 1200–1207. [[CrossRef](#)]
16. Geng, Y.; Zhang, L.; Chen, X.; Xue, B.; Fujita, T.; Dong, H. Urban ecological footprint analysis: A comparative study between Shenyang in China and Kawasaki in Japan. *J. Clean. Prod.* **2014**, *75*, 130–142. [[CrossRef](#)]
17. Liu, H. The impact of human behavior on ecological threshold: Positive or negative?—Grey relational analysis of ecological footprint, energy consumption and environmental protection. *Energy Policy* **2013**, *56*, 711–719. [[CrossRef](#)]
18. Nunes, L.M.; Catarino, A.; Ribau Teixeira, M.; Cuesta, E.M. Framework for the inter-comparison of ecological footprint of universities. *Ecol. Indic.* **2013**, *32*, 276–284. [[CrossRef](#)]
19. Blasi, E.; Passeri, N.; Franco, S.; Galli, A. An ecological footprint approach to environmental—Economic evaluation of farm results. *Agric. Syst.* **2016**, *145*, 76–82. [[CrossRef](#)]
20. Li, X.; Tian, M.; Wang, H.; Wang, H.; Yu, J. Development of an ecological security evaluation method based on the ecological footprint and application to a typical steppe region in China. *Ecol. Indic.* **2014**, *39*, 153–159. [[CrossRef](#)]
21. Hunter, C.; Shaw, J. The ecological footprint as a key indicator of sustainable tourism. *Tour. Manag.* **2007**, *28*, 46–57. [[CrossRef](#)]
22. Butnariu, A.; Avasilcai, S. Research on the Possibility to Apply Ecological Footprint as Environmental Performance Indicator for the Textile Industry. *Procedia Soc. Behav. Sci.* **2014**, *124*, 344–350. [[CrossRef](#)]
23. Herva, M.; Álvarez, A.; Roca, E. Combined application of energy and material flow analysis and ecological footprint for the environmental evaluation of a tailoring factory. *J. Hazard. Mater.* **2012**, *237–238*, 231–239. [[CrossRef](#)]
24. Wu, X.F.; Yang, Q.; Xia, X.H.; Wu, T.H.; Wu, X.D.; Shao, L.; Hayat, T.; Alsaedi, A.; Chen, G.Q. Sustainability of a typical biogas system in China: Emergy-based ecological footprint assessment. *Ecol. Inform.* **2015**, *26*, 78–84. [[CrossRef](#)]
25. Erb, K.H. Actual land demand of Austria 1926–2000: A variation on Ecological Footprint assessments. *Land Use Policy* **2004**, *21*, 247–259. [[CrossRef](#)]
26. Siche, R.; Pereira, L.; Agostinho, F.; Ortega, E. Convergence of ecological footprint and emergy analysis as a sustainability indicator of countries: Peru as case study. *Commun. Nonlinear Sci. Numer. Simul.* **2010**, *15*, 3182–3192. [[CrossRef](#)]
27. Turner, K.; Lenzen, M.; Wiedmann, T.; Barrett, J. Examining the global environmental impact of regional consumption activities—Part 1: A technical note on combining input-output and ecological footprint analysis. *Ecol. Econ.* **2007**, *62*, 37–44. [[CrossRef](#)]

28. Wiedmann, T.; Lenzen, M.; Turner, K.; Barrett, J. Examining the global environmental impact of regional consumption activities—Part 2: Review of input-output models for the assessment of environmental impacts embodied in trade. *Ecol. Econ.* **2007**, *61*, 15–26. [[CrossRef](#)]
29. Nguyen, H.X.; Yamamoto, R. Modification of ecological footprint evaluation method to include non-renewable resource consumption using thermodynamic approach. *Resour. Conserv. Recycl.* **2007**, *51*, 870–884. [[CrossRef](#)]
30. Liu, Q.; Lin, Z.; Feng, N.; Liu, Y. A Modified Model of Ecological Footprint Accounting and its Application to Cropland in Jiangsu, China. *Pedosphere* **2008**, *18*, 154–162. [[CrossRef](#)]
31. Chen, B.; Chen, G.Q. Modified ecological footprint accounting and analysis based on embodied exergy—A case study of the Chinese society 1981–2001. *Ecol. Econ.* **2007**, *61*, 355–376. [[CrossRef](#)]
32. Odum, H.T. Environmental Accounting—EMERGY and Environmental Decision Making. *Child Dev.* **1996**, *42*, 1187–1201. [[CrossRef](#)]
33. Viglia, S.; Civitillo, D.F.; Cacciapuoti, G.; Ulgiati, S. Indicators of environmental loading and sustainability of urban systems. An emergy-based environmental footprint. *Ecol. Indic.* **2018**, *94*, 82–99. [[CrossRef](#)]
34. Odum, H.T. Self-organization, transformity, and information. *Science* **1988**, *242*, 1132–1139. [[CrossRef](#)] [[PubMed](#)]
35. Vega-Azamar, R.E.; Glaus, M.; Hausler, R.; Oropeza-García, N.A.; Romero-López, R. An emergy analysis for urban environmental sustainability assessment, the Island of Montreal, Canada. *Landsc. Urban Plan.* **2013**, *118*, 18–28. [[CrossRef](#)]
36. Zhang, X.; Shen, J.; Wang, Y.; Qi, Y.; Liao, W.; Shui, W.; Li, L.; Qi, H.; Yu, X. An environmental sustainability assessment of China's cement industry based on emergy. *Ecol. Indic.* **2017**, *72*, 452–458. [[CrossRef](#)]
37. Zhao, S.; Li, Z.; Li, W. A modified method of ecological footprint calculation and its application. *Ecol. Model.* **2005**, *185*, 65–75. [[CrossRef](#)]
38. Chen, B.; Chen, G.Q. Ecological footprint accounting based on emergy—A case study of the Chinese society. *Ecol. Model.* **2006**, *198*, 101–114. [[CrossRef](#)]
39. Peng, W.; Wang, X.; Li, X.; He, C. Sustainability evaluation based on the emergy ecological footprint method: A case study of Qingdao, China, from 2004 to 2014. *Ecol. Indic.* **2018**, *85*, 1249–1261. [[CrossRef](#)]
40. Zhao, S.; Song, K.; Gui, F.; Cai, H.; Jin, W.; Wu, C. The emergy ecological footprint for small fish farm in China. *Ecol. Indic.* **2013**, *29*, 62–67. [[CrossRef](#)]
41. Yang, J.; Ding, Y.; Chen, R. Spatial and temporal of variations of alpine vegetation cover in the source regions of the Yangtze and Yellow Rivers of the Tibetan Plateau from 1982 to 2001. *Environ. Geol.* **2006**, *50*, 313–322. [[CrossRef](#)]
42. Li, X.L.; Huang, B.N. The cause of black soil patch grassland in Qinghai province and management countermeasures. *Grassl. China* **1995**, *4*, 64–66. [[CrossRef](#)]
43. Ma, C.; Zhao, J. Quantitative evaluation of resource and environment pressure in Qinghai Province, China based on footprint family. *Chin. J. Appl. Ecol.* **2016**, *27*, 1248–1256. [[CrossRef](#)]
44. Zhao, Z.; Xie, C.; Wu, T.; Fang, J. Tibet eco-economic system evaluation based on emery theory. *J. Guizhou Norm. Univ. Sci.* **2005**, *33*, 88–95. [[CrossRef](#)]
45. Puntso, D.T. Environmental Protections and Sustainable Development of Tibet, China. *J. Tibet Univ.* **2008**, *6*, 12–14.
46. Gao, X.; Ma, L. Application of the energy value ecological footprint model: A case study of Wuwei City, Gansu Province. *J. Northwest Univ. Natl. Philos. Soc. Sci.* **2014**, *2*, 104–110. [[CrossRef](#)]
47. Lan, S.; Pei, Q.; Lu, H. *Ecological and Economics System Analysis*; Chemical Industry Press: Beijing, China, 2002. [[CrossRef](#)]
48. Sui, C.; Lan, S. Emergy Analysis of Guangzhou Urban Ecosystem. *Chongqing Environ. Sci.* **2001**, *23*, 4–6. [[CrossRef](#)]
49. Zhao, G.; Ding, F.; Shang, J. *Ecological Economics*; Chemical Industry Press: Beijing, China, 2008.
50. Zhu, Y. Study on Agro-Ecosystem's Sustainable Development of Hunan Based on the Emergy Theory. Ph.D. Thesis, Central South University of Forestry and Technology, Changsha, China, 2010.
51. Brown, M.T.; Ulgiati, S. Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems. *Ecol. Model.* **2004**, *178*, 201–213. [[CrossRef](#)]
52. Liu, Z.H.; Li, L.T.; McVicar, T.R.; Van Niel, T.G.; Yang, Q.K.; Li, R. Introduction of the Professional Interpolation Software for Meteorology Data: ANUSPLIN. *Meteorol. Mon.* **2008**, *34*, 92–100. [[CrossRef](#)]

53. Liu, Z.H.; McVicar, T.R.; Li, L.; Van Niel, T.G.; Yang, Q.K.; Li, R.; Mu, X.M. Interpolation for time series of meteorology variables using ANUGPLIN. *J. Northwest A F Univ.* **2008**, *36*, 227–234. [[CrossRef](#)]
54. Xiong, D. Disscussio on Ecological Footprint Theory: Applied to Regional Sustainable Development Evaluation. *Prog Geogr.* **2003**, *22*, 618–626.
55. Wang, R. *Emergy-based analysis for the development of agro-ecosystem in Shanxi Province*; Hunan Agricultural University: Changsha, China, 2009.
56. Chen, B.; Chen, Z.M.; Zhou, Y.; Zhou, J.B.; Chen, G.Q. Emergy as embodied energy based assessment for local sustainability of a constructed wetland in Beijing. *Commun. Nonlinear Sci. Numer. Simul.* **2009**, *14*, 622–635. [[CrossRef](#)]
57. Zhao, X.; Liu, S.; Zhao, H. Application of Ecological Footprint in Evaluating Regional Sustainable Development Based on Energy Analysis Theory—A Case Study in Gansu Province. *Arid Zone Res.* **2011**, *28*, 524–531.
58. Wu, L. Dynamic evaluation of China sustainable development based on the ecological footprint index. *J. China Agric. Univ.* **2005**, *10*, 94–99.
59. Chen, C.Z.; Lin, Z.S. Multiple timescale analysis and factor analysis of energy ecological footprint growth in China 1953–2006. *Energy Policy* **2008**, *36*, 1666–1678. [[CrossRef](#)]
60. Ulanowicz, R.E. *Growth and Development: Ecosystems Phenomenology*; Springer: New York, NY, USA, 1986. [[CrossRef](#)]
61. Deng, J. Introduction to Grey Systems Theory. *J. Grey Syst.* **1989**, *1*, 1–24. [[CrossRef](#)]
62. Xie, N.M.; Yuan, C.Q.; Yang, Y.J. Forecasting China's energy demand and self-sufficiency rate by grey forecasting model and Markov model. *Int. J. Electr. Power Energy Syst.* **2015**, *66*, 1–8. [[CrossRef](#)]
63. Lin, C.S.; Liou, F.M.; Huang, C.P. Grey forecasting model for CO₂ emissions: A Taiwan study. *Appl. Energy* **2011**, *88*, 3816–3820. [[CrossRef](#)]
64. Hamzacebi, C.; Es, H.A. Forecasting the annual electricity consumption of Turkey using an optimized grey model. *Energy* **2014**, *70*, 165–171. [[CrossRef](#)]
65. Wang, Y.F. Predicting stock price using fuzzy grey prediction system. *Expert Syst. Appl.* **2002**, *22*, 33–38. [[CrossRef](#)]
66. Pao, H.T.; Fu, H.C.; Tseng, C.L. Forecasting of CO₂ emission, energy consumption and economic growth in China using an improved grey model. *Energy* **2012**, *40*, 400–409. [[CrossRef](#)]
67. Wang, X.P.; Ding, S.X. Analysis on social-economic sustainable development in Qinghai Province based on ecological footprint model. *China Popul. Resour. Environ.* **2011**, *21*, 40–43.
68. Liu, Z.J.; Chen, K.L.; Zhao, A.Q.; Su, M.X. Analysis of ecological footprint of Xining city based on emergy theory. *Territory & Nat. Resour. Study* **2011**, *1*, 5–7.
69. An, B.S.; Cheng, G.D. Dynamic analysis of the ecological footprint and carrying capacity of Tibet. *Acta Ecological Sinica* **2014**, *34*, 1002–1009.
70. Li, P.; Sun, Z.B.; Fang, J.P.; Feng, P. The sustainable development assessment in Tibet based on the dynamic analysis of ecological footprint. *J. Soil Water Conserv.* **2015**, *29*, 327–331.
71. Pan, J.W.; Gai, Z.Y. Conflicts Between Economic and Ecological Development in China's Pasturing Areas and Reasons for These Conflicts. In *Ecological Economics and Harmonious Society*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 119–128. [[CrossRef](#)]
72. Weng, B.; Wang, Y.; Huang, Y.; Ying, Z.; Huang, Q. Dynamic changes of ecological footprint and ecological capacity in Fujian Province. *Chin. J. Appl. Ecol.* **2006**, *17*, 2153–2157.
73. Wei, Y.; Wu, C. Dynamic analysis of ecological sustainability based on ecological footprint model in Guizhou province. *Ecol. Environ. Sci.* **2011**, *20*, 102–108.
74. Qin, Q. The Study of Sustainable Development of Ecological in Shanxi Province Based on the Model of Ecological. Master's Thesis, Shanxi University, Taiyuan, China, 2013.
75. Zhang, J.; Yao, F.; Zheng, L.; Yang, L. Evaluation of grassland dynamics in the Northern-Tibet Plateau of china using remote sensing and climate data. *Sensors* **2007**, *7*, 3312–3328. [[CrossRef](#)] [[PubMed](#)]
76. Wang, P.; Lassoie, J.P.; Morreale, S.J.; Dong, S. A critical review of socioeconomic and natural factors in ecological degradation on the Qinghai-Tibetan Plateau, China. *Rangel. J.* **2015**, *37*, 1–9. [[CrossRef](#)]

77. Geng, Y.; Sarkis, J.; Ulgiati, S. Pushing the boundaries of scientific research: 120 years of addressing global issues: Economics: Sustainability, wellbeing, and the circular economy in China and worldwide. *Science* **2016**, *6278*, 73–76.
78. Yang, M. Policy of giving rewards and subsidies for grassland ecological conservation in Tibetan Plateau. *Ecol. Econ.* **2014**, *10*, 2–9.



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