Postprint on Spatial Distribution Differences of Per Capita Ecological Footprint and Per Capita Ecological Carrying Capacity in Chengdu City

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Abstract

The ecological footprint method quantitatively assesses the sustainable development status of a region by comparing natural resources consumed by human activities with the ecological carrying capacity provided by natural ecosystems. This study employs the ecological footprint model to calculate the ecological footprint and ecological carrying capacity of Chengdu from 2009 to 2014, and reveals their spatial evolution patterns through spatial analysis. The results indicate: (1) From 2009 to 2014, the average per capita ecological footprint across all districts, cities, and counties exhibited a declining trend year by year, decreasing from 2.759 hm^2/person in 2009 to 1.937 hm^2/person in 2014. The basic pattern displayed a distribution characteristic of low in the central area, high in the southwest, and moderate in the two wings, with high per capita ecological footprints concentrated in Pujiang County, Dayi County, and Qionglai City in the southwestern direction; (2) The per capita carrying capacity of Chengdu from 2009 to 2014 demonstrated a relatively stable yet declining trend, decreasing from 0.2314 hm^2/person in 2009 to 0.2215 hm^2/person in 2014, with its spatial distribution characteristics showing good spatial consistency with the ecological footprint; (3) The per capita ecological deficit/surplus temporally appeared to be gradually improving, but its essence was a trend of increasingly severe ecological deficit. Spatially, it exhibited a distribution pattern opposite to that of per capita ecological carrying capacity, characterized by a "high-low, low-high" relationship, with a diffusion-type distribution spreading from the five central urban districts to the surrounding areas. Except for the five urban districts, all other regions remained in deficit throughout the study period, with the most severely affected area concentrated in Pujiang County in the southwestern direction, reaching a maximum deficit of -9.3189 hm^2/person. There is an urgent need to establish effective ecological footprint regulation and compensation mechanisms.

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Full Text

Spatial Differences in Per Capita Ecological Footprint and Per Capita Ecological Carrying Capacity in Chengdu

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Abstract

The ecological footprint method compares natural resources consumed by human activities with the ecological carrying capacity provided by natural ecosystems to quantitatively assess regional sustainable development status. Using the ecological footprint model, this study calculated the ecological footprint and ecological carrying capacity of Chengdu from 2009 to 2014. The results show: (1) The average per capita ecological footprint across all districts and counties exhibited a 逐年下降 (year-by-year decreasing) trend, from 2.759 hm^2/cap to 1.937 hm^2/cap. The basic spatial pattern showed low values in the central area, medium values in the two wings, and high values concentrated in the southwestern Pujiang County. (2) Chengdu' s per capita ecological carrying capacity showed a relatively stable but declining trend during 2009–2014, from 0.2314 hm^2/cap to 0.2215 hm^2/cap. Its spatial distribution characteristics demonstrated good spatial consistency with the ecological footprint distribution. (3) The per capita ecological deficit/surplus showed improving trends over time, but the essential trend was increasingly severe ecological deficit. The spatial distribution was dispersed in the five urban districts, while all other areas showed deficits during the study period. The most severe deficit area was concentrated in Pujiang County in the southwest, with a per capita ecological deficit of -9.3189 hm^2/cap. The distribution pattern exhibited diffusion characteristics, showing an inverse distribution compared to per capita ecological carrying capacity, spreading from the central five urban districts outward. Effective ecological footprint regulation and supplementary mechanisms are urgently needed.

Keywords: per capita ecological footprint; per capita ecological carrying capacity; per capita ecological deficit/surplus; city (county, region); Chengdu City

1. Introduction

The ecological footprint method, first proposed by ecological economists [1], serves as a quantitative approach for measuring regional sustainable development status. Its dynamic changes are closely related to regional socio-economic development and represent an important indicator for measuring the degree of natural resource utilization and sustainability conditions [2-4]. The concept was introduced to China in 1995 [5], and recent research by Chinese scholars has primarily focused on three aspects: (1) Combining the ecological footprint model with other models [10-11] or improving the model itself [12-14]. For instance, Zhang Zhiqiang et al. first applied ecological footprint theory in domestic scientific research. Xiang Shujian [12] and others addressed limitations in yield factor adjustments, ecological deficit/surplus indicators, and the physical quantity characteristics of ecological footprints by constructing calculation methods for production footprint, pollutant emission footprint, and trade footprint. Fang Kai [14] utilized an improved three-dimensional ecological footprint model with data from multiple countries to overcome deficit transfer problems between land types by meticulously tracking changes in flow capital and stock capital on various land carriers. Zhou Tao [15] and others analyzed major defects and debates in the basic model, focusing on evolution and corrections in parameter adjustments and account expansion. (2) Expanding ecological footprint applications to other fields. For example, Zhang Jinhe et al. proposed the concept of tourism ecological footprint based on ecological footprint methods and tourist consumption, establishing calculation sub-models. Li Bingyi [23] took Jincheng City during new urbanization as a study object, enriching urban ecological security research cases and providing references for sustainable development of resource-based cities in economic transition. He Jia [25] and others evaluated Jiangsu Province' s ecological benefits based on emergy ecological footprint and data envelopment analysis, proposing sustainable development suggestions. (3) Applying ecological footprint models to assess sustainability at different scales [20-25]. However, most existing research focuses on large provincial-scale regions using static or dynamic time series analyses. Although the ecological footprint method has demonstrated good applicability across different spatial scales—from global to specific regions [26-27]—few studies have analyzed ecological footprints from both temporal and spatial dimensions, especially examining internal dynamic changes and spatial dynamic differences within a region from a spatial perspective. Particularly, literature analyzing the spatial evolution of ecological footprints across districts and counties within a city jurisdiction is scarce.

As a mega-central city in western China and a western transportation hub, Chengdu holds a strategically important position economically. It exerts comprehensive radiation and driving effects on surrounding areas. Following the "One Belt, One Road" economic strategy proposed in 2015, Chengdu serves as a starting point city and a supply source for the "Northern Silk Road." It has become a key node connecting the Silk Road Economic Belt, the Bangladesh-China-India-Myanmar Economic Corridor, and the Yangtze River Economic Belt. However, with rapid growth in various economic indicators, Chengdu' s resource consumption has increased daily, creating enormous ecological pressure that threatens sustainable development. Alleviating ecological pressure has become an urgent task. Most scholars have studied Chengdu' s ecological footprint by treating the city as a whole, which may obscure spatial differences among districts and counties, creating difficulties for subsequent application of research findings and limiting practical guidance. This study selects Chengdu' s districts and counties as research objects, calculates per capita ecological footprint, per capita ecological carrying capacity, and per capita ecological deficit/surplus from 2009 to 2014, visualizes the results, reveals dynamic spatial differences, and clarifies internal resource consumption conditions in Chengdu using ArcGIS, aiming to provide scientific basis for properly handling sustainable relationships among population, resources, and environment and for formulating relevant policies.

2. Study Area Overview

Chengdu, the capital of Sichuan Province, is located in central Sichuan and the western Sichuan Basin, with coordinates between 102°54 -104°53 E and 30°05 -31°26 N. The city exhibits significant topographic differences, extending 192 km east-west and 166 km north-south, with a total area of 12,390 km². The favorable climate conditions (average annual temperature of 16°C) create advantageous conditions for agricultural production and management. By the end of 2014, the city' s total population was 4,320,000, with a forest coverage rate of 36.8% and a natural growth rate of 4.66‰.

3. Data Sources and Methods

3.1 Data Sources To ensure consistent calculation standards, research data were primarily obtained from the *Chengdu Statistical Yearbook (2010–2015)* and land use survey data of Chengdu' s districts and counties from 2009 to 2014.

3.2 Ecological Footprint Method The ecological footprint method transforms regional resource and energy consumption into the land area required for material production. By comparing ecological footprint demand with ecological carrying capacity, if demand exceeds supply, it represents ecological deficit, indicating high pressure on land production load and unstable ecosystems. If demand is less than carrying capacity, it represents ecological surplus, indicating reasonable land use and sustainable land resource utilization.

The per capita ecological footprint is calculated as:

$$ef = \sum_{i=1}^{n} \frac{P_i \times C_i}{N \times E_j}$$

where j represents land use type, i represents consumption goods and input types, C_i is the annual consumption of the ith consumer good, P_i is the global average annual production of the ith consumer good, N is the population number, and E_j is the equivalence factor for the jth land type.

The per capita ecological carrying capacity is calculated as:

$$ec = \sum_{j=1}^{m} \frac{A_j}{N \times Y_j \times E_j}$$

where A_j is the area of a certain type of biologically productive land in a country or region, Y_j is the yield factor, E_j is the equivalence factor for the jth land type, N is the population number, and ec is the per capita available ecosystem carrying capacity.

Based on Chengdu' s specific production and consumption conditions, this study establishes ecological footprint accounts with selected indicators. Following Yang Yi et al. [28], we used average equivalence factors across multiple years. To improve calculation accuracy and combining Sichuan Province' s comprehensive agricultural land production capacity survey and evaluation results, we determined yield factors for Chengdu' s cultivated land, forest land, grassland, water bodies, built-up land, and fossil fuel land as 2.34, 1.64, 1.66, 0.91, 0.19, 1.00, 1.40, and 1.66, respectively, with corresponding equivalence factors of 0.48, 0.32, 1.64, 2.34, etc.

4. Results and Analysis

4.1 Temporal Dynamics of Per Capita Ecological Footprint Chengdu' s per capita ecological footprint showed an overall declining trend from 2009 to 2014, significantly influenced by cultivated land ecological footprint, decreasing from 2.759 hm^2/cap to 1.937 hm^2/cap. The overall trend basically aligned with cultivated land per capita ecological footprint. The main reason is that as the region with the best comprehensive conditions in Sichuan Province, Chengdu has abundant agricultural products, resulting in relatively high ecological footprints. A noticeable decline occurred in 2011, primarily due to low pork prices during this period, which also kept beef and mutton prices low, causing farmers' enthusiasm to drop sharply and resulting in significantly reduced meat production. Chengdu' s implementation of motor vehicle license plate restrictions also contributed to decreased energy consumption.

Using two-step clustering with standards of 1.95, 2.63, 3.53, 5.30, and 9.76 hm^2/cap, regions were classified into low, medium-low, medium, medium-high, and high levels.

4.2 Spatial Pattern and Dynamic Evolution of Per Capita Ecological Footprint [Figure 1: see original paper] shows the temporal evolution law of Chengdu' s per capita ecological footprint from 2009 to 2014. Through spatial analysis of per capita ecological footprints across districts and counties from 2009 to 2014, the spatial pattern exhibited "low in the middle, medium in the two wings" characteristics, centered on Chengdu' s five urban districts. Qingbaijiang District and Longquanyi District belonged to low and medium-low ecological footprint areas, maintaining levels below 2.63 hm^2/cap, mainly because these areas have been positioned as satellite cities of Chengdu' s main urban area with secondary and tertiary industries as their leading sectors, resulting in generally low agricultural product output.

The highest ecological footprints were found in Pujiang County, Dayi County, and relatively high values in Xinjin County and Chongzhou City, with per capita ecological footprints above 5.30 hm^2/cap. These areas, located in Chengdu' s third circle layer, have slower secondary and tertiary industry development but abundant cultivated land resources with generally high quality, serving as Chengdu' s main agricultural product supply areas. Dujiangyan City, Jintang County, and Shuangliu County, as Chengdu' s second circle layer districts and counties, reflected Chengdu's average ecological footprint level at approximately 3.53 hm^2/cap, facing dual pressures of economic development and cultivated land protection, mainly relying on external inputs from surrounding counties.

The spatial pattern of per capita ecological footprint remained relatively stable with little change. The five urban districts consistently belonged to low ecological footprint levels; Xindu District and Qingbaijiang District belonged to medium-low levels; Jintang County and Shuangliu County belonged to medium levels; Chongzhou City and Xinjin County belonged to medium-high levels; and Qionglai City and Pujiang County belonged to high levels. During 2009–2014, 73.33% of districts and counties experienced no change in ecological footprint level, indicating stable development strategies and unchanged division of labor among districts and counties.

[Figure 2: see original paper] shows the spatial distribution of per capita ecological footprint across districts and counties from 2009 to 2014. Dramatic changes in ecological footprint patterns mainly occurred in high-level and low-level areas. High-level changes concentrated in Dayi County, which, among high-level counties, has relatively complex landform types with a relatively large proportion of hilly areas, relatively weak stable agricultural production capacity, and rapidly developing secondary and tertiary industries in recent years, causing its agricultural product output to decline and its ecological footprint level to decrease from high to medium-high. Low-level evolution mainly occurred in Wenjiang District, Pixian County, and Longquanyi District, which decreased from medium-low to low levels. Wenjiang District' s leading industry has gradually transformed from traditional grain crop cultivation to flower and seedling production. Pixian County, despite abundant cultivated land resources, has positioned itself to undertake industrial transfers from Chengdu enterprises, with gradually strengthening secondary and tertiary industries. Longquanyi District has developed rural tourism and sightseeing agriculture, resulting in a significant decline in grain sown area and 逐年下降 (year-by-year decreasing) agricultural product output.

4.3 Analysis of Per Capita Ecological Carrying Capacity and Deficit/Surplus

4.3.1 Temporal Dynamics Based on the ecological carrying capacity model and deducting 12% for biodiversity maintenance [32], per capita ecological deficit/surplus was calculated by subtracting per capita ecological carrying capacity from per capita ecological footprint. From 2009 to 2014, Chengdu' s per capita carrying capacity showed a relatively stable but declining trend, from 0.2314 hm^2/cap to 0.2215 hm^2/cap, while per capita ecological deficit/surplus was mainly in a deficit state but with an overall improving trend.

The stability of per capita carrying capacity is primarily due to China's strictest farmland protection system. Although cultivated land area decreases annually, the reduction rate gradually slows. While construction land inevitably occupies cultivated land and urbanization continues advancing, the carrying capacity of built-up land has improved, but the overall effect is limited. The improvement in per capita ecological deficit/surplus is not due to increased carrying capacity but rather to the assumption in ecological footprint calculations that consumption equals production. As living standards improve, people' s dietary structure has changed, with decreased grain consumption but increased demand for other meat, eggs, and dairy products, resulting in rising impacts on the ecological environment. The essential trend is increasingly severe per capita ecological deficit.

[Figure 3: see original paper] shows the temporal evolution law of Chengdu's per capita carrying capacity from 2009 to 2014. [Figure 4: see original paper] shows the temporal evolution of per capita ecological footprint, per capita ecological carrying capacity, and per capita ecological deficit/surplus in Chengdu from 2009 to 2014.

4.3.2 Spatial Pattern and Dynamic Evolution Using clustering standards of 0.22, 0.25, 0.29, 0.36, and 0.45 hm^2/cap for per capita carrying capacity, and -1.71, -2.29, -3.16, -5.01, and -9.32 hm^2/cap for per capita ecological deficit/surplus, two-step clustering analysis was performed.

[Figure 5: see original paper] shows the spatial distribution of per capita ecological carrying capacity across districts and counties from 2009 to 2014. The spatial pattern and dynamic evolution of per capita ecological carrying capacity and deficit/surplus showed that high carrying capacity areas were mainly stably distributed in Dayi County, Qionglai City, and Pujiang County in southwestern Chengdu, while these areas simultaneously exhibited the largest ecological deficits. Low ecological carrying capacity was mainly distributed in the five urban districts of central Chengdu, Qingbaijiang District, and Longquanyi District, which showed lighter deficits or slight surpluses. The spatial pattern of per capita carrying capacity and deficit/surplus showed an inverse relationship, forming an interlocking pattern.

The evolution of per capita carrying capacity pattern was relatively intense, while the per capita ecological deficit/surplus pattern was relatively stable. The main areas with intense evolution of per capita carrying capacity were Qionglai

City, which fluctuated between high and medium-high levels, and Wenjiang District and Xindu District, which evolved to low levels. The five urban districts oscillated between medium-low and low levels, showing a trend toward lower carrying capacity levels. The per capita ecological deficit/surplus pattern gradually fluctuated toward deficit, mainly because recent urbanization has occupied large amounts of high-quality cultivated land, and people's living standards have improved, with the supply from resource-output districts and counties unable to meet the growing demand from input-type districts and counties.

5. Conclusion

Through calculations and analysis of the temporal and spatial dynamics of per capita ecological footprint, per capita ecological carrying capacity, and per capita ecological deficit/surplus across Chengdu' s districts and counties from 2009 to 2014, the results align with Chengdu' s specific agricultural land production capacity and economic development levels. The temporal evolution shows that per capita ecological footprint has a declining trend, per capita ecological carrying capacity is relatively stable with a decreasing trend, and per capita ecological deficit/surplus appears to improve but essentially shows a worsening trend. From 2009 to 2014, per capita ecological footprint decreased by 0.8222 hm^2, per capita ecological carrying capacity decreased by 0.0099 hm^2, and ecological deficit improved by 0.7863 hm^2. However, this declining trend does not represent reduced natural demand in Chengdu but rather an unsustainable decline. The decrease rate of per capita ecological carrying capacity is far slower than that of per capita ecological footprint, but the essential trend is increasingly expanding ecological deficit in Chengdu.

Spatially, per capita ecological footprint and per capita carrying capacity show spatial consistency but inverse distribution with per capita ecological deficit/surplus. The distribution pattern is basically "low in the middle and high around." Per capita ecological footprint and per capita carrying capacity evolution are relatively intense, mainly occurring in high-level and low-level areas, showing a gradual shrinkage of high-level areas and expansion of low-level areas. Under their combined effects, the spatial pattern of per capita ecological deficit/surplus is relatively stable. The study area is clearly divided into ecological resource input and output regions with obvious circle-layer phenomena. The ecological footprint urgently needs regulation.

6. Recommendations

When calculating per capita ecological footprint, this study used production data to approximate consumption data when consumption data were unavailable, following other scholars' experiences. This calculation approach resulted in a declining trend in ecological footprint. This study used Second National Land Survey data, which limited the time span. Future research should combine questionnaire surveys to obtain more accurate consumption data for more precise ecological footprint calculations and integrate remote sensing data to extend the study period for more realistic spatiotemporal evolution patterns. The study found that Chengdu' s ecological footprint can be clearly divided into ecological resource input and output regions. The formation of these two regions is determined by the functional positioning of Chengdu' s districts and counties. The five urban districts are ecological resource input regions, while Dayi County, Qionglai City, Pujiang County, and Xinjin County are output regions. The two regions form a certain complementarity in per capita ecological footprint. However, Jintang County and Shuangliu County show trends of becoming resource input regions. Chengdu itself cannot achieve balance within its administrative area. Establishing reasonable ecological footprint regulation mechanisms, implementing ecological compensation from input regions to output regions, and promoting development of output regions are urgent issues to be addressed for achieving coordinated development across different circle layers in Chengdu.

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Note: Figure translations are in progress. See original paper for figures.