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Study on the Evaluation of Carbon Emission Efficiency of Land Use in Chengdu-Chongqing City Cluster

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ABSTRACT

Land is the carrier of human survival, and exploring land use carbon emissions and its efficiency is extremely important for implement low-carbon land use and local future development planning. Based on the data of Chengdu-Chongqing City Cluster, this paper explores the changes of land use carbon emission and its efficiency of 16 cities in the Chengdu-Chongqing City Cluster from 2014 to 2022 by using relevant models and software, and analyses the results. The results show that (1) in terms of carbon sinks, since the Chengdu-Chongqing City Cluster is in the southwestern part of the country and has rich vegetation cover, while Chongqing has the largest area under its jurisdiction, it has the largest amount of carbon sink absorption, followed by Ya'an and Mianyang. (2) As for carbon sources, it is related to the degree of regional development, and since Chengdu and Chongqing are the best developed, their carbon emissions are the largest. (3) In terms of carbon emissions, based on the data of carbon sinks and sources, it is concluded that Chongqing and Chengdu have the largest carbon emissions. (4) In terms of carbon emission efficiency, Chengdu's carbon emission efficiency has always been growing steadily, while the rest of the cities have both increases and decreases.

KEYWORDS

Land use carbon emission; Efficiency; Chengdu-Chongqing City Cluster

1. INTRODUCTION

Carbon emissions are one of the important influences on global climate change. In recent decades, the rapid development of the global economy and the rapid increase in the use of fossil fuels have led to a gradual increase in global carbon emissions [1], which in turn has caused global warming as well as severe climatic phenomena such as the frequent occurrence of extreme weather, which poses a serious challenge to the sustainable development of the economy and society and to the maintenance of the healthy functioning of natural ecosystems [2]. As early as 1988, the United Nations Intergovernmental Panel on Climate Change (IPCC), jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), brought the issue of global warming and other climate issues to the forefront of the international arena, and the signing of the United Nations Framework Convention on Climate Change (UNFCCC) on 9 May 1992 marked the beginning of a new phase of global climate governance. 1997 saw the adoption of the Kyoto Accord at the third UN Climate Conference. Conference adopted the Kyoto Protocol, which brought the limitation of greenhouse gas emissions into the realm of law, proposing to keep atmospheric emissions of greenhouse gases within a reasonable and stable range, and to avoid the development of human societies from being affected by drastic climate change. Now, on 12 December 2015, the Paris Climate Conference signed the Paris Agreement to replace the Kyoto Protocol, which further proposes new international rules for global climate governance beyond 2020 and is an important milestone in the development of global climate governance.

Since the reform and opening up, China's rapid economic growth has created a miracle in the economic history of mankind, but it has also been accompanied by a large amount of fossil energy consumption. According to the statistics of the International Energy Agency (IEA), as of 2007, China has surpassed the United States to become the world's largest CO2 emitting country. The total amount of carbon dioxide emissions in China will continue to increase as a result of the continuing development of the domestic economy and the long-term transformation of different industries. As a major emitter of greenhouse gases, China has taken on the important responsibility of low carbon and emission reduction, and has been actively involved in mitigating global climate change. In June 2007, the Chinese government released the China National Climate Change Programme, which is the first comprehensive policy document in this area for China and even for developing countries, and which comprehensively describes the measures that China will need to take in the face of climate change before 2010 [3] In September 2020, General Secretary Xi Jinping proposed a "dual-carbon" goal at the 75th General Debate of the United Nations General Assembly, i.e., China's carbon emissions should strive to peak around 2030 and work towards neutrality around 2060, and at the subsequent Climate Ambition Summit proposed that by 2030 At the subsequent Climate Ambition Summit, it was proposed that by 2030, the intensity of carbon dioxide emissions per unit of GDP would be reduced by 60-65 per cent compared to 2005, and the proportion of non-fossil energy consumption would be increased to around 25 per cent [4].

As the basic carrier of human production and life, changes in the way and intensity of land use directly or indirectly affect carbon emissions. Existing studies have shown that land use change has become the largest contributor to greenhouse gas emissions after fossil energy combustion, with more than 30% of the total carbon emissions from human activities from the 1860s to the end of the 20th century attributable to changes in land use [5]. In 2019, in a report released by the IPCC, it was stated that land is capable of absorbing up to one-third of global emissions from industrial production and fossil fuels, suggesting that land has a very important role in controlling atmospheric CO2 levels and maintaining ecosystem stability.

Over the past few decades, with the accelerated industrialisation and urbanisation, the Chengdu-Chongqing City Cluster has experienced rapid economic development. However, this rapid development has also brought about a major shift in land use, breaking the balance between land for production and living and land for ecological protection, leading to a significant rise in carbon emissions from land use, and posing a serious threat to the local and even wider ecological environment.

At present, research results on land use carbon emissions at home and abroad are fruitful, mainly focusing on two parts: land use carbon emission accounting research and land use carbon emission efficiency measurement research.

Research on land-use carbon emission accounting: Currently, the main research is based on the mechanism of land-use carbon emission, and the accounting method is divided into the following two aspects. Firstly, direct carbon emission accounting: direct carbon emission accounting for land use refers to the carbon emission generated by the change of land use type in the natural ecosystem and accounting for it. At present, there are three main methods in academia for accounting direct carbon emissions from land use: model simulation method, sample plot inventory method and remote sensing estimation method. The representative of the model simulation method is the bookkeeping model, which was proposed by Professor Houghton [6] in the 1980s, and was initially used to account for the carbon balance of the whole process of carbon exchange between terrestrial ecosystems and the atmosphere, and has been gradually improved, and is now widely used in the changes of carbon emissions caused by land-use changes at the national scale or regional scale. Calle [7] (2016) measured the land use carbon fluxes in Southeast Asia, South Asia, and East Asia over the period 1980-2009 and analysed the differences between the land use carbon emission effects in different regions through a bookkeeping model. Yang Xuhong et al. [8] (2019) estimated the total carbon emissions due to land use changes between 2.94 and 5.61 Pg during the period of 1661-1980 by bookkeeping model using the data of arable land reclamation in China during the past 300 years. The sample plot inventory method was originally proposed by Browns (1984), the basic principle of which is to investigate the carbon stock changes in the study area and then account for regional carbon emissions. Fang Jingyun et al. [9] (2007) combined the sample survey method with the biomass conversion factor method and the normalised vegetation index (NVI) to assess the carbon sink capacity of forests, grasslands and shrublands in China, and the carbon emission coefficients obtained by the method have been adopted in many articles so far. In the 1990s, with the continuous improvement of remote sensing technology, the method of measuring carbon emissions from land use through remote sensing data came into being. The basic principle of this method is to obtain land use transfer data based on remote sensing images in different periods, and then calculate carbon emissions based on the relationship between different land use types and remote sensing data. Because this method has the advantages of being able to compare the spatial and temporal differences in carbon emissions in different regions, easy access to data, and high accuracy of calculation, Li Zihe et al. [10] (2023) obtained the land-use status of Gansu Province in five time periods from 2000 to 2020 through remote sensing images, calculated the carbon emissions of different land-use types, and analyzed the factors affecting land-use carbon emissions in Gansu Province by combining the propensity value method and principal component analysis. The influencing factors of land use carbon emission in Gansu Province were analysed. Secondly, land use indirect carbon emission accounting, this method mainly calculates the carbon emissions indirectly generated by human beings in production activities. Currently, the commonly used methods of accounting for indirect carbon emissions from land use include the material balance method, the actual measurement method and the carbon emission coefficient method. The material balance method is based on the law of mass conservation, quantitative analysis of the energy consumed by people in production and life, so as to find out the carbon dioxide emissions generated by energy consumption, Ma Kai et al. [11] (2018) used the material balance method to calculate the carbon emissions generated by the combustion of different coal types. The measurement method is to detect the flow, concentration and flow rate of the emission gas through certain equipment and technical support, and then calculate the total amount of carbon dioxide emissions in the region, but this method has the disadvantages of higher cost and smaller detection range when measuring carbon emissions, so fewer cases use this method. Carbon emission coefficient method is currently the most common method, with simple operation, easy access to data and other advantages, its specific operation is based on the IPCC published data on energy consumption multiplied by the corresponding carbon emission coefficient, to find out the carbon emissions of various energy sources, and then find out the total amount of carbon emissions. Wu C et al. [12] (2015) through the establishment of the interrelationship between energy consumption and land use type. Using the carbon emission coefficient method, the scale and structure of carbon emissions from land use in the study area were estimated, and it was proposed that strengthening the management of energy-intensive land is an important measure to reduce carbon emissions. Wang Shuai et al. [13] (2019) counted the consumption of fertilisers, pesticides, and diesel fuel from the perspective of inputs of agricultural production materials, and measured the carbon emission effect of agricultural soil and water resources development in Henan Province through the conversion of carbon emission coefficients.

Research on measuring the carbon emission efficiency of land use: Compared with research on the efficiency of land use and other carbon emission efficiencies, there are relatively few results on researching the carbon emission efficiency of land as the main body. By comparing the existing literature, it is found that scholars use different methods to measure and analyse the carbon emission efficiency of land use from different perspectives. At present, the commonly used methods and models for measuring the carbon emission efficiency of land use mainly include data envelopment analysis (DEA), subsequent frontier analysis (SFA), Malmquist index model and SBM model. Li Lele et al. [14] (2019) took the prefecture-level cities in Shanxi Province as the research object, used the carbon emissions calculated from coal consumption, oil consumption and natural gas consumption as the input indicators, took the value added per capita of each industry as the output indicators, and used the CCR mode and BBC mode of the DEA model to calculate the technical, total and scale efficiencies of the carbon emissions from land use of the 11 prefectures, according to which the corresponding carbon emission efficiency is proposed for different regions inShanxi Province. Accordingly, corresponding low-carbon emission reduction strategies are proposed for different regions in Shanxi Province. Yu Dunchong et al. [15] (2015) calculated the carbon emission efficiencies of China's provinces in 2006 and 2011 with the help of the SFA method, selecting the urbanisation rate, per capita road area, and other nine factors of production as the input indicators, and carbon emissions per unit of GDP as the output indicators. Feng Wei et al. [16] (2023) used the SBM model with non-expected outputs to incorporate the net carbon emissions of 72 prefectural-level cities in the Yellow River Basin as non-expected outputs into the evaluation system of land-use carbon emission efficiency, analysed the evolution of their land-use carbon emission efficiency and spatial and temporal patterns, and put forward the corresponding policy recommendations. Zhang Miao et al. [17] (2023) measured the land use carbon emission efficiency data of 30 provinces in China by combining the SBM model of non-desired outputs with the social network analysis method, and explored the evolution of its spatial correlation network and its formation mechanism by using carbon emissions as non-desired outputs. Dong Jie et al. [18] (2016) used the DEA and Malmquist index model to analyse the change characteristics of land-use carbon emission efficiency in Hubei Province between 2001 and 2011 by incorporating the carbon emission intensity of agricultural land and the carbon emission intensity of construction land into the input indicators and the value added of the three major industries in the region as the output indicators.

2. OVERVIEW OF THE STUDY AREA AND DATA SOURCES

2.1. Overview of the Study Area

The Chengdu-Chongqing City Cluster is located in the Sichuan Basin, at the intersection of the Yangtze River Economic Belt and the "One Belt, One Road". It consists of the Chengdu and Chongqing megacities, and is one of the emerging national-level city clusters in western China, as well as an important strategic platform for the development of western China. Its scope covers 15 cities in Sichuan Province (Mianyang, Dazhou and some districts in Ya'an) and 27 districts in Chongqing Municipality, parts of Kaizhou and Yunyang, with a total area of about 185,000 square kilometres. In this study, due to differences in the statistical calibre of the statistical yearbook data and the scale of the study, a total of 156 districts in the whole of Chongqing Municipality and 15 prefectural-level cities in Sichuan Province were selected as the study area.

2.2. Data Sources

In this paper, relevant basic data for 2014-2022 have been obtained from authoritative institutions such as the Resource and Environment Science and Data Centre of the Chinese Academy of Sciences, Sichuan Statistical Yearbook, Sichuan Municipal and State Statistical Yearbooks, Chongqing Statistical Yearbook, China Urban Statistical Yearbook, China Energy Statistical Yearbook, etc., and the data required for the model have been further calculated.

3. RESEARCH METHODOLOGY

3.1. Methods of Accounting for Carbon Emissions From Land Use

Based on the land use data of Chengdu-Chongqing Urban Agglomeration, this paper refers to the China Land Cover Dataset Classification System (CLCD classification system), and classifies land use into six types: arable land, forest land, grassland, water bodies, unused land and construction land, and by further analysing the functions of different types of land in terms of carbon emission, the arable land and construction land are categorized as carbon sources, producing positive carbon emissions; while forest land, grassland, water bodies and unused land are categorised as carbon sinks, producing negative carbon emissions. In this paper, the carbon emission coefficient method is used to assess the carbon emissions of different types of land, in which the direct carbon emission coefficient method is used to account for arable land, forest land, grassland, water bodies, and unutilised land, while the indirect carbon emission coefficient method is used to account for construction land.

3.1.1. Direct carbon emissions from land use

Referring to the existing research results, the formula for calculating direct carbon emissions from land use is as follows:

$$C_{\mathrm{i}} = \sum e_i = \sum S_i \times \delta_i \tag{1}$$

Where Cidenotes total direct carbon emissions, eidenotes carbon emissions from the ith land-use type, Sidenotes the area of the ith land-use type, and δidenotes the carbon emission coefficient for the ith land-use type, where a positive carbon emission coefficient denotes carbon emissions, and a negative carbon emission coefficient denotes carbon sequestration.

(1) Determination of carbon emission factors for arable land

In the process of agricultural production, arable land is both a carbon sink and a carbon source. On the one hand, crops fix carbon dioxide in the air in the body of plants through photosynthesis in the process of growth, which is manifested as a carbon sink; on the other hand, the oxidative decomposition of soil microorganisms, the respiration of crops, as well as the use of pesticides, fertilisers, mulch films and agricultural machinery by humans in farming will produce carbon dioxide, which is manifested as a carbon source. Taken together and in conjunction with existing literature [19-21], the carbon emission factor for arable land was determined to be 0.4595t/(hm^2*a).

(2) Determination of carbon emission factors for forest land

Woodland is one of the most important carbon sinks on earth, and there are many kinds of vegetation in woodland, which mainly fixes carbon dioxide in the air in plants or soil through photosynthesis, and the amount of carbon dioxide absorbed by photosynthesis is much larger than the amount of carbon dioxide produced by plant respiration. The Chengdu-Chongqing urban agglomeration is located in the southwestern part of China, in the hilly and basin area, with a large amount of woodland and rich vegetation. Referring to the existing studies ([) (9, 22) (-) (24) (]), the carbon emission coefficient of the forest land was determined to be -0.6125t/(hm(2)-a).

(3) Determination of carbon emission factors for grassland

Grassland is an important part of the carbon sink, and its principle of action is similar to that of woodland, which is carbon sequestration through photosynthesis of plants, but the carbon sequestration capacity and stability of grassland is far less than that of woodland. Combined with the existing research results [9], the carbon emission factor of grassland is determined to be -0.0210t/(hm^2*a).

(4) Determination of carbon emission factors for water bodies

Water bodies manifest their carbon sink role in two main ways: on the one hand, the water body itself can dissolve a small amount of carbon dioxide, and on the other hand, plankton as well as plants in the water can absorb a certain amount of carbon dioxide through photosynthesis. According to the existing literature [25-27], the carbon emission factor for water bodies is determined to be -0.0253t/(hm(2)*a).

(5) Determination of carbon emission factors for unused land

Unutilised land refers to land that is difficult to develop, such as sandy land and saline land, which has a weak carbon emission and carbon sequestration capacity. Based on the results of existing research [9, 28], the carbon emission coefficient of unused land is determined to be -0.005t/(hm(2)*a).

The land use carbon emission factors are shown in the table below:

Table 1. Land-use carbon emission factors

Land use type	Carbon emission factor
arable land	0.4595
woodland	-0.6125
grassland	-0.0210
body of water	-0.0253
unused land	-0.0050

3.1.2. Indirect carbon emissions from land use

Carbon dioxide emissions from construction land mainly come from energy consumption of secondary and tertiary industries in the process of development, and such carbon emissions are not suitable to be obtained by multiplying the area of construction land by the carbon emission factor, but are indirectly estimated through energy consumption, and the specific calculation formula is as follows.

$$C_{\mathrm{j}} = \sum_{i=1}^{n} M_i \times E_i \times Q_i \tag{2}$$

Where Cjdenotes the total indirect carbon emissions, Midenotes the consumption of the ith energy source, Eiis the standard coal conversion factor of the ith energy source, and Qiis the carbon emission factor of the ith energy source.

In this paper, the energy standard coal conversion coefficients come from the energy conversion coefficient table of China Energy Statistical Yearbook, the carbon emission coefficients are mainly adopted from the IPCC National Greenhouse Gas Emission Guidelines, and the sources of carbon emissions from construction land are mainly from industry, construction, transport, wholesale and retail industries, as well as accommodation and catering industries, and the 12 major energy sources in the Sichuan and Chongqing regions are selected for calculation.

The standard coal conversion factors and carbon emission factors for each energy type are shown in the table below:

Table 2. Table of conversion factors for standard coal and carbon emission factors for various energy categories

Type of energy	Standard coal conversion factors (in kgce/kg, kgce/m3, kgce/kw-h)	Carbon emission factor
raw coal	0.7143	0.7559
refined coal	0.9000	0.7559
coke (processed coal used in blast furnace)	0.9714	0.8550
coke oven gas	0.5929	0.3548
crude oil	1.4286	0.6185
petrol	1.4714	0.5538
diesel	1.4714	0.5714
diesel oil	1.4571	0.4483
fuel oil	1.4286	0.5857
liquefied petroleum gas	1.7143	0.5042
petroleum	1.215	0.5921
electrical power	0.1229	0.7330

3.1.3. Net carbon emissions from land use

Net carbon emissions from land use are the combination of direct and indirect carbon emissions, as per the formula below:

$$C = C_i + C_j \tag{3}$$

Where C represents net carbon emissions from land use, Cirepresents direct carbon emissions and Cjrepresents indirect carbon emissions.

3.2. Methods for Measuring the Carbon Emission Efficiency of Land Use

By summarizing the existing research results on the carbon emission efficiency of land use and other carbon emission efficiencies, and taking into account the current development situation and characteristics of the Chengdu-Chongqing city cluster, four types of input indicators are selected, namely, land input, labour input, capital input and energy input, of which, land input is divided into two categories, one is a source of carbon, which includes construction land and arable land, and the other is a sink of carbon, which includes forest land, grassland, water bodies and unused land. The land input is divided into two categories, one is carbon source, including construction land and arable land, and the other is carbon sink, including forest land, grassland, water body and unused land, and the above six land types are used to comprehensively consider the land input situation; the number of employees and the total investment in fixed assets can directly reflect the situation of the labour input and the capital input; and because of the development gap between the different cities in Chengdu-Chongqing City Cluster, the total energy consumption is chosen to measure the energy input intensity. Since the carbon emission efficiency of land use refers to the maximum economic benefit and the lowest carbon emission under a certain input, this paper chooses the economic output as the desired output and the carbon emission output as the non-desired output, in which the economic output is reflected by the primary industry GDP, the secondary industry GDP, and the tertiary industry GDP, and the carbon emission output is represented by the net carbon emission from land use as calculated. The carbon emission output is represented by the net carbon emission from land use.

In summary, the indicator system constructed is shown in the table below:

Table 3. Land-use carbon efficiency indicator system

Division of indicators	Type of indicator	Specific indicators factor	unit (of measure)
Input	land input	Carbon sources: built-up land, cropland Carbon sinks: forest land, grassland, water bodies, unused land	hectares
	Labour input	Number of employees	ten thousand people
	capital investment	Total investment in fixed assets	billions
	Energy inputs	Total energy consumption	million tonnes of standard coal
Expected outputs	Economic output	Primary sector GDP	billions
		Gross secondary sectoral product (GSP)	
		Tertiary GDP	
Non-expected outputs	Carbon output	Net carbon emissions from land use	tonnes

Since the traditional DEA model suffers from biased efficiency values due to slack problems in inputs and outputs, the use of the Super-SBM model, which includes non-expected outputs, not only takes into account the effects of slack variables, but also solves the problem of the inability to rank and compare effective decision-making units. The specific formula is as follows:

$$\rho = \min \frac{\frac{1}{\mathrm{m}}\sum_{i=1}^{m}\frac{\bar{x}_i}{x_{i_0}}}{\frac{1}{s_1+s_2}\left(\sum_{t=1}^{s_1}\frac{\bar{y}_t^a}{y_{t_0}^a}+\sum_{k=1}^{s_2}\frac{\bar{y}_k^b}{y_{k_0}^b}\right)}$$

$$\begin{cases} x_0 = x\gamma + n^-, y_0^a = y^a\gamma - n^a, y_0^b = y^b\gamma + n^b \\ \bar{x} \ge \sum_{j=1,\ne 0}^{n}\gamma_j x_j, \bar{y}^a \le \sum_{j=1,\ne 0}^{n}\gamma_j y_j^a, \bar{y}^b \le \sum_{j=1,\ne 0}^{n}\gamma_j y_j^b \\ \bar{x} \ge x_0, \bar{y}^a \le y_0^a, \bar{y}^b \ge y_0^b \\ \sum_{j=1,\ne 0}^{n}\gamma_j = 1, s^- \ge 0, s^a \ge 0, s^{-a} \ge 0, \gamma \ge 0 \end{cases} \tag{4}$$

Where ρ is the value of carbon emission efficiency of land use in Chengdu-Chongqing urban agglomeration cities, x, ya, ybrepresent the input variables, desired output variables and non-desired output variables, m, s(1), s2 represent the number of corresponding variables, vector n-, na, n(b)are the relaxation variables of the input variables, the slack variables of the desired outputs, and non-desired outputs, and γ is the weighting coefficient. weight coefficients.

4. ANALYSIS OF RESULTS

4.1. Analysis of Land-Use Carbon Emission Results

Based on the various types of data obtained, the carbon sinks, sources and net carbon emissions of each city in the Chengdu-Chongqing urban agglomeration in 2014-2022 were obtained as shown in the following table:

Table 4. Carbon emissions data from carbon sinks, 2014-2022

Year Region	2014	2015	2016	2017	2018	2019	2020	2021	2022
Chengdu	-16.80	-17.77	-18.79	-19.15	-19.46	-19.84	-20.14	-20.19	-20.29
Zigong	-1.62	-1.72	-1.82	-1.88	-1.98	-2.10	-2.16	-2.16	-1.96
Luzhou	-35.75	-36.35	-36.11	-35.42	-33.82	-33.81	-34.23	-34.49	-35.94
Deyang	-6.92	-7.00	-7.20	-7.37	-7.54	-7.81	-8.10	-8.12	-8.50
Mianyang	-64.55	-64.82	-65.86	-65.98	-66.43	-67.48	-68.69	-68.82	-68.89
Suining	-2.99	-3.24	-3.24	-3.93	-4.04	-4.45	-4.73	-4.75	-5.92
Neijiang	-2.22	-2.28	-2.28	-2.37	-2.48	-2.64	-2.77	-2.78	-2.83
Leshan	-46.20	-46.74	-49.84	-46.68	-46.58	-46.97	-46.62	-46.49	-46.93
Nanchong	-9.88	-10.16	-11.00	-10.99	-10.90	-11.75	-12.44	-12.89	-15.12
Meishan	-9.64	-9.96	-10.36	-10.36	-10.39	-10.59	-10.67	-10.69	-10.81
Yibin	-30.62	-30.78	-30.91	-30.78	-31.30	-31.94	-32.27	-32.31	-30.91
Guang'an	-7.02	-7.02	-6.82	-6.79	-6.63	-6.88	-6.97	-7.01	-7.12
Dazhou	-51.06	-50.68	-51.38	-52.62	-53.34	-54.68	-55.70	-55.84	-55.42
Ya'an	-71.26	-71.78	-72.68	-73.00	-72.98	-73.03	-72.63	-72.71	-73.31
Ziyang	-1.56	-1.64	-1.57	-1.56	-1.70	-2.13	-2.38	-2.38	-2.95
Chongqing	-272.59	-273.35	-275.70	-276.83	-277.08	-282.26	-284.85	-285.75	-287.39

Table 5. Carbon emissions data from carbon sources, 2014-2022

Year Region	2014	2015	2016	2017	2018	2019	2020	2021	2022
Chengdu	2213.46	2127.50	2008.15	2131.68	2233.79	2341.56	2292.11	2417.51	2280.60
Zigong	273.27	259.42	229.62	236.82	242.88	247.34	235.51	244.27	228.94
Luzhou	403.15	390.82	354.98	365.47	377.56	392.33	380.06	398.35	379.92
Deyang	386.04	368.85	335.26	342.98	354.03	365.53	349.76	367.71	347.93
Mianyang	485.23	473.77	435.52	456.77	472.96	492.41	478.75	502.78	480.88
Suining	281.18	270.38	239.83	242.90	252.77	259.48	247.66	255.98	242.71
Neijiang	323.87	307.63	273.22	273.60	278.09	283.31	269.50	279.13	262.31
Leshan	339.02	328.08	289.80	294.37	306.90	318.08	311.25	321.99	305.49
Nanchong	531.16	507.43	456.18	467.97	483.16	495.13	472.36	488.60	458.31
Meishan	290.42	280.49	250.01	256.24	262.43	269.99	259.76	270.45	256.82
Yibin	441.58	423.91	385.69	400.72	435.32	457.71	449.16	473.24	455.07
Guang'an	290.56	278.84	250.73	257.40	264.38	273.52	265.55	274.17	255.74
Dazhou	476.77	461.83	417.52	428.37	437.86	449.17	433.13	451.27	428.76
Ya'an	146.86	142.48	126.96	127.17	128.29	133.26	128.93	134.63	128.32
Ziyang	267.43	257.66	190.21	190.60	190.98	194.70	187.66	193.32	183.67
Chongqing	3415.42	6677.58	3134.36	5819.08	3134.80	3099.14	3174.17	3221.90	3089.89

Table 6. Data on net carbon emissions from land use, 2014-2022

Year Region	2014	2015	2016	2017	2018	2019	2020	2021	2022
Chengdu	2196.66	2109.73	1989.36	2112.53	2214.34	2321.72	2271.97	2397.32	2260.31
Zigong	271.65	257.70	227.80	234.94	240.90	245.25	233.35	242.11	226.98
Luzhou	367.40	354.47	318.86	330.05	343.74	358.51	345.83	363.86	343.99
Deyang	379.12	361.86	328.06	335.61	346.49	357.72	341.67	359.59	339.44
Mianyang	420.68	408.95	369.66	390.79	406.53	424.92	410.07	433.95	411.98
Suining	278.19	267.14	236.02	238.97	248.73	255.04	242.93	251.22	236.79
Neijiang	321.65	305.35	270.89	271.24	275.61	280.67	266.73	276.35	259.48
Leshan	292.82	281.34	242.96	247.69	260.32	271.12	264.63	275.50	258.56
Nanchong	521.28	497.26	445.19	456.98	472.26	483.38	459.92	475.71	443.19
Meishan	280.78	270.53	239.65	245.88	252.04	259.39	249.10	259.76	246.01
Yibin	410.96	393.13	354.78	369.94	404.02	425.78	416.89	440.93	424.16
Guang'an	283.54	271.82	243.90	250.64	257.75	266.64	258.59	267.16	248.62
Dazhou	425.71	411.15	366.14	375.76	384.53	394.49	377.43	395.43	373.34
Ya'an	75.60	70.70	54.28	54.17	55.31	60.23	56.30	61.92	55.01
Ziyang	265.87	256.02	188.64	189.03	189.29	192.57	185.28	190.94	180.72
Chongqing	3142.82	6404.22	2858.66	5542.24	2857.72	2816.88	2889.32	2936.15	2802.49

4.1.1. Characteristics of changes in carbon sinks

The carbon sinks of the regions in the Chengdu-Chongqing City Cluster show an overall fluctuating upward trend from 2014 to 2022, with the carbon sinks of Ya'an City and Mianyang City significantly higher than those of other regions, amounting to -733,100 tonnes and -688,900 tonnes in 2022 respectively, mainly thanks to their rich woodland and grassland resources. The carbon sink of Chengdu City grows year by year, reaching -202.9 thousand tonnes in 2022, which is closely related to urban greening projects and ecological protection policies. It is worth noting that Zigong's carbon sink in 2022 is 0.20 million tonnes lower than that in 2022, which may be related to the shrinking of arable land area or the decline of vegetation cover.

4.1.2. Characteristics of carbon source emissions

Carbon emissions show a staged characteristic of "first decline, then rise and then fluctuate". Chongqing's carbon emissions jumped to 66,775,800 tonnes in 2015, much higher than in other years, which may be related to the stage-by-stage adjustment of the energy consumption data in the statistical calibre; since then, it has gradually dropped back to 30,898,900 tonnes in 2022, which reflects the effectiveness of optimising the industrial structure. Carbon sources in Chengdu city fell to a low of 2008.15 million tonnes in 2016, and then rebounded to 24.1751 million tonnes in 2021 due to urban expansion and industrial development. Prefecture-level cities in Sichuan, such as Deyang and Mianyang, have relatively stable carbon source emissions of 3,479,300 tonnes and 4,808,800 tonnes in 2022, with industrial energy consumption being the main contributing source.

4.1.3. Trends in net carbon emissions

The total net carbon emissions are basically consistent with the trend of carbon source changes. In Chongqing, net carbon emissions peaked at 64,042,200 tonnes in 2015, and will drop to 28,024,900 tonnes in 2022, showing the effectiveness of emission reduction under the "double carbon" target. Chengdu's net carbon emissions remain in the range of 20-24 million tonnes, with 22.631 million tonnes in 2022, still at a high level. Ya'an City has always had the lowest net carbon emissions, with 550,100 tonnes in 2022, matching its high carbon sink and low industrial emissions. Some cities, such as Nanchong, have a net carbon emission reduction of 325,200 tonnes in 2022 compared with 2021, which may be related to the improvement of agricultural carbon sinks or energy efficiency improvements.

4.2. Analyses of Land-Use Carbon Efficiency Results

Using Dearun software as a calculation tool, the land use carbon emission efficiency of the Chengdu-Chongqing urban agglomeration from 2014 to 2022 was obtained as shown in the following table:

Table 7. Land-use carbon efficiency

Year Region	2014	2015	2016	2017	2018	2019	2020	2021	2022
Chengdu	1.7327	1.8550	1.7321	1.7234	1.7474	1.8432	1.9081	1.9982	1.9641
Zigong	1.8484	1.8192	3.7083	1.4065	1.2129	1.1466	1.1429	1.1382	1.1620
Luzhou	1.0420	1.0465	1.0119	1.3051	1.2791	1.7065	2.9019	2.9559	1.4381
Deyang	1.0537	1.0407	1.0372	1.0094	1.0338	1.1281	1.1130	1.1125	1.1077
Mianyang	0.4098	0.4097	0.4250	0.4010	0.4403	1.0033	1.0074	1.0080	1.0084
Suining	1.0020	0.5512	0.5268	0.5922	0.6162	1.0131	1.0365	1.0464	1.0931
Neijiang	1.0230	1.0532	1.0203	1.0248	1.0337	1.1315	1.1992	1.1563	1.1713
Leshan	0.5017	0.4724	0.5000	0.4546	0.5198	0.6087	0.6456	0.6490	0.6204
Nanchong	0.4899	0.4661	0.4861	0.5021	0.5631	1.0009	1.0019	1.0028	0.7306
Meishan	0.4805	0.5104	0.4848	0.5173	0.5158	0.6780	0.6989	0.6994	0.7041
Yibin	0.5874	0.6044	0.5819	1.0168	1.0272	1.0934	1.0850	1.0921	1.0963
Guang'an	1.0006	1.0011	0.5438	1.0906	1.2930	1.2279	1.1169	1.0727	1.0026
Dazhou	1.0376	1.0546	0.4358	0.4906	0.6149	1.0062	1.0072	1.0135	1.0076
Ya'an	0.2537	0.2322	0.2486	0.2677	0.2835	0.2763	0.2666	0.2695	0.2617
Ziyang	1.0150	1.0237	1.0064	1.0184	1.0069	1.0343	1.0270	1.0264	1.0275
Chongqing	1.2837	1.5798	1.2635	1.4099	1.2055	1.2142	1.2222	1.2116	1.2043

4.2.1 Overall analysis of efficiency levels

Chengdu and Chongqing are the long-term leaders in efficiency, reaching 1.9641 and 1.2043 respectively in 2022, forming the "Chengdu-Chongqing efficiency plateau". Chengdu's efficiency advantage stems from the level of land intensification and low-carbon technology inputs; Chongqing's efficiency surged to 1.5798 in 2015, which is directly related to the low-carbon transformation of industries in Liangjiang New Area. Zigong City, the efficiency value of 3.7083 in 2016, is the year of salt chemical energy efficiency and photovoltaic project put into operation, but after 2017 due to the recovery of traditional industries fell back to 1.1-1.4; Yibin City, the efficiency of 2017-2022 continued to be > 1, 1.0963 in 2022, benefiting from the Ningde era of power battery base to drive the industrial upgrading.

4.2.2 Regional differences and time evolution

High-efficiency areas: Zigong City reached an efficiency value of 3.7083 in 2016, the highest in the udy period, probably related to the sudden improvement of industrial energy efficiency in that year, but then fell back to 1.1-1.4, showing a lack of stability; Yibin City has a continuous efficiency value of > 1 since 2017, and reaches 1.0963 in 2022, benefiting from the low-carbon transformation of the power battery industry. Medium and low efficiency areas: Leshan and Meishan have efficiency values of < 0.7 for a long time, and 0.6204 and 0.7041 in 2022, reflecting the high carbon emission intensity of traditional industries and the urgent need to improve the efficiency of land use. The efficiency value of Ya'an City is always < 0.3 and 0.2617 in 2022, which is related to its characteristic of outstanding ecological protection function but low economic output. Trend changes: the efficiency values of Mianyang City and Suining City increase significantly after 2019, jumping from 0.4403 and 0.6162 to more than 1.0, which may be related to the construction of the science and technology city and the layout of new energy industries; the efficiency value of Nanchong City falls back to 0.7306 in 2022, which needs to pay attention to the lagging problem of its industrial restructuring.

4.2.3 Efficiency drivers

The efficiency value is significantly correlated with the level of economic development and industrial structure. Core cities such as Chengdu and Chongqing have obvious efficiency advantages due to the high proportion of tertiary industries and advanced energy technologies, while resource-based industries such as Ya'an and Leshan have low efficiency. In addition, the efficiency of many places will increase after 2019, which is directly related to the implementation of regional low-carbon policies after the "dual-carbon" target is put forward.

5. RECOMMENDATION

5.1. Strengthen Carbon Sink Capacity Building and Optimise Ecological Land Use Structure

(1) Strengthening the protection and restoration of woodland and grassland resources. Targeting areas with carbon sink advantages such as Ya'an City and Mianyang City, expanding forest coverage, promoting the construction of ecological barriers in the upper reaches of the Yangtze River, and focusing on the implementation of the project of returning ploughland to forests and treating degraded grasslands. It has established a system for measuring and monitoring the carbon sinks of woodlands, and incorporated the effectiveness of ecological protection into local assessment indicators.

(2) Promoting the expansion of urban green space. Drawing on Chengdu's experience in building a "park city", increase the area of urban green space and three-dimensional greening, and enhance the carbon sequestration capacity of vegetation in the built-up area; in 2022, Chengdu's carbon sink will reach 202,900 tonnes, and projects such as green roofs and eco-corridors can be promoted to alleviate the effect of urban heat islan and enhance carbon absorption at the same time.

(3) Enhancing the carbon sink potential of water bodies and unused land. Ecological restoration of water bodies in the Tuo River, Jialing River and other river basins will be implemented to promote carbon sequestration by aquatic plants; and unused land such as saline and alkaline land and sandy land will be converted into inefficient land for carbon sinks by means of vegetation restoration techniques, so as to gradually increase the amount of carbon absorbed per unit area.

5.2. Strictly Control The Emission Intensity of Carbon Sources and Promote Industrial Energy Transformation

(1) Optimise industrial structure and eliminate backward production capacity. For high carbon source areas such as Chongqing Municipality and Chengdu Municipality (30.8989 million tonnes of carbon source in Chongqing in 2022), accelerate the low-carbon transformation of the secondary industry, focus on promoting the green technology upgrading of iron and steel, chemical industry, etc., and establish a negative list of industrial access with reference to the experience of eliminating 237 backward production capacity enterprises in Chongqing's Two Rivers New Area. Yibin City relies on the power battery industry to achieve sustained efficiency > 1, and can promote the layout of the new energy industry chain within Sichuan to attract low-carbon manufacturing clusters.

(2) Enhancing energy use efficiency and promoting clean energy. The industrial sector promotes the experience of Zigong City in 2016 to improve the energy efficiency of the salt chemical industry, and implements coal-fired boiler renovation, waste heat recovery and other projects in Deyang, Mianyang and other industrial towns. Expand the proportion of natural gas, hydropower and other clean energy,

and 28% penetration rate of new energy vehicles in Chengdu in 2022, which can be used to promote new energy transport systems within the city cluster, build a network of charging piles, and reduce carbon emissions from transport.

(3) Optimising the management of carbon emissions from construction sites. In view of the high proportion of indirect carbon emissions from construction land, establish a "land-energy-carbon" linkage control mechanism: implement a double assessment of land area ratio and carbon emission intensity in industrial parks, and promote the intensive use of industrial land; pilot the construction of "low-carbon industrial parks" in Chongqing and Chengdu; and provide distributed photovoltaic and energy storage facilities. The pilot construction of "low-carbon industrial parks" in Chongqing and Chengdu will be supported by distributed photovoltaic and energy storage facilities.

5.3. Improving the Policy Guarantee System and Strengthening Implementation Support

(1) Building a low-carbon land-use policy framework. Incorporate the "dual-carbon" goal into national spatial planning, and designate carbon sink protection zones and low-carbon development demonstration zones; implement differentiated protection policies for arable land, forest land and other land used for carbon sinks, such as raising the ecological compensation standard, and incentivising farmers to participate in carbon-consolidating agriculture.

(2) Increase investment in low-carbon technologies and funds. Set up a low carbon development fund for the Chengdu-Chongqing city cluster, focusing on supporting the research and development of low carbon industrial technologies such as power batteries in Yibin and photovoltaic in Chengdu; and promote the cooperation model of "government + enterprises + scientific research institutions", for example, the Mianyang Science and Technology City can establish a carbon efficiency enhancement laboratory in conjunction with a university to overcome key industrial energy-saving technologies.

(3) Strengthening public participation and assessment and supervision. Establish a public system for carbon emission information, and regularly publish reports on the carbon efficiency of land use in each city; carry out the selection of "low-carbon communities" and "green factories", and guide enterprises and residents to participate in emission reduction actions. Carbon efficiency indicators will be incorporated into the performance assessment of local governments, and early warning interviews will be conducted in areas where the efficiency has declined for three consecutive years (e.g. Nanchong City, where the efficiency will fall back to 0.7306 in 2022).

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