Asian Agricultural Research 2024, 16 (10): 21 -24, 27 DOI: 10.19601/j.cnki.issn1943 -9903.2024.10.003

Carbon Emission Measurement and Regional Difference Analysis of China's Construction Industry

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Abstract Green and low-carbon development of construction industry is one of the important ways to achieve the "dual carbon" goal in China. This study first measured the carbon emissions of the construction industry in 30 provinces in China, and then used the Dagum Gini coefficient and its decomposition method to explore the regional differences and sources of carbon emissions of the construction industry in China. The results show that the carbon emissions of construction industry in China generally show an upward trend, and there are significant differences in carbon emissions of construction industry among provinces, and the main source of regional differences is inter-regional differences. However, the contribution rate of inter-regional differences showed a significant downward trend, while the contribution rate of hyperbolic density increased day by day, and the contribution rate of intra-regional differences increased slightly. The results of this study will provide a reference for China to formulate more reasonable carbon emission reduction targets and differentiation strategies for the construction industry.

Key words Construction industry, Carbon emissions, Regional differences, Dagum Gini coefficient

1 Introduction

In the national economic system, the construction industry not only plays a vital role as a pillar industry, but also becomes an indispensable part for China to achieve the goal of "carbon peaking" and "carbon neutrality" ("dual carbon") because of its significant high energy consumption and high emission characteristics[1]. In this context, the *14th Five-Year Plan for the Development of Construction Industry* clearly points out that accelerating the transformation of construction industry to green and low-carbon is the decisive measure to achieve the strategic goal. In view of this, the urgency of reducing carbon emissions in the construction industry is highlighted, and it has attracted great attention and in-depth research from academic circle.

Previous studies on carbon emissions in the construction industry have mostly focused on emission accounting at the provincial level, analyzed its spatiotemporal evolution in detail[2-4], and discussed in depth how multiple factors such as energy structure adjustment, economic development level, urbanization process, environmental policy implementation, and technological innovation affect the carbon emission level of the construction industry[5-7]. In addition, some scholars have also used the model to predict and analyze the future trend of carbon emissions in the construction industry[8]. However, in the analysis framework of regional differences, the existing research is still insufficient to identify the absolute difference of carbon emissions in construction industry and the contribution rate of intra-group and inter-group differences, which needs to be filled urgently. Based on this, this study aims to build a comprehensive carbon emission accounting system for the construction industry, which not only covers the direct carbon emissions caused by the direct energy consumption of the construction industry, but also includes the indirect carbon emissions caused by the use of five major building materials, such as steel and cement, so as to make a detailed quantitative assessment of the carbon emissions of the construction industry in 30 provinces of China. In this study, the Dagum Gini coefficient and its decomposition technology were introduced to carefully analyze the regional differences of carbon emissions in China's construction industry, and the main sources of these differences were traced. We intend to provide a scientific basis and decision-making reference for policy formulation and strategy optimization to promote the green and low-carbon development of China's construction industry.

2 Research methods and data sources

2.1 Measurement of carbon emissions in construction industry In this study, we took 30 provinces and cities in China as the research object, and selected the data of 18 years from 2005 to 2022. All the data were from *China Energy Statistics Yearbook and China Construction Statistics Yearbook*, and the missing data were supplemented by interpolation. With reference to the existing literature, we divided the carbon emissions of construction industry into direct carbon emissions (carbon emissions from 17 kinds of energy consumption, such as raw coal and coke) and indirect carbon emissions (carbon emissions from the use of 5 kinds of building materials, such as steel and wood). The calculation process is as shown in formula (1):

$$C^k = \sum_{i=1}^{17} C_i^k + \sum_{j=1}^{5} C_j^k = \sum_{i=1}^{17} (E_i^k \times O_i^k \times LCV_i^k \times CF_i^k) + \sum_{j=1}^{5} E_j^k \times \delta_j \quad (1)$$

where C^k represents the total carbon emissions of the construction industry in the k^{th} province; C_i^k represents the carbon emission of the i^{th} energy consumption of the construction industry in the k^{th}

Received: July 1, 2024 Accepted: September 3, 2024

Supported by School-level Natural Science Project of Jiangxi University of Technology (232ZRYB02).

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province; C_j^k represents the carbon emission of the j^{th} material consumption in the construction industry of the k^{th} province; E_i^k, O_i^k, LCV_i^k separately represent the terminal consumption, carbon oxidation rate, average lower calorific value and carbon emission factor of the i^{th} energy in the construction industry of the k^{th} province; E_j^k and δ_j represent the consumption of the j^{th} material in the construction industry of the k^{th} province and the corresponding carbon emission coefficient.

2.2 Dagum Gini coefficient and its decomposition method

In order to explore the spatial differences and sources of carbon emissions in the construction industry in the eastern, central and western regions of China, we use the Dagum Gini coefficient and its decomposition method to identify the absolute and relative differences and their sources. The specific formula is as follows:

$$G = G_w + G_{nb} + G_t \quad (2)$$

$$G = \frac{\sum_{j=1}^{k}\sum_{h=1}^{k}\sum_{i=1}^{n_j}\sum_{r=1}^{n_h} |y_{ji} - y_{hr}|}{2n^2\mu} \quad (3)$$

$$G_w = \sum_{j=1}^{k} G_{jj} p_j S_j \quad (4)$$

$$G_{nb} = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_s + s_j) D_{jh} \quad (5)$$

$$G_t = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_h s_j)(1 - D_{jh}) \quad (6)$$

where G represents the overall Gini coefficient; G_w, G_{nb}, and G_t represent the contributions of intra-regional differences, inter-regional differences, and hyperbolic density, respectively; i and j are different regions; h and r are different provinces and cities; k is the number of regions and h is the number of provinces; $h_i(h_j)$ is the number of provinces in $i(j)$ region; $y_{ji}(y_{hr})$ is the construction industry carbon emissions of province $h(r)$ in region $j(i)$; μ is the mean value of construction industry carbon emissions of each province; D_{jh} is the relative impact of construction industry carbon emissions of region i and region j.

3 Measurement and analysis of carbon emissions of construction industry in provinces of China

In this study, we comprehensively considered the carbon emissions from direct energy consumption of the construction industry and the carbon emissions from the use of five major building materials to calculate the carbon emissions from the construction industry in provinces of China. According to the eastern, central and western regions, we calculated the average carbon emissions of the construction industry in each region and listed the carbon emission values of the construction industry in each province and region in Table 1.

Table 1 Carbon emissions of some construction industries in each province from 2005 to 2022 (10^4 t)

Province	Year					Province	Year				
	2005	2009	2013	2017	2022		2005	2009	2013	2017	2022
Beijing	4 138	5 539	6 618	7 688	10 119	Hubei	4 729	9 396	42 329	36 038	29 294
Tianjin	1 424	3 008	7 340	4 375	4 945	Hunan	4 026	6 752	10 232	19 444	21 420
Hebei	5 038	6 682	23 864	14197	15 672	Inner Mongolia	1 012	2 613	2 865	3 337	1 286
Liaoning	3 225	9 680	21 385	4 691	3 719	Guangxi	1 401	2 034	6 604	10 028	10 863
Shanghai	3 752	4 498	5 483	5 840	63 450	Chongqing	1 946	4 891	10 019	11 910	11 164
Jiangsu	10 388	20 064	38 361	40 259	50 066	Sichuan	3 513	6 773	28 143	30 691	50 304
Zhejiang	15 822	25 071	47 870	55 978	42 229	Guizhou	812	2 709	6 197	6 573	14 486
Fujian	3 463	6 758	16 501	30 789	49 304	Yunnan	1 276	2 350	13 518	6 416	8 346
Shandong	6 207	12 147	16 313	16 355	14 317	Shaanxi	2 038	4 910	7 352	10 785	24 367
Guangdong	6 759	8 851	14 802	16 706	29 620	Gansu	959	1 452	3 636	2 841	2 274
Hainan	727	526	1 527	712	915	Qinghai	181	496	611	741	815
Shanxi	2 999	4 225	4 682	5 185	7 395	Ningxia	291	588	1 607	922	1 151
Jilin	1 062	2 056	12 352	3 018	3 133	Xinjiang	793	1 342	2 983	2 346	8 354
Heilongjiang	1 105	1 712	3 767	2 231	1 984	Eastern	5 540	9 348	18 188	17 963	25 850
Anhui	2 655	4 878	10 015	14 166	31 796	Central	2 687	4 876	12 796	14 694	15 856
Jiangxi	1 607	2 651	7 152	14 214	15 741	Western	1 293	2 742	7 594	7 872	12 128
Henan	3 316	7 338	11 839	23 253	16 087	Whole country	3 222	5 733	12 866	13 391	18 154

Table 1 indicates that from 2005 to 2022, the average carbon emissions of China's construction industry showed an upward trend, with a significant increase in 2022 compared with 2005, with an average annual growth rate of 10.7%. From the provincial level, the carbon emissions of construction industry in different provinces are quite different. Taking 2022 as an example, the provinces with relatively high carbon emissions in construction industry, such as Shanghai, Jiangsu, Zhejiang, Fujian and Sichuan, are mostly located in the eastern region, with only two provinces in the central region, Anhui and Hubei, and only Sichuan in the western region. In addition, during the observation period, there are also great differences among provinces and cities in the three regions. Taking the carbon emissions of the construction industry in the eastern region in 2022 as an example, the carbon emissions of the construction industry in Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong and other economically developed coastal cities are much higher than those in other provinces in the same region.

Fig. 1 shows the evolution trend of the average carbon emissions of the construction industry in China and the three regions from 2005 to 2022. It can be seen that during the observation period, the average carbon emissions of the construction industry in the eastern region are higher than those in the whole country, as well as in the central and western regions. Before 2012, the average carbon emission of construction industry in the central region was slightly lower than national average level, and in 2012 and most years after that, the average carbon emission of construction industry in the central region was slightly higher than national level, and the average carbon emission of construction industry in the central region was higher than that in the western region, which are mainly related to the market environment of regional construction industry, the overall level of economic development, the level of infrastructure construction and other internal and external factors. From the perspective of its change process, the overall trend of the average carbon emissions of the national construction industry shows a trend of "rise-fall-rise-fall-rise", with a faster growth rate before 2012 and a lower growth rate after 2012, with the highest value of 194.74 million t in 2019; the overall trend of the eastern region is similar to that of the whole country, while the central region shows a fluctuating trend of "rise-fall-rise-fall-rise-decline", and the average carbon emissions of the construction industry fluctuate greatly from 2011 to 2015; the average carbon emissions of the construction industry in the western region showed an upward trend before 2012, a fluctuating and stable trend from 2012 to 2017, and then an increasing trend. The average carbon emission of the construction industry in the eastern region is much higher than national average level in the same period, while that in the western region is much lower than national average level, and the difference between the western and eastern regions is the largest and shows the evolution trend of expansion-reduction-expansion, while the central region is the closest to the national average level.

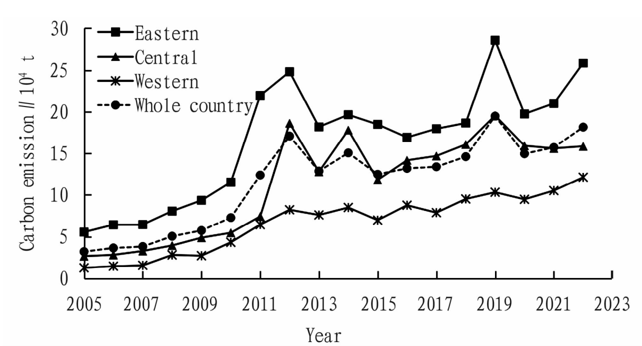

Fig. 1 Average trend of carbon emissions of construction industry in China's provinces from 2005 to 2022

4 Regional differences and decomposition of carbon emissions in China's construction industry

In order to explore the regional disparity of carbon emissions in China's construction industry, we used the Dagum Gini coefficient decomposition method to decompose the regional disparity of carbon emissions in the construction industry into the intra-regional differences in the eastern, central and western regions, the inter-regional differences in the east-central, east-western and central-western regions, and the hyperbolic density (Table 2). During the observation period, the average Gini coefficient of carbon emissions in China's construction industry was 0.495, which increased from 0.470 in 2005 to 0.507 in 2022, with an average annual growth rate of 0.45%. From the perspective of change trend, the carbon emissions of China's construction industry show a trend of "first falling, then rising, then falling and then stabilizing", reaching the minimum in 2008 (0.454), then rising to the maximum in 2012 (0.579), then falling sharply to 0.471 in 2013, and finally tending to be flat in 2014 – 2022, fluctuating around 0.490. These reflect that the regional gap of carbon emissions in China's construction industry presents a trend of first narrowing, expanding, narrowing and relatively stable development, and that there is a problem of unbalanced regional development of carbon emissions in China's construction industry.

Among the regional differences, the western provinces have the largest gap in carbon emissions of the construction industry, with an average Gini coefficient of 0.465, followed by the eastern (0.442) and the central (0.357). From the perspective of change trend, the Gini coefficient of the eastern, central and western regions increased by 18.23%, 41.35% and 48.91% respectively during the investigation period, which means that the regional gap is widening. The change of Gini coefficient in the eastern region showed a trend of "first slowly rising and falling, then sharply rising and falling, then rapidly rising and slowly falling", reaching the maximum in 2011 (0.538) and then sharply falling to the minimum in 2014 (0.372). During the investigation period, the Gini coefficient in the central region fluctuated gently at first, then rose sharply, then declined, and finally rose slowly, with the minimum value (0.266) in 2005 and the maximum value (0.544) in 2012; during the investigation period, the Gini coefficient in the western region showed a trend of "first rising, then falling and then rising", reaching a maximum of 0.568 in 2012.

Among the regional differences, the average Gini coefficient of eastern and western provinces is the largest (0.521), followed by central and western provinces (0.449) and eastern and central (0.447), indicating that the gap between eastern and western provinces is the largest. From the perspective of change trend, the Gini coefficient of eastern and central, eastern and western and central and western all showed a downward trend during the investigation period, with a fall of 16.46%, 3.31% and 31.10%, respectively, indicating that the gap between regions was narrowing during the investigation period, and the gap between central and western regions was narrowing most significantly. However, there is still an imbalance in carbon emissions in the construction industry among regions.

From the perspective of difference source and contribution rate, the carbon emission gap of China's construction industry mainly comes from the gap between regions, with an average contribution rate of 44.145%, but the contribution rate of the gap between regions generally shows a fluctuating downward trend, from

65.167% in 2005 to 34.608% in 2022. The regional gap increased slowly from 26.455% in 2005 to 31.418% in 2022, while the hyperbolic density increased rapidly from 8.379% in 2005 to 33.974% in 2022, and the contribution rate to the regional difference of carbon emissions in the construction industry increased significantly.

Table 2 Dagum Gini coefficient and difference decomposition of carbon emissions in China's construction industry from 2005 to 2022

Year	Difference source and contribution rate // %			Dagum Gini coefficient						
	Intra-regional	Inter-regional	Hyperbolic density	Overall	Eastern	Central	Western	Eastern-central	Eastern-western	Central-western
2005	26.455	65.167	8.379	0.470	0.384	0.266	0.366	0.395	0.514	0.373
2006	26.922	63.119	9.960	0.497	0.418	0.302	0.337	0.441	0.532	0.368
2007	27.721	60.524	11.756	0.487	0.418	0.310	0.384	0.423	0.528	0.401
2008	30.250	53.023	16.727	0.454	0.431	0.271	0.393	0.427	0.490	0.349
2009	28.307	58.623	13.070	0.456	0.397	0.299	0.376	0.404	0.494	0.371
2010	29.151	47.726	23.122	0.482	0.396	0.272	0.518	0.416	0.513	0.437
2011	30.896	51.212	17.892	0.569	0.538	0.271	0.516	0.541	0.604	0.429
2012	30.031	38.994	30.974	0.579	0.485	0.544	0.568	0.525	0.583	0.591
2013	30.229	40.587	29.185	0.471	0.404	0.394	0.476	0.425	0.488	0.459
2014	29.126	35.204	35.670	0.488	0.372	0.500	0.462	0.443	0.468	0.524
2015	30.418	44.706	24.876	0.479	0.437	0.395	0.429	0.445	0.500	0.437
2016	32.144	29.359	38.498	0.489	0.468	0.444	0.477	0.466	0.501	0.480
2017	31.279	34.519	34.202	0.507	0.486	0.405	0.497	0.465	0.535	0.489
2018	31.637	28.879	39.484	0.503	0.492	0.391	0.502	0.469	0.528	0.480
2019	30.065	43.648	26.287	0.499	0.462	0.313	0.512	0.433	0.544	0.464
2020	30.681	32.704	36.615	0.488	0.463	0.334	0.494	0.440	0.518	0.463
2021	31.271	32.007	36.722	0.484	0.447	0.335	0.525	0.432	0.513	0.471
2022	31.418	34.608	33.974	0.507	0.454	0.376	0.545	0.460	0.531	0.489
Mean	29.889	44.145	25.966	0.495	0.442	0.357	0.465	0.447	0.521	0.449

5 Conclusions and implications

In this study, we employed the IPCC carbon emission factor accounting method and the direct and indirect method to calculate the carbon emissions of the provincial construction industry in China, and on this basis, we applied Dagum Gini coefficient and decomposition method to scientifically calculate and decompose the relative differences of carbon emissions of the construction industry. The results show that the average carbon emissions of construction industry in China take on an upward trend, and the carbon emissions of construction industry in different provinces are quite different, and the average carbon emissions of construction industry in the eastern region are higher than those in the whole country, as well as in the central and western regions. From the perspective of regional differences, the overall Gini coefficient of carbon emissions in China's construction industry is 0.495, showing a trend of "first falling, then rising, then falling and then stabilizing", and there is a certain degree of insufficient regional development imbalance. In the regional gap, the western region has the largest gap in carbon emissions of the construction industry, followed by the eastern and central regions, and the regional gap of the three regions is expanding. In the inter-regional gap, the average Gini coefficient between the eastern and western regions is the largest, the gap between the eastern and central regions and the gap between the central and western regions are significantly reduced, while the gap between the eastern and western regions is slightly reduced. From the perspective of difference source and contribution rate, the carbon emission gap of construction industry in China mainly comes from the gap between regions, with an average contribution rate of 44.145%, but the contribution rate of the gap between regions generally shows a fluctuating downward trend, while the contribution rate of hyperbolic density is increasing, and the contribution rate of regional differences is small. In the process of energy saving and emission reduction in the construction industry in the future, on the one hand, we should promote the clean energy consumption in the construction industry, on the other hand, we should develop new energy-saving building materials to replace the production and use of traditional high-energy-consuming building materials, and finally, we should formulate energy-saving and emission reduction targets and strategies that are compatible with the actual situation of the region.

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vegetation with abundant self-growing flowering wild plants[7]. The lawn is not fertilized or watered, and is irregularly pruned once every autumn, the grass clippings are left in the lawn after pruning, chemical fertilizers and pesticides are not used[8], and the lawn is not pruned in spring and summer, so that a large number of dicotyledonous plant species in the lawn will blossom. It is recommended to increase the diversity of spontaneous plants in lawns, to provide food and shelter for insects, amphibians and birds, and as well as a pleasant sensory experience for people.

3.4.3 Using self-growing grasses and wild flowers to form natural grassland. Lawn originated from natural grazing grassland. The use of self-growing grasses and annual and perennial broadleaf flowering wildflowers forms a stable natural community[9], presenting a natural grassland with advantages in terms of maintenance, aesthetics and biodiversity[10]. It is suggested that the natural grassland landscape should be constructed with low intervention. For example, malignant invasive plants such as *Erigeron annuus*, *Alternanthera philoxeroides* and *Lepidium virginicum* in natural grassland should be found and removed in time, and protect native self-growing grasses and wild flower in that natural grassland to the maximum extent. The natural grassland is covered with green grass, various wild flowers alternate, natural regeneration, and extensive management, which not only shows different landscape effects, but also is more conducive to maintaining the sustainable ecological community of urban biodiversity.

4 Conclusions

The biodiversity of urban spontaneous plants is an important part of urban ecosystem. The spontaneous plants in the lawn not only improve the biodiversity of the lawn, but also provide food and shelter for insects, amphibians and birds, and provide pleasant sensory experience for people. We investigated the spontaneous plants in eight different types of parks in Hangzhou by field survey. A total of 89 species of 27 families of spontaneous plants were found in Hangzhou urban parks, of which Asteraceae, Fabaceae and Poaceae were the dominant families. The life forms are mainly perennial herbs, and the growth forms are mostly erect. According to the screening criteria, 20 spontaneous plants, such as *Ranunculus sieboldii*, *Taraxacum mongolicum* and *Corydalis decumbens*, are recommended for potential exploitation. According to the spontaneous plants of lawn, we put forward three application models, which were ornamental lawn, semi-natural succession of lawn and natural grassland.

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