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Carbon footprint of different industrial spaces based on energy consumption in China

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Abstract: Using energy consumption and land use data of each region of China in 2007, this paper established carbon emission and carbon footprint model based on energy consumption, and estimated the carbon emission amount of fossil energy and rural biomass energy of different regions of China in 2007. Through matching the energy consumption items with industrial spaces, this paper divided industrial spaces into five types: agricultural space, living & industrial-commercial space, transportation industrial space, fishery and water conservancy space, and other industrial space. Then the author analyzed the carbon emission intensity and carbon footprint of each industrial space. Finally, advices of decreasing industrial carbon footprint and optimizing industrial space pattern were put forward. The main conclusions are as following: (1) Total amount of carbon emission from energy consumption of China in 2007 was about 1.65 GtC, in which the proportion of carbon emission from fossil energy was 89%. (2) Carbon emission intensity of industrial space of China in 2007 was 1.98 t/hm^2, in which, carbon emission intensity of living & industrial-commercial space and of transportation industrial space was 55.16 t/hm^2 and 49.65 t/hm^2 respectively, they were high-carbon-emission industrial spaces among others. (3) Carbon footprint caused by industrial activities of China in 2007 was 522.34×10^6 hm^2, which brought about ecological deficit of 28.69×10^6 hm^2, which means that the productive lands were not sufficient to compensate for carbon footprint of industrial activities, and the compensating rate was 94.5%. As to the regional carbon footprint, several regions have ecological profit while others have not. In general, the present ecological deficit caused by industrial activities was small in 2007. (4) Per unit area carbon footprint of industrial space in China was about 0.63 hm^2/hm^2 in 2007, in which that of living & industrial-commercial space was the highest (17.5 hm^2/hm^2). The per unit area carbon footprint of different industrial spaces all presented a declining trend from east to west of China.

Keywords: industrial space; carbon footprint; carbon emission intensity; energy consumption; China

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1 Introduction

Issues of global warming and greenhouse gas emissions are increasingly becoming one of the major technological as well as important social and political challenges. They are closely related to energy generation and use (Pierucci, 2008). Anthropogenic carbon emission from traditional fossil-fuel energy consumption is one of the main causes of global warming. To explore the impact of human activities on global carbon cycle, carbon emission caused by economic development and energy consumption has become the major concern and a "hot spot" in academic circles (Soytasa *et al*., 2007; Qi *et al*., 2004; Zhang, 2006; Liu *et al*., 2002; Zhu *et al*., 2009).

1.1 Researches on carbon emissions from industrial activities

In essence, the impact of human economic and energy activities on regional carbon cycle is largely achieved by changing the industrial space pattern. The alteration of industrial space structure and the regional differences will change the pattern of human energy consumption, and further affect the rate of regional carbon cycle. Therefore, industrial activities and the carbon emission effects have also become the concern of scholars at home and abroad. For example, Schipper *et al*. (2001) analyzed the carbon emission intensity of 9 manufacturing sectors of 13 IEA countries using factor decomposition method, which explained the main reasons for growth in carbon emissions since 1990 and made evaluations combined with the targets of Kyoto Protocol; Chang *et al*. (1998) studied the industrial carbon emission and its structural decomposition of Taiwan based on the input-output approach. Casler *et al*. (1998) used model method to analyze the structure of U.S. carbon emissions, which maintained that the use of alternative energy was the major factor causing carbon emission decline. Chen *et al*. (2009) analyzed the embodied carbon emissions from final consumption and industrial process of all industrial sectors in China based on input-output analysis. Yu *et al*. (2009) and Wei *et al*. (2009) used input-output analysis to compare the carbon leakage and transfer of different industries in the study of carbon emissions embodied in international trade. In addition, some scholars carried out researches on the relationship between different industries and carbon emissions (Zhang, 2005; Tan *et al*., 2008).

Based on the study of carbon emission, the study on low-carbon economy and its relationship with energy consumption also became a hot topic. Kawase R (2006) used an improved kaya identity to study factor decomposition on carbon emissions, and carried out scenario forecast on carbon emission reduction targets of different countries; Shimada K (2007) established a future regional scale, low-carbon economic scenario analysis method; Zhuang Guiyang (2005, 2007) analyzed the possible paths and potential for low-carbon development in China's economy. Gomi K (2010) studied carbon emission and the future low-carbon economic development of Tokyo City using scenario analysis method.

The above studies provide important theoretical references to low-carbon economic planning based on industrial carbon emission reduction. However, most of these studies focused on the impact of industrial structure on carbon emissions, without considering carbon emission intensity and its discrepancy of different industrial spaces. Industrial activity is always associated with a certain space. Therefore, to implement carbon emission of industrial activities on different spaces will be of great importance for analyzing and comparing per space carbon emission intensity of different industrial activities, and further taking reasonable measures of industry regulation and space pattern optimization to finally reduce regional carbon emissions.

1.2 Researches on carbon footprint

Carbon footprint was put forward based on the concept of ecological footprint; it is the measure of the amount of direct or indirect CO_2 emissions caused by an activity (or accumulation of a product in life cycle) (Wiedmann *et al*., 2007). There are two views on the comprehension of carbon footprint: one defines it as carbon emission of human activities (Wiedmann *et al*., 2007; BP, 2006; Energetics), that is to measure it with emission amount; the other one regards carbon footprint as part of ecological footprint: that is the ecological carrying capacity required in absorbing CO_2 emission from fossil fuel combustion (Wiedmann *et al*., 2007; Global Footprint Network), which measures in area.

As the measurement of impact and pressure of human activities on the environment, carbon footprint has become the new focus in the field of ecology in recent years. Such as "Living Planet Report" (World Wildlife Fund, 2008) in calculating ecological footprint, carbon footprint as a separate category includes not only the direct carbon emissions caused by fossil fuel combustion, but also indirect carbon emissions brought by foreign imports. The results showed that the global ecological footprint per capita was 2.7 hm^2, in which carbon footprint was 1.41 hm^2, which demonstrated that carbon footprint was an important factor causing human ecological impact; Sovacool *et al*. (2010) carried out an assessment and analysis on twelve metropolitan carbon footprints and put forward policy proposals to reduce carbon footprint; Kenny *et al*. (2009) compared and analyzed the performance of six carbon footprint models for use in Ireland. Schulz (2010) took Singapore as the case, studied the direct and indirect greenhouse gas emission footprint of a small and open economic system, he thought that indirect pressures of urban systems should be included in discussions of effective and fair adaptation and mitigation strategies. Some Chinese scholars carried out beneficial exploration on carbon footprint studies from the angle of carbon footprint accounting (Huang *et al*., 2009), carbon footprint per capita and carbon footprint products (Guo, 2009), the infection and inductivity of carbon footprint (Lai *et al*., 2006), etc. Overall, carbon footprint research is still in its early days and further development is needed, especially in the field of regional differences in carbon footprint of various human energy activities.

1.3 The aim and meaning of this paper

From the above studies, we can see that in order to combine the study on industrial carbon emission and carbon footprint, in the study of energy carbon emissions, not only carbon emission from industrial activities should be considered, but also the analysis on carbon emission intensity of different industrial spaces and its carbon footprint effects are needed. From the point of view of industrial spaces, this paper established carbon emission model based on energy consumption. Through matching industrial spaces with energy consumption items, we studied carbon emission intensity of different industrial spaces and regional differences of carbon footprint. Finally, advices of decreasing industrial carbon footprint and optimizing industrial space pattern were put forward.

2 Data and methods

2.1 Data sources

At present the main sources of energy are fossil energy, electricity, biomass, solar, hydraulic, wind and nuclear energy, and traditional energy, in which fossil energy is the representative, is the main cause of carbon emissions. Thus this paper only calculated the carbon emissions from major traditional high-carbon energy sources, including fossil energy and rural biomass energy. Industrial energy consumption, land use data, crop yield, output value of farming, forestry, animal husbandry and fishery of various provinces, municipalities and autonomous regions in China by 2007 were adopted. Among them, energy consumption data are from "China Energy Statistical Yearbook", the land use data, crop yield, sown area, output value and other data are from "China Statistical Yearbook", and the standard coal consumption of electricity supply is from CEINET industry database. Due to the lack of relevant data in Tibet Autonomous Region, Taiwan Province, Hong Kong and Macao Special Administrative Regions, all data sources and results in this paper did not include these areas.

2.2 Carbon emission from energy consumption

By establishing energy carbon emission model to calculate the annual carbon emission from major energy consumption in various provinces, municipalities and autonomous regions (Formula 1):

$$Ct = \sum (Ch + Cb) \tag{1}$$

where Ct is the total amount of carbon emissions; Ch is the carbon emission from fossil energy consumption; and Cb is the carbon emission from rural biomass energy consumption. The method is as follows:

$$Ch = \sum Qh_i \times NCV_i \times \left(Cf_i \times \frac{1}{1000} \times \frac{12}{44} + Mf_i \times \frac{1}{1000} \times \frac{12}{16} \right) \tag{2}$$

where Ch is the total amount of carbon emission from fossil energy consumption; Qh_i is the fossil energy consumption type i; NCV_i the net calorific value of energy; Cf_i is the default CO_2 emission factor; Mf_i the default CH_4 emission factors. Given values of NCV_i, Cf_i and Mf_i from IPCC are used. 1/1000 is the unit conversion coefficient, 12/44 and 12/16 are the conversion coefficients of carbon content in CO_2 and CH_4 respectively. $Cf_i = A_i \times B_i$, A_i is the default carbon content; B_i the default carbon oxide factor.

$$Cb = \sum Qb_i \times Db_i \times Eb_i \tag{3}$$

where Cb is the carbon emission from rural biomass energy consumption; Qb_i the energy consumption type i (firewood, biogas and straw); Db_i the carbon emission coefficient; the average of coal carbon emission coefficient from domestic scholars is adopted here (Table 1); Eb_i is the standard coal coefficient.

Table 1 Transfer coefficient of carbon emission (tC/t)

Item	Carbon emission coefficient (tC/t)								
Carbon emission coefficient	0.702	0.756	0.726	0.7476	0.7329	0.651	0.703	0.7193837	0.717235
Source	Wang Gang (2006)	Wang Gang (2006)	Wang Gang (2006)	Xu Guoquan (2006)	Tan Dan (2008)	Gao Shuting (1994)	Wang Xuena (2006)	He Jienan/ORNL (2008;1990)	This paper (average)

2.3 Carbon emission intensity of different industrial spaces

In order to calculate carbon emission and carbon footprint of different industrial spaces, based on energy consumption items of Energy Balance Table and land use classification system, we cited the study of Li (2009) as a reference, and on the basis of merger, decomposition and appropriate adjustments, we established the corresponding relationship between different industrial spaces and carbon emission items (Table 2). Be noted that: (1) the industrial space here not only means the industry itself, but also refers to the spatial extent of industrial activities sustained by land; (2) carbon emission of different industries were merged in order to combine the divided industrial spaces with land use data, and carbon emission per space was calculated; (3) living & industrial-commercial space mainly refers to human living and production space or human resident space; (4) given that rural energy use is mainly centralized in the rural residential areas, thus its carbon emission was incorporated into living & industrial-commercial space; (5) other sectors in the Energy Balance Table can not be easily subdivided further, thus incorporated into other industrial space; (6) agriculture, forestry and animal husbandry are mainly for carbon absorption with little human carbon emission, thus incorporated into agricultural space. Carbon emission intensity of industrial space is calculated as follows:

$$Cp_i = Ct_i/S_i \tag{4}$$

$$Cp = \sum Ct_i / \sum S_i \tag{5}$$

where Cp is the carbon emission intensity of provincial industrial space; Cp_i is the carbon emission intensity of various industrial spaces (t/hm^2); i is the different types of industrial space; S_i is the type i industrial space land area; Ct_i is the type i carbon emission amount.

Table 2 The corresponding relationship between industrial spaces and carbon emission items

<table>
<tr><th>Industrial spaces division</th><th>Land use type</th><th colspan="2">(Energy Balance Table) Energy consumption items</th></tr>
<tr><td rowspan="3">Living & industrial-commercial space</td><td>Urban built-up land</td><td colspan="2">Construction
Wholesale and retail, hotels and catering service
Urban residential consumption</td></tr>
<tr><td>Rural settlements</td><td colspan="2">Rural residential consumption</td></tr>
<tr><td>Independent mining land</td><td colspan="2">Industry</td></tr>
<tr><td>Transportation industrial space</td><td>Transportation land</td><td colspan="2">Transport, storage, postal & telecommunications services</td></tr>
<tr><td rowspan="3">Agricultural space</td><td>Cultivated land
Garden land</td><td>Farming</td><td rowspan="5">Farming, forestry, animal husbandry, fishery and water conservancy</td></tr>
<tr><td>Wood land</td><td>Forestry</td></tr>
<tr><td>Grassland</td><td>Animal husbandry</td></tr>
<tr><td rowspan="2">Fishery and water conservancy space</td><td>Water body</td><td>Fishery</td></tr>
<tr><td>Water conservancy infrastructure</td><td>Water conservancy</td></tr>
<tr><td>Other industrial space</td><td>Unused land
Special use land</td><td colspan="2">Other</td></tr>
</table>

2.4 Carbon footprint of different industrial spaces

In this paper, carbon footprint is defined as the productive land (vegetation) area needed in absorbing carbon emissions, which means the ecological footprint of carbon emissions. Since the energy carbon emission calculation includes the carbon emissions from rural biomass energy, thus here agricultural vegetation was regarded as part of the carbon footprint. NEP reflects the carbon fixation capacity of vegetation, that is to say the carbon absorption amount of per hectare vegetation per year (Xie *et al*., 2008). In this paper, NEP indicators were adopted to reflect the carbon absorption of different vegetation, and further calculated the area of productive land needed in absorbing carbon emissions (carbon footprint). The method is as follows:

$$CF = Ct \times \left(\frac{P_f}{NEP_f} + \frac{p_g}{NEP_g} + \frac{P_a}{NEP_a} \right) \tag{6}$$

where CF is the carbon footprint (hm^2) brought by the total amount of carbon emissions (Ct); P_f, P_g and P_a are the total carbon absorption proportion of forest, grassland and farmland respectively; NEP_f, NEP_g and NEP_a are the NEP of forest, grassland and farmland respectively. Here employed the NEP results of forest and grassland of Xie *et al*. (2008). The NEP of farmland was calculated as follows:

$$NEP_a = C_S / S = \sum_i C_d / s \tag{7}$$

where i is the crop type i; C_S is the total carbon absorption of crop during growth period; S is the cultivated land area; C_d is the carbon absorption of certain crop during whole growth period; $C_d = C_aD_w = C_aY_w/H$, C_a is the carbon absorption rate; Y_w is the economic output; D_w is the biological yield; H is the economic coefficient. The economic coefficients and carbon absorption rates of China's main crops can be seen in reference (Li, 2000; Zhao *et al*., 2007).

Based on the analysis of total carbon footprint, per unit area carbon footprint of different industrial spaces can be obtained by carbon footprint of certain industrial space divided by the corresponding industrial space land area.

3 Results and discussion

3.1 Results analysis

(1) Total amount of carbon emission from energy consumption of China in 2007 was about 1.65 GtC (1 Gt = 10^9 t), in which the carbon emissions from fossil energy and rural biomass energy consumption were 1.46 GtC and 0.19GtC respectively and the proportions were 89% and 11%. The largest amount of regional carbon emission was in Hebei Province (0.14 GtC). The regions in which total carbon emission amount exceeding 100 MtC (1Mt = 10^6 t) were Shandong, Liaoning and Henan provinces, mainly associated with the high energy consumption of these regions; the smallest amount was in Hainan Province, being only 4.85 MtC. In addition, the carbon emission amount in western China, such as Qinghai and Ningxia, was also relatively small (Figure 1).

There were differences in carbon emission constitution in various regions of China. Overall, regional carbon emission was mainly constituted of carbon emission from fossil energy. However, carbon emission from fossil energy occupied a large proportion in eastern China, mostly above 90%, while in western China carbon emission from rural biomass energy held

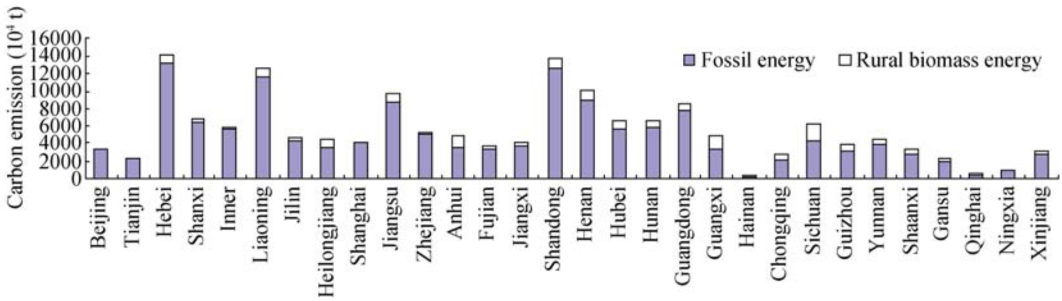


Figure 1 Carbon emission from energy consumption of different regions

a relatively large proportion, in which Guangxi and Sichuan even reached 30%. This was mainly related to the different energy consumption structure of different regions, for that in western China the proportion of rural energy use was relatively high.

(2) Among the five industrial spaces, the carbon emission of living & industrial-commercial space was the highest, for 1.47 GtC, which accounted for nearly 90% of the total carbon emissions, followed by that of transportation industrial space accounting for 7.3%. Carbon emission amount of other types of industry was relatively small (Table 3). It demonstrated that energy consumption was mainly concentrated in the fields of production, living and transportation.

There were significant regional differences in the constitution of carbon emission of industrial spaces. In general, the carbon emissions of most regions were mainly constituted of carbon emission of living, production and transportation industrial space. The carbon emission proportion of living & industrial-commercial space in central and western China was higher than that in some developed provinces of eastern China. For instance, the proportions of Henan, Anhui, Hebei, Jiangxi and Shanxi provinces were all more than 93%, and that of Hebei was even as high as 95.7%; the proportions of Beijing and Shanghai were relatively low, which were 75.1% and 69.4% respectively. It indicated that the energy consumption of production, living and industry and mining was higher in central and western China than that in eastern China. The carbon emission proportion of transportation industrial space in the developed Beijing and Shanghai was high, 24.6% for Shanghai, while that in central and western China was low, only 2.8% for Hebei. This demonstrated that in the developed, transportation and population concentrated areas, due to the development and concentration of transportation industries, with limited industrial space, the carbon emission intensity was relatively high.

Table 3 Carbon emission of different industrial spaces

Industrial space	Carbon emission		Land area (10^6 hm^2)	Carbon emission intensity of industrial space (t/hm^2)
	Total (10^6 t)	%		
Agricultural space	30.74	1.87	505.46	0.06
Living & industrial-commercial space	1467.54	89.12	26.61	55.16
Transportation industrial space	120.19	7.30	2.42	49.65
Fishery and water conservancy space	3.18	0.19	36.80	0.09
Other industrial space	25.11	1.52	259.20	0.10
Total	1646.77	100	830.49	1.98

(3) Carbon emission intensity of industrial spaces of China in 2007 was 1.98 t/hm^2, in which, carbon emission intensity of living & industrial-commercial space and transportation industrial space were 55.16 t/hm^2 and 49.65 t/hm^2 respectively. The carbon emission intensity of other three types of industrial space was lower, with that of agricultural space only 0.06 t/hm^2 (Table 3). There were large regional differences in carbon emission intensity of industrial spaces. Generally the carbon emission intensity of central and eastern China was significantly higher than that of the western region. The highest was in Shanghai for 49.68 t/hm^2, the lowest in Qinghai for 0.083 t/hm^2, a difference of nearly 600 times (Figure 2). In addition, the carbon emission intensity of living & industrial-commercial space, transportation industrial space, other industrial space and agricultural space of Shanghai were 128.01 t/hm^2, 521.79 t/hm^2, 41.43 t/hm^2 and 0.95 t/hm^2 respectively, all of which were the highest of the country. It demonstrated that Shanghai had high carbon emissions while the land resources of various types of space were scarce and intense, resulting in high carbon emission intensity and carbon density. Furthermore, various types of industrial spaces of Beijing, Tianjin, Jiangsu and Zhejiang also had high carbon emission intensity.

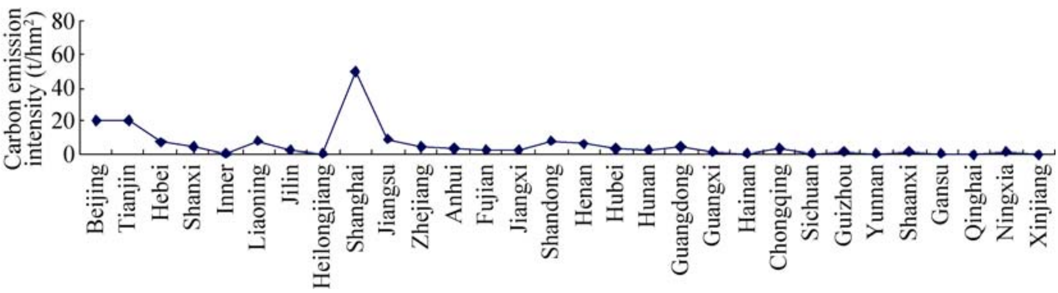


Figure 2 Carbon emission intensity of industrial spaces in different regions

(4) Carbon footprint caused by industrial activities of China in 2007 was 522.34×10^6 hm^2, while the area of productive land was only 493.65×10^6 hm^2, which brought about ecological deficit of 28.69×10^6 hm^2 (Table 4), equivalent to 3.46% of the country's total land area. It meant that the productive land area was not sufficient to compensate carbon footprint of industrial spaces, and the compensating rate was 94.5%. The primary reason was that in 2007 China's carbon emission from energy consumption evidently exceeded the carbon absorption of productive land. The results also showed that: based on the fact that the calculation in this paper included the carbon absorption of farmland, although there was carbon deficit of industrial activities in China, the deficit was not large, thus generally the most part of annual carbon emission from energy consumption of industrial activities can be absorbed by the country's productive land.

As to various regions, the carbon footprint of Hebei Province was the largest for 44.71×10^6 hm^2, the smallest was that of Hainan Province, with only 1.54×10^6 hm^2 (Figure 3). Regional difference in the carbon footprint was basically in accordance with that of carbon emission from energy consumption (Figure 1). Moreover, due to the large differences in productive land area of various regions, the ecological deficit varied significantly. The ecological deficit of Hebei was the highest, which reached 34.31×10^6 hm^2. Shandong, Liaoning, Jiangsu, Henan and Guangdong provinces also had high ecological deficit. Some regions

Table 4 Main results of different industrial spaces

Industrial space	Carbon footprint (10^6 hm^2)	Productive land area (10^6 hm^2)	Ecological deficit (10^6 hm^2)	Land area (10^6 hm^2)	Per unit area carbon footprint (hm^2/hm^2)
Agricultural space	9.75	–	–	505.46	0.02
Living & industrial-commercial space	465.49	–	–	26.61	17.50
Transportation industrial space	38.12	–	–	2.42	15.75
Fishery and water conservancy space	1.01	–	–	36.80	0.03
Other industrial space	7.96	–	–	259.20	0.03
Total	522.34	493.65	28.69	830.49	0.63

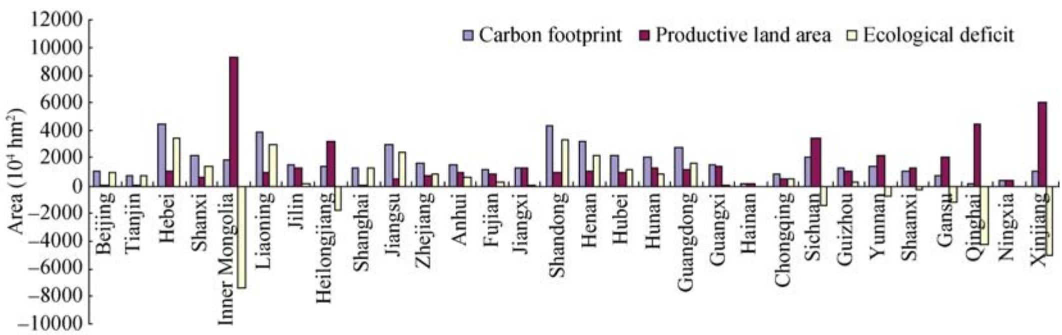


Figure 3 Carbon footprint and ecological deficit of industrial activity in different regions

which possessed large area of productive land had ecological profit (the ecological deficit is negative), such as Inner Mongolia, Heilongjiang, Qinghai, Xinjiang, Sichuan, Gansu and Yunnan provinces, among which Inner Mongolia had the highest ecological profit for 74.34×10^6 hm^2 (Figure 3). The ecological profit was mainly due to the high vegetation coverage of those regions. Therefore, in the provincial level, some regions with low energy consumption and high vegetation coverage can fully compensate for their own carbon emission from energy consumption.

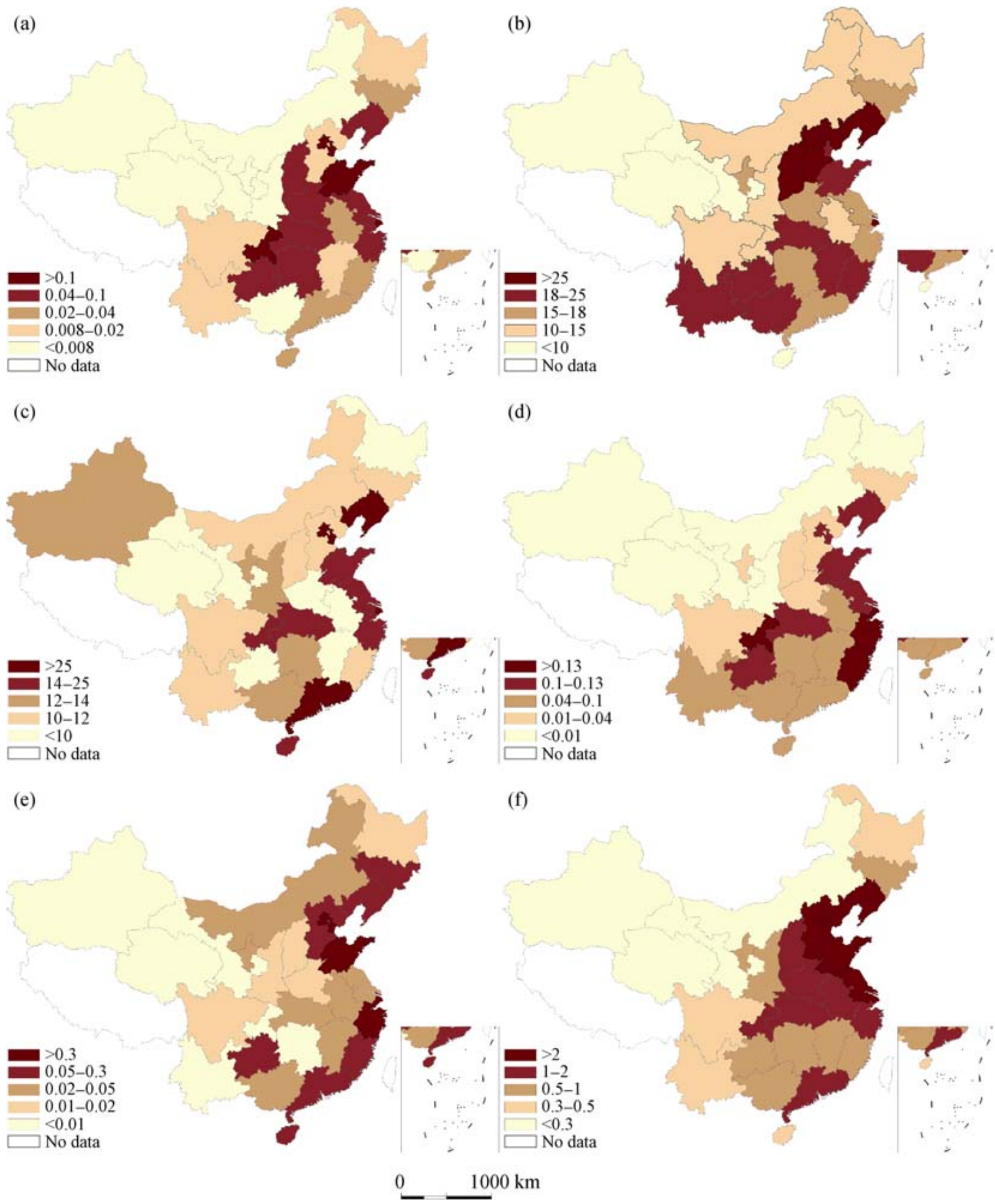
(5) Per unit area carbon footprint of industrial space in China was 0.63 hm^2/hm^2 in 2007. Different industrial spaces had large differences in per unit area carbon footprint, in which living & industrial-commercial space was the highest (17.5 hm^2/hm^2), followed by transportation industrial space (15.75 hm^2/hm^2), agriculture space the least with only 0.02 hm^2/hm^2 (Table 4). Per unit area carbon footprint of different industrial spaces of various provinces and regions varied significantly. Per unit area carbon footprint of industrial space of various provinces and regions presented a declining trend from central and eastern China to the western part (Figure 4f). Per unit area carbon footprint of Shanghai was the largest, up to 15.76 hm^2/hm^2, followed by Tianjin and Beijing, then the North China and the eastern coastal areas with generally above 1 hm^2/hm^2, again followed by South China. Per unit area carbon footprint of the northeastern and western regions was relatively low, of which the lowest was in Qinghai Province with only 0.03 hm^2/hm^2 (Table 5). In addition, the research found that in the 30 provincial administrative units studied in this paper, there were 14 provinces with per unit area carbon footprint greater than 1 hm^2/hm^2, and 16 provinces with per unit area carbon footprint less than 1 hm^2/hm^2. The latter ones included South China, northeast and southwest regions with better ecological environment, and the underdeveloped western regions, indicating that there were about half of the provinces in China in which

Table 5 Sorting of per unit area carbon footprint of different industrial spaces in different regions (hm^2/hm^2)

Rank	Region	Agricultural space	Region	Living & industrial-commercial space	Region	Transportation industrial space	Region	Fishery and water conservancy space	Region	Other industrial space	Region	Industrial space of various regions
	China	0.02	China	17.50	China	15.75	China	0.03	China	0.03	China	0.63
1	Shanghai	0.30	Shanghai	40.60	Shanghai	165.51	Fujian	0.29	Shanghai	13.14	Shanghai	15.76
2	Beijing	0.17	Liaoning	31.12	Beijing	41.43	Zhejiang	0.14	Beijing	2.27	Beijing	6.46
3	Tianjin	0.13	Beijing	28.94	Guangdong	31.21	Chongqing	0.14	Tianjin	2.15	Tianjin	6.44
4	Chongqing	0.11	Hebei	27.89	Tianjin	28.81	Shanghai	0.10	Shandong	0.74	Jiangsu	2.83
5	Shandong	0.11	Shanxi	26.57	Liaoning	27.75	Beijing	0.08	Zhejiang	0.43	Shandong	2.76
6	Jiangsu	0.07	Tianjin	24.79	Shandong	22.46	Shandong	0.08	Jilin	0.25	Liaoning	2.66
7	Zhejiang	0.05	Guizhou	23.65	Hubei	21.95	Hubei	0.07	Liaoning	0.20	Hebei	2.37
8	Guizhou	0.05	Yunnan	20.77	Hainan	21.66	Guizhou	0.06	Fujian	0.20	Henan	1.93
9	Hubei	0.05	Guangxi	20.27	Zhejiang	18.29	Tianjin	0.06	Hebei	0.11	Zhejiang	1.56
10	Hunan	0.05	Fujian	20.01	Chongqing	16.32	Liaoning	0.06	Guizhou	0.08	Guangdong	1.51
11	Shanxi	0.05	Shandong	18.29	Jiangsu	14.27	Jiangsu	0.05	Hainan	0.06	Shanxi	1.38
12	Henan	0.04	Hubei	18.21	Xinjiang	13.90	Guangdong	0.05	Guangdong	0.06	Hubei	1.13
13	Liaoning	0.04	Jiangxi	18.17	Ningxia	13.66	Hainan	0.04	Ningxia	0.04	Anhui	1.12
14	Fujian	0.04	Zhejiang	17.75	Shaanxi	13.28	Yunnan	0.03	Hubei	0.04	Chongqing	1.02
15	Jilin	0.03	Jiangsu	17.65	Hunan	12.62	Hunan	0.03	Inner Mongolia	0.04	Hunan	0.98
16	Guangdong	0.02	Hunan	17.40	Guangxi	12.15	Anhui	0.03	Jiangsu	0.03	Fujian	0.93
17	Anhui	0.02	Henan	16.14	Yunnan	11.93	Jiangxi	0.02	Jiangxi	0.02	Jilin	0.79
18	Hainan	0.02	Guangdong	15.84	Shanxi	11.45	Guangxi	0.01	Guangxi	0.02	Jiangxi	0.78
19	Yunnan	0.02	Jilin	15.75	Jilin	11.19	Sichuan	0.01	Anhui	0.02	Guizhou	0.70
20	Heilongjiang	0.02	Ningxia	15.51	Fujian	10.93	Henan	0.01	Sichuan	0.02	Guangxi	0.66
21	Jiangxi	0.02	Chongqing	14.66	Hebei	10.52	Shanxi	0.00	Shanxi	0.02	Ningxia	0.61
22	Hebei	0.011	Shaanxi	13.46	Sichuan	10.42	Jilin	0.00	Heilongjiang	0.02	Shaanxi	0.51
23	Sichuan	0.010	Sichuan	13.36	Inner Mongolia	10.22	Hebei	0.00	Henan	0.02	Hainan	0.44
24	Shaanxi	0.009	Inner Mongolia	13.32	Henan	9.75	Ningxia	0.003	Shaanxi	0.011	Sichuan	0.41
25	Guangxi	0.008	Heilongjiang	11.04	Guizhou	9.55	Heilongjiang	0.002	Chongqing	0.007	Yunnan	0.38
26	Gansu	0.007	Anhui	11.02	Jiangxi	8.66	Shaanxi	0.002	Qinghai	0.005	Heilongjiang	0.32
27	Xinjiang	0.006	Xinjiang	8.92	Heilongjiang	8.29	Xinjiang	0.002	Yunnan	0.005	Gansu	0.19
28	Ningxia	0.006	Gansu	7.91	Anhui	7.25	Inner Mongolia	0.001	Hunan	0.005	Inner Mongolia	0.17
29	Inner Mongolia	0.004	Qinghai	6.55	Gansu	6.98	Gansu	0.0002	Gansu	0.003	Xinjiang	0.06
30	Qinghai	0.000	Hainan	5.16	Qinghai	4.28	Qinghai	0.000	Xinjiang	0.002	Qinghai	0.03

per unit area carbon footprint of industrial space was less than the area of the region itself.

There were also large regional differences in per unit area carbon footprint of different industrial spaces. Generally per unit area carbon footprint of different industrial spaces all presented a declining trend from east to west of China (Figures 4a–4e). The largest per unit



(a) Carbon footprint of agricultural space (b) Carbon footprint of living & industrial-commercial space
(c) Carbon footprint of transportation industrial space (d) Carbon footprint of fishery and water conservancy space
(e) Carbon footprint of other industrial space (f) Carbon footprint of industrial space of various regions

Figure 4 Distribution of per unit area carbon footprint of different industrial spaces in different regions (hm^2/hm^2)

area carbon footprint of fishery and water conservancy space was that of Fujian Province (0.29 hm^2/hm^2), and the largest per unit area carbon footprint of other types of industrial space was all in Shanghai, in which that of living & industrial-commercial space, transportation industrial space and other industrial space were 40.6 hm^2/hm^2, 165.51 hm^2/hm^2 and

13.14 hm^2/hm^2 respectively. The above values of Shanghai were not only far ahead of the provinces and regions of the country, but also far greater than the national average of various industrial spaces (Table 5). Moreover, in the types of living & industrial-commercial space, transportation industrial space and other industrial space, Beijing, Tianjin and the eastern developed areas also had high carbon footprint intensity. In contrast, in Qinghai, Xinjiang, Inner Mongolia and other western regions and Hainan Province, per unit area carbon footprint of various industrial spaces were all relatively low. Specific results were in Table 5.

The results indicated that, on the one hand the economically developed eastern regions had high energy consumption, resulting in high carbon emissions; on the other hand the eastern regions, especially municipalities with land shortage, due to the industrial space concentration, the carbon emission intensity of various industrial spaces was high, which led to high carbon footprint. Instead, due to the larger land area and less energy consumption, the carbon footprint intensity of various industrial spaces of the western regions was lower. For instance, the lowest of living & industrial-commercial space and transportation industrial space were in Hainan (5.16 hm^2/hm^2) and Qinghai (4.28 hm^2/hm^2) respectively, which were 1/8 and 1/39 of Shanghai (Table 5). The carbon footprint of agriculture space and fishery and water conservancy space in the western regions was even lower. For example in Qinghai Province, since there was little carbon emission from energy consumption of these two types of land, the carbon footprint was almost negligible.

3.2 Discussion

3.2.1 About carbon emission

The carbon emission result of this paper was slightly higher than that of other Chinese scholars in recent years (Table 6). There are two main reasons: First, the carbon emission calculation of this paper included carbon emission from fossil energy and rural biomass energy consumption; the total amount of carbon emission would be 1.46 GtC if we only included that from fossil energy. Second, the calculation of this paper was based on the data of the year 2007, thus it is reasonable that the results had a certain degree of growth compared with those of other researches in 2003–2005 (Table 6).

Compared with the results of abroad, the carbon emission of 2007 in China in this paper (1.647 GtC) was relatively low. For example, the carbon emission of China collected by CDIAC was 1.783 GtC in 2007.

Table 6 Comparison of results with other authors

Author	Carbon emission (GtC)	Year	Reference
Wei Yiming	1.37	2004	Wei *et al.*, 2008
Xiao Lian	1.127	2003	Xiao, 2008
Liu Hongguang	1.13	2004	Liu *et al.*, 2009
Xu Guoquan	1.28	2004	Xu *et al.*, 2006
Liu Qiang	1.505	2005	Liu *et al.*, 2008
Wei Baoren	1.282	2005	Wei, 2007
Chen Qingtai	1.3–2.0	2020	Chen, 2004
CDIAC	1.783	2007	CDIAC, 2010
This paper	1.647	2007	

3.2.2 About carbon footprint

It should be noted that the carbon emission of industrial space of this article placed more weight on the carbon intensity analysis of industrial activities, so as to understand the spatial carbon emission density caused by different industrial activities. Since the land only plays the role of space sustaining, rather than the source of carbon emission, thus carbon emission does not mean the emission from the land itself, but the carbon emission from industrial activities sustained by land.

As to different regions, the large land area of certain industrial space would probably make the result of per unit area carbon footprint of the corresponding industrial space a little too small. For instance, per unit area carbon footprint of Anhui Province was 1.12 hm^2/hm^2, ranking 13th in China, which was at high level; however, due to the relatively large area of living & industrial-commercial space and transportation industrial space, per unit area carbon footprint of the two types of space ranked 26th and 28th in the country. The overall carbon footprint of Xinjiang was low, yet because of the small area of transportation industrial space, per unit area carbon footprint of transportation industrial space in Xinjiang was relatively high, ranking 12th in the country (Table 5). The results indicated that based on the calculation method of carbon footprint of industrial space in this paper, the carbon footprint of regional different industries was affected by the structure of regional industrial land.

3.3 Policy recommendations

In order to reduce regional carbon emission intensity and carbon footprint, the following measures can be considered: (1) the use of fossil energy is the primary reason causing carbon emission. Therefore, to innovate on traditional energy structure and use clean energy, is the main way to reduce regional per unit area carbon emission and carbon footprint. (2) The central and western regions should minimize the energy consumption of living and industry and mining, in particular to reduce the use of rural biomass energy, so as to lower the carbon emission intensity of living & industrial-commercial space; the eastern regions should adopt clean energy in the transportation industry as much as possible, in order to reduce the carbon pollution of transportation sector. (3) To strengthen the ecological management and protection of the regions with ecological profit, and enhance the carbon fixation efficiency of productive land, which can effectively reduce regional carbon emission level and intensity. (4) The key to reduce carbon emission intensity and carbon footprint is to adjust industrial space pattern and regulate the industrial activities (such as construction industry, transportation industry, etc.) of high carbon footprint. (5) To consider carbon footprint effect in the industrial space arrangement and planning, introduce the concept of carbon emission reduction, on the one hand reduce carbon pollution of the high-carbon-emission spaces through industrial regulation, on the other hand minimize carbon emission intensity of per industrial space through improving energy efficiency and energy structure.

4 Conclusions and perspectives

Based on the energy consumption and land use data of various provinces, municipalities and autonomous regions of China in 2007, this paper carried out the accounting of carbon emission from fossil energy and rural biomass energy of various provinces and regions by establishing energy carbon emission and carbon footprint model; through matching industrial space with energy consumption items, the carbon emission intensity and carbon footprint of different industrial spaces were compared and analyzed.

The main disadvantages and error sources are: (1) the division of industrial spaces was based on energy carbon emission items and land classification system. Since the correspondence between the data should be considered, some of the industrial spaces were not subdivided. Thus there was inevitably some error in the corresponding relationship between industrial spaces and carbon emission items. (2) As to different regions, there might be little differences in the total amount of carbon emission; however, the large area of certain industrial space might make the per unit area carbon footprint result a little too small, and vice versa. In addition, due to the difficulty in combining time-series data of land and energy at the provincial level, this paper only studied the regional difference in carbon footprint from energy consumption of different industrial spaces, the variation characteristics of carbon footprint of industrial space in various provinces and regions on temporal dimension were not analyzed.

Based on the above deficiencies, the following two aspects should be strengthened in the future research: (1) different industrial spaces should be further divided, in order to precisely calculate the carbon emission of different land use types and industrial spaces, to provide theory support for low-carbon economy planning based on optimizing industrial space pattern; (2) to further integrate the research of carbon emission of industrial activities and land use. On the one hand study the variation law of carbon emission of industrial activities sustained by land, on the other hand study the carbon flux and carbon metabolism of different land use types and the carbon emission effect of land use type conversion, so as to establish comprehensive carbon cycle model which includes both natural carbon emission and socio-economic carbon emission on the regional scale.

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