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Urban carbon footprint and carbon cycle pressure: The case study of Nanjing

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Abstract: Urban carbon footprint reflects the impact and pressure of human activities on urban environment. Based on city level, this paper estimated carbon emissions and carbon footprint of Nanjing city, analyzed urban carbon footprint intensity and carbon cycle pressure and discussed the influencing factors of carbon footprint through LMDI decomposition model. The main conclusions are as follows: (1) The total carbon emissions of Nanjing increased rapidly since 2000, in which the carbon emission from the use of fossil energy was the largest. Meanwhile, carbon sinks of Nanjing presented a declining trend since 2000, which caused the decrease of carbon compensation rate and the increase of urban carbon cycle pressure. (2) The total carbon footprint of Nanjing increased rapidly since 2000, and the carbon deficit was more than ten times of total land areas of Nanjing in 2009, which means Nanjing confronted high carbon cycle pressure. (3) Generally, carbon footprint intensity of Nanjing was on decrease and the carbon footprint productivity was on increase. This indicated that energy utilization rate and carbon efficiency of Nanjing was improved since 2000, and the policy for energy conservation and emission reduction taken by Nanjing's government received better effects. (4) Economic development, population and industrial structure are promoting factors for the increase of carbon footprint of Nanjing, while the industrial carbon footprint intensity was inhibitory factor. (5) Several countermeasures should be taken to decrease urban carbon footprint and alleviate carbon cycle pressure, such as: improvement of the energy efficiency, industrial structure reconstruction, afforestation and environmental protection and land use control. Generally, transition to low-carbon economy is essential for Chinese cities to realize sustainable development in the future.

Keywords: carbon footprint; carbon cycle pressure; LMDI; Nanjing

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1 Introduction

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 its 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), that is to measure it in emission amount; the other one regards carbon footprint as part of ecological footprint, which means the ecological carrying capacity required in absorbing CO_2 emission from fossil fuel combustion (Wiedmann *et al*., 2007; Global Footprint Network, 2012; Zhao *et al*., 2011), which measures in area. The above two definitions both appeared in the past studies. Generally speaking, the former was mainly applied in the micro-level study, and the latter was mostly used in the macro-level study.

The carbon footprint could be studied based on different levels, such as industries or products, urban & regional or national level. Carbon footprint analysis is an established method for systematically quantifying carbon sources and sinks throughout the lifetime of goods and services (Strohbach *et al*., 2012), especially on the product or industrial level. For example, Fan *et al*. (2012) analyzed the embedded carbon footprint of Chinese urban households. Teodoru *et al*. (2012) analyzed the net carbon footprint of a newly created boreal hydroelectric reservoir in northern Quebec, Canada. Wells *et al*. (2012) analyzed the carbon footprint of a paperback book, the cover and inside papers of which were produced in the United States and printed in Canada. Cheng *et al*. (2011) estimated the carbon footprint of China's crop production over 1993–2007 based on the inputs of China's agricultural activities. Filimonau *et al*. (2011) analyzed the carbon footprint of hotels through Life Cycle Energy Analysis, which provided a carbon impact appraisal method for tourist accommodation. Adom *et al*. (2012) analyzed the regional carbon footprint of dairy feeds for milk production in the United States. Chang *et al*. (2012) studied the optimal expansion of drinking water infrastructure system considering carbon footprint. Bakhshi and Demonsabert (2012) estimated the carbon footprint of the municipal water cycle. Pattara *et al*. (2012) discussed the carbon footprint of wine supply chain based on Life Cycle Analysis (LCA). The above studies about carbon footprint on micro-level were mostly finished through LCA Method. These studies gave us important thoughts and methods on the estimation and assessment of carbon footprint.

On city or regional level, carbon footprint was mainly used to analyze the environmental impact of human carbon processes. For example, based on life cycle approach, Strohbach *et al*. (2012) simulated carbon sequestration by growing trees of urban green space project in Leipzig, Germany and contrasted it with all related carbon sources. Sovacool and Brown (2010) analyzed the carbon footprint of 12 metropolitan cities 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. We see that the carbon footprint researches on city or regional level were mostly focused on carbon emission estimation of each sector and the corresponding measures to decrease the carbon footprint. Therefore, researches on the ecological impact and carbon cycle pressures caused by urban human activities should be further strengthened.

On national level, the studies of carbon footprint were mainly focused on the ecological footprint of anthropogenic carbon emissions. For example, in ecological footprint calculation of "Living Planet Report" (World Wildlife Fund, 2008), 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 very important in human ecological impact. Zhao *et al*. (2011) and Chuai *et al*. (2012) analyzed the carbon footprint of different industrial spaces in different regions of China, and discussed the carbon deficit of different regions. Aichele and Felbermayr (2012) evaluated the impacts of ratification of binding Kyoto commitments on carbon footprint and emissions, and the results highlight the difficulties of unilateral climate policies.

From the above introduction, we see that the previous studies were mostly focused on: (1) the carbon footprint of the products or certain industrial level based on LCA; (2) the calculation of greenhouse gases or carbon emissions of human activities of different sectors. And the carbon footprint in the previous studies was mostly measured in emission amount, which is not enough to quantitatively assess the environmental impact of human activities. Through establishing theoretical framework and estimation method for urban carbon footprint, this paper estimated the carbon emission and carbon footprint, analyzed urban carbon footprint intensity and carbon cycle pressure of Nanjing city, and further discussed the influencing factors of carbon footprint through LMDI decomposition model.

2 Data and methods

2.1 Study area and data sources

Nanjing, a rapidly developing city in eastern China, has a heavy chemical industry, so carbon emissions in Nanjing will increase rapidly. With rapid economic growth and urban expansion and high environmental pressure, Nanjing faces huge carbon cycle pressure, which is representative of developing cities in China. So we take Nanjing city as the case. For the urban statistical system in China is based on the administrative scope, the whole administrative areas of Nanjing was considered in this paper, which includes 11 urban districts (Xuanwu, Baixia, Qinhuai, Jianye, Gulou, Xiaguan, Pukou, Liuhe, Qixia, Yuhuatai and Jiangning) and two counties (Lishui and Gaochun) (Figure 1). The whole area is 6582.31 km^2.

Most of our data were derived from yearbooks. Annual population, GDP, amount of urban waste, yields of principal crops, livestock, rice field area and industrial production were from the Statistical Yearbook of Nanjing City and Statistical Yearbook of Jiangsu Province; energy consumption data were derived from the Environmental Report of Jiangsu Province, Statistical Yearbook of Nanjing City, General Economic Surveying Yearbook of Jiangsu Province and others; living energy consumption data of Nanjing were from the Urban Statistical Construction Yearbook of China and Urban Construction Statistical Report of Jiangsu Province; soil data were from sampling data (100 cm in depth) in Jiangsu province by Institute of Soil Science, Chinese Academy of Sciences; land use data were from the second land survey data of Department of Land and Resources, Jiangsu Province.

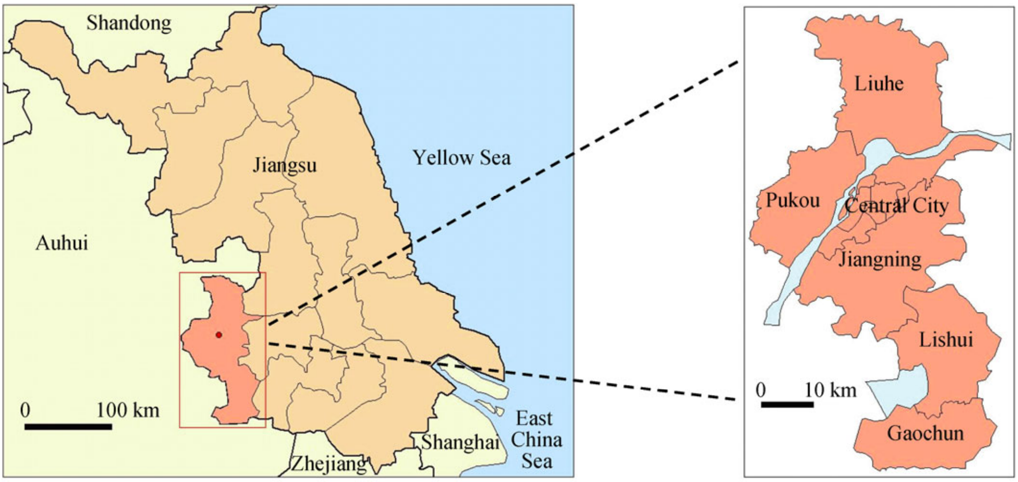

Figure 1 The location and administrative divisions of Nanjing city

2.2 Theoretical framework of urban carbon emissions and carbon footprint

Urban carbon emissions include carbon emitted from both urban anthropogenic activities and natural processes. The former include carbon emission from energy consumption, industrial processes, straw combustion, paddy methane, human respiration, animal and wastes, and the latter include emissions from respiration of vegetation and soil and the carbon emission from water body (Figure 2).

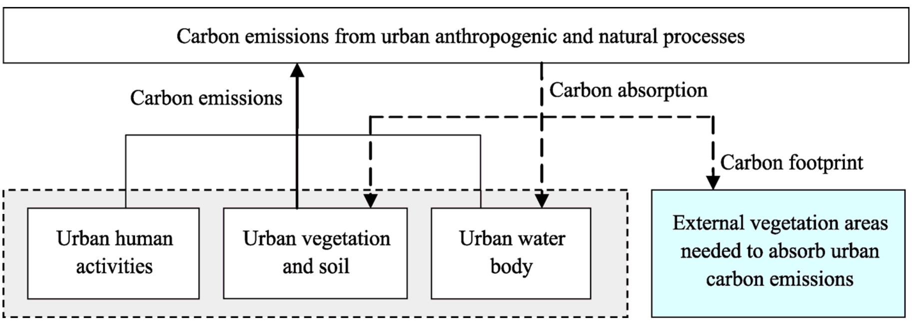

Figure 2 The framework of urban carbon emissions and carbon footprint

On the contrary, urban carbon sinks mainly include carbon absorption through photosynthesis of vegetation and carbon sequestration of water body. Generally, with large energy consumption, urban carbon sinks were much less than carbon emissions. Therefore, the carbon emitted by urban human activities will be absorbed by external vegetation areas, the area of which represents the amount of carbon footprint, i.e., the environmental impact of urban anthropogenic carbon processes (Figure 2). The larger the carbon footprint, the higher the urban carbon cycle pressure. Through the relation of carbon sources, carbon sinks and carbon footprint, the urban carbon cycle pressure could be measured by carbon footprint intensity, carbon compensation rate and carbon cycle pressure index.

2.3 Method for carbon emission estimation

(1) Anthropogenic carbon emissions

Anthropogenic carbon emissions include carbon from energy consumption, industrial processes, straw combustion, paddy methane, human respiration, animal and wastes. The carbon estimation from energy consumption was calculated by the method of Zhao *et al*. (2012), and other items of anthropogenic carbon emissions were estimated by the carbon emission factors of IPCC (2006).

(2) Natural carbon emissions

Carbon emissions from respiration by vegetation and soil could be estimated by the following methods:

$$CE_{veg} = \sum_i R_{veg-i} \times Area_{veg-i} \tag{1}$$

$$CE_{soil} = \sum_i R_{soil-i} \times Area_{soil-i} \tag{2}$$

where CE_{veg} and CE_{soil} is the carbon emission from respiration by vegetation and soil respectively, $R_{veg\text{-}i}$ is the carbon emission factor from respiration of different vegetation types (forest, grassland, cropland and urban greenbelt), $R_{soil\text{-}i}$ is the carbon emission factor of soil respiration under different vegetation types (Fang *et al*., 1996), $Area_{veg\text{-}i}$ and $Area_{soil\text{-}i}$ is the area of different vegetation and soil types respectively.

Carbon emissions from water body could be estimated by the following method:

$$CE_{water} = Area_{lake} \times CE_{lake} + Area_{river} \times CE_{river} \tag{3}$$

where CE_{water} is the carbon emission from water body, $Area_{lake}$ and $Area_{river}$ is the lake area and total drainage area of rivers, CE_{lake} and CE_{river} is the carbon emission factor of lake and river respectively. The carbon emission factor of river is 0.026 t/km^2·a, which is the value of the Yangtze River Basin. The carbon emission factor of lake is 0.041 t/km^2.a, which is the value of eastern plain of China (Ye and Chen, 1992).

2.4 Method for carbon footprint analysis

(1) Urban carbon sinks

Urban carbon sinks include not only carbon absorption by vegetations but also carbon sequestration by terrestrial water areas. In ecosystem, Gross Primary Productivity (GPP) is the rate at which an ecosystem's producers capture and store a given amount of chemical energy as biomass in a given length of time, while Net Primary Productivity (NPP) is the rate at which all the plants in an ecosystem produce net useful chemical energy. Net ecosystem productivity (NEP) reflects the carbon fixation capacity of vegetation, namely, the carbon absorption amount of per hectare vegetation per year (Xie *et al*., 2008). The relationships between them are as follows:

$$NPP = GPP - R \tag{4}$$

$$NEP = NPP - RH \tag{5}$$

where R and RH is the carbon emissions by autotrophic respiration and heterotrophic respiration. Therefore, only NEP can represent the carbon storage of ecosystem, i.e. the carbon sinks of ecosystem. So the carbon sink of ecosystem in this paper was measured by the vegetation carbon sinks and carbon sequestration by water body, as follows:

$$C_s = \sum NEP_i \times Area_i + CI_{water} \tag{6}$$

where C_s is the total carbon sink of urban terrestrial ecosystem; NEP_i is the NEP of vegetation type i (i=1~4, is the forest, grassland, cropland and urban greenbelt respectively); CI_{water} is the annual carbon sequestration of water body (Duan *et al*., 2008). Here the NEP results of forest and grassland were from Xie *et al*. (2008) and the NEP result of urban greenbelt was from Guan *et al*. (1998). The NEP of farmland was estimated by the following method:

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

$$C_d = C_a D_w = C_a Y_w / H \tag{8}$$

where i is the crop type i; C_c is the total carbon absorption of crops during the whole growth period; S is the cultivated land area; C_d is the carbon absorption of certain crop during the whole growth period; 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 coefficient and carbon absorption rate of China's main crops were from Li (2000).

(2) Urban carbon footprint

In this paper, carbon footprint is defined as the productive land (vegetation) areas needed in absorbing carbon emissions, which means the ecological footprint of carbon emissions (Zhao *et al*., 2011). Since carbon emissions from rural biomass energy and straw combustion were considered in the total, thus the agricultural vegetation was regarded as part of the total carbon footprint. Here, NEP indicators were adopted to reflect the carbon absorption of different vegetations (forest, grassland, cropland and urban greenbelt, etc.). Therefore, the areas of productive land required in absorbing carbon emissions (carbon footprint) could be calculated. The method is as following:

$$CF = CE_{hum} \times \left(\frac{P_f}{NEP_f} + \frac{p_g}{NEP_g} + \frac{P_a}{NEP_a} + \frac{P_u}{NEP_u} \right) \tag{9}$$

where CF is the carbon footprint (hm^2) brought by the total carbon emissions (CE_{hum}); P_f, P_g, P_a and P_u is the total carbon absorption proportion of forest, grassland, cropland and urban greenbelt respectively; NEP_f, NEP_g, NEP_a and NEP_u is the NEP of forest, grassland, cropland and urban greenbelt respectively. For lack of the parameters in Nanjing, the values of NEP_f, NEP_g and NEP_u were derived from the results of other researches in China (Xie *et al*., 2008; Guan *et al*., 1998). The value of NEP_a was estimated by formula (7).

(3) Urban carbon footprint intensity and carbon footprint productivity

The total urban carbon footprint could not essentially reflect the carbon effect of city's economic development. Therefore, carbon footprint intensity and carbon footprint productivity was defined and applied to further analyze the relationship between carbon footprint and Gross Domestic Production (GDP). Carbon footprint intensity (hm^2/yuan) is the carbon footprint of per unit GDP, which means the vegetation needed in absorbing the carbon emissions from the production of per unit GDP. Generally, the higher the carbon footprint intensity, the lower per unit carbon footprint benefit. Carbon footprint productivity (yuan/hm^2) is the ratio of GDP and carbon footprint, which reflects the economic value of per unit carbon footprint. High carbon footprint productivity means high economic productivity and low energy consumption. Obviously, we can see a negative correlation between carbon footprint intensity and carbon footprint productivity.

(4) Carbon footprint elasticity

Here, carbon footprint elasticity was defined as the ratio of changing rage of carbon footprint and GDP during certain time span, as follows:

$$\varepsilon=\frac{\left(\frac{CF_t}{CF_0}\right)^{1/t}-1}{\left(\frac{GDP_t}{GDP_0}\right)^{1/t}-1} \tag{10}$$

where ε is carbon footprint elasticity, CF_0 and CF_t is the carbon footprint of base year and the year t, GDP_0 and GDP_t is the GDP of base year and year t. Obviously, if the increasing rate of carbon footprint is higher than that of GDP, the carbon footprint elasticity will be greater than 1; oppositely, the carbon footprint elasticity will be less than 1. Therefore, the lower the carbon footprint elasticity is, the higher the carbon footprint productivity will be.

(5) Decomposition analysis of carbon footprint by LMDI model

In order to analyze the factors that influence the change of carbon footprint, here the carbon footprint equation was established according to the Kaya identity, as follows:

$$C=\sum_i \frac{C_i}{G_i}\times\frac{G_i}{G}\times\frac{G}{P}\times P \tag{11}$$

where C is the total carbon footprint of fossil energy consumption, C_i is the carbon footprint of industry i, G_i is the GDP of industry i, G is the total GDP and P is the population. Here, we assume that:

$$f_i=\frac{C_i}{G_i};\quad s_i=\frac{G_i}{G};\quad g=\frac{G}{P} \tag{12}$$

Then, the carbon footprint could be expressed as the product of several factors such as industrial carbon footprint intensity effect (f_i), industrial structural effect (s_i), economic development factor (g) and population factor (p), as follows:

$$C=\sum_i f_i\times s_i\times g\times p \tag{13}$$

According to equation (13), contribution value and contribution rate of each factor could be decomposed by LMDI model. Here, we assume that the carbon footprint of start year is C^0 and the carbon footprint of year T is C^T. Then, the change of carbon footprint during study period (0–T) could be expressed as follows:

$$\begin{aligned}\Delta C&=C^T-C^0=\sum_i f_i^T\times s_i^T\times g^T\times p^T-\sum_i f_i^0\times s_i^0\times g^0\times p^0\\&=\Delta C_{fi}+\Delta C_{Si}+\Delta C_g+\Delta C_p+\Delta C_{rsd}\end{aligned} \tag{14}$$

$$D=\frac{C^T}{C^0}=D_f D_s D_g D_p D_{rsd} \tag{15}$$

where ΔC_{fi}, ΔC_{si}, ΔC_g and ΔC_p is the contribution value of each factor (f_i, s_i, g and p) respectively; D_f, D_s, D_g and D_p is the contribution rate of each factor (f_i, s_i, g and p) respectively; ΔC_{rsd} and D_{rsd} is the decomposition residuals. They could be expressed as follows:

$$D_f=\exp(W\Delta C_{fi});\quad D_s=\exp(W\Delta C_{si});\quad D_g=\exp(W\Delta C_g);\quad D_p=\exp(W\Delta C_p);\quad D_{rsd}=1$$

$$W=\frac{\ln D}{\Delta C};\ \Delta C_{fi}=\sum_i\frac{C_i^T-C_i^0}{\ln C_i^T-\ln C_i^0}\times\ln\frac{f_i^T}{f_i^0};\quad \Delta C_{Si}=\sum_i\frac{C_i^T-C_i^0}{\ln C_i^T-\ln C_i^0}\times\ln\frac{s_i^T}{s_i^0};$$

$$\Delta C_g = \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \times \ln \frac{g^T}{g^0};\ \Delta C_p = \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \times \ln \frac{p^T}{p^0};\ \Delta C_{rsd} = 0 \tag{16}$$

2.5 Method for urban carbon cycle pressure analysis

Here, several indicators were adopted to analyze the urban carbon cycle pressure, as follows:

(1) Human carbon effect index

Human carbon effect index was an indicator to measure the impacting extent of anthropogenic activities on urban carbon cycle.

$$C_{hum} = CE_{hum} / Ct \times 100\% \tag{17}$$

where C_{hum} is the human carbon effect index, Ct is the total urban carbon emissions, which include anthropogenic and natural carbon emissions.

(2) Carbon compensation rate

Carbon compensation rate is the ratio of terrestrial carbon sink and anthropogenic carbon emissions.

$$C_p = C_s / CE_{hum} \times 100\% \tag{18}$$

where C_p is urban carbon compensation rate. It reflects the proportion of anthropogenic emissions that absorbed by local terrestrial ecosystems. The higher the carbon compensation rate is, the stronger the local carbon sink intensity of local ecosystem will be.

(3) Carbon cycle pressure index

Carbon cycle pressure index (C_m) is the ratio of anthropogenic carbon emissions and terrestrial carbon sink.

$$C_m = CE_{hum} / C_s \tag{19}$$

There exists negative correlation between carbon cycle pressure index and carbon compensation rate. C_m is less than 1 means the urban carbon emissions could be absorbed by local terrestrial ecosystems, while C_m is higher than 1 means additional external ecosystems are needed to absorb the excessive urban anthropogenic carbon emissions.

3 Results

3.1 Urban carbon sources and sinks of Nanjing

Carbon emissions of Nanjing include both anthropogenic and natural carbon emissions. The former include carbon emissions from fossil energy and biomass energy use, straw combustion, industrial processes, paddy methane, animals, human respiration and wastes, while the latter include carbon emissions from respiration of vegetation and soil and the carbon emission from water body. In the above items, carbon emission from fossil energy was the largest (2625.21×10^4 t in 2009), and the proportion of which increased from 69.25% to 79.68%. Carbon emission from industrial processes was 355.38×10^4 t in 2009, which accounted for 10.79%. All the other carbon emissions only accounted for no more than 10% in the total, indicated that the most carbon emissions come from urban production processes and fossil energy consumption (Table 1).

Table 1 Carbon emissions and its composition of Nanjing city (10^4 t)

Year	Fossil energy	Biomass energy	Straw com-bustion	Industry	Paddy	Ani-mals	Human	Vege-tation	Soil	Water	Solid waste	Waste water	Total
2000	990.15	24.75	10.71	123.53	5.54	22.50	44.94	160.14	40.33	0.0202	4.33	2.82	1429.78
2001	991.65	23.76	10.26	152.44	4.85	25.26	42.18	168.64	43.98	0.0203	4.68	2.82	1470.55
2002	1054.34	22.22	9.54	221.96	4.29	25.97	45.08	182.88	49.37	0.0208	4.85	2.80	1623.32
2003	1262.69	19.08	8.26	244.17	3.74	26.69	40.29	169.00	46.35	0.0209	5.57	2.84	1828.70
2004	1528.17	20.47	9.01	276.86	4.37	25.64	38.17	178.94	48.94	0.0209	6.28	2.85	2139.72
2005	1939.38	19.80	8.72	319.45	4.52	24.56	36.62	175.91	48.49	0.0208	7.04	2.92	2587.44
2006	2086.41	19.16	8.51	349.27	4.16	17.62	37.34	176.10	48.58	0.0208	7.27	2.93	2757.38
2007	2303.80	17.06	7.67	363.39	3.86	13.06	36.51	168.68	46.84	0.0209	7.47	2.94	2971.30
2008	2378.50	18.58	8.53	326.96	4.28	13.49	35.55	178.62	49.14	0.0209	7.71	2.94	3024.31
2009	2625.21	17.81	8.32	355.38	4.10	12.91	34.81	176.61	48.75	0.0209	7.95	2.90	3294.78

The total carbon sinks of Nanjing city slowly declined since 2000. It decreased from 191.04×10^4 t in 2000 to 186.28×10^4 t in 2009 with a decreasing rate of 2.49% (Figure 3). This means that with the urbanization and the expansion of construction land, the vegetation land (especially the cropland) was occupied (Figure 4), which caused the decrease of total carbon sink function and the increase of ecological pressure of Nanjing.

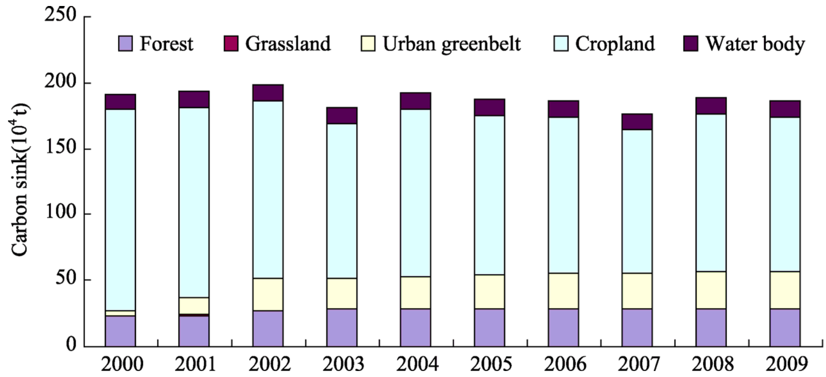

Figure 3 Carbon sinks of Nanjing terrestrial ecosystems

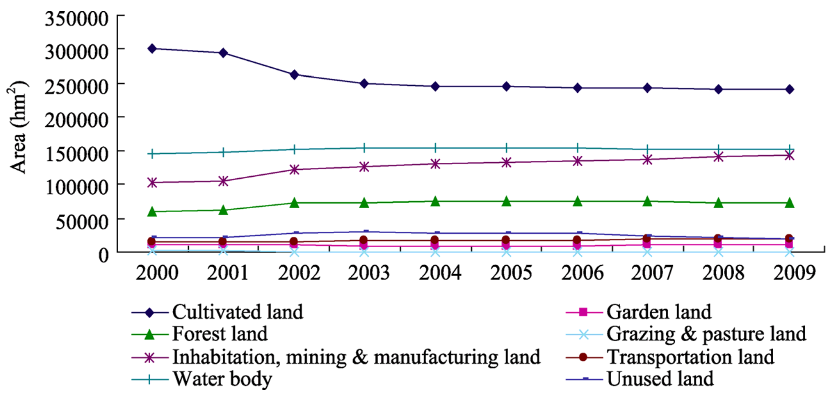

Figure 4 Land use structure and its changes between 2000 and 2009 in Nanjing city

As to the composition of carbon sinks, that of cropland was the highest (63.31% in 2009). But the carbon sinks of cropland presented a declining trend from 152.89×10^4 t in 2000 to 117.93×10^4 t in 2009, while the proportion of cropland decreased from 80.03% to 63.31%. The decrease of carbon sinks of cropland was mainly caused by the reducing of cultivated land areas, which was caused by the expansion of city and the traffic facilities (Figures 3 and 4). With rapid economic development, more and more suburban cropland was replaced by industrial or residential land, which further decreased the carbon sink function of terrestrial ecosystem inevitably. Further, the cropland was abandoned as uncultivated by farmers was also one of the important reasons. This will in turn caused the decrease of total crop yield and biological carbon storage. The carbon sinks of forest and water body were both increased since 2000, which was caused by the expansion of forest land and water area. Especially, carbon sinks of urban greenbelt of Nanjing increased drastically from 3.76×10^4 t in 2000 to 28.11×10^4 t in 2009 (Figure 3), with the proportion increasing from 1.97% to 15.09%, indicated that trees planting in urban areas and ecological protection on natural vegetations in Nanjing obtained better ecological effect. Because there was little grassland, the carbon sink of it was almost negligible. Generally, with the rapid urbanization of Nanjing in recent years, the total carbon emissions increased drastically, which caused the increase of regional carbon cycle pressure.

3.2 Urban carbon footprint of Nanjing

From the annual structure of productive land use in Nanjing, we see that the productive land was relatively limited. In the four main vegetation types, the area of urban greenbelt increased rapidly, the forest presented a slightly increasing trend, while the cultivated land and grassland decreased obviously. Generally, the total productive land of Nanjing basically kept stable (about 40×10^4 hm^2 annually), and the area of cultivated land was the highest, which accounted for about 60% in 2009 (Table 2).

Table 2 Productive land use area of Nanjing city (10^4 hm^2)

Year	Forest	Grassland	Urban greenbelt	Cultivated land	Total
2000	6.07	0.1862	1.11	31.23	38.59
2001	6.25	0.1790	3.75	30.52	40.70
2002	7.18	0.0739	7.04	27.17	41.46
2003	7.25	0.0050	7.10	26.01	40.36
2004	7.42	0.0051	7.34	25.51	40.27
2005	7.39	0.0051	7.52	25.50	40.42
2006	7.40	0.0048	7.89	25.32	40.61
2007	7.38	0.0047	8.13	25.26	40.77
2008	7.35	0.0047	8.23	25.18	40.76
2009	7.33	0.0047	8.32	25.10	40.76

According to the estimation method, the NEP of each vegetation type could be obtained. We found that the NEP of farmland was higher than that of other vegetation types. For example, in 2009, the NEP of farmland, forest, grassland and urban greenbelt was 4.70 t/hm^2, 3.81 t/hm^2, 0.95 t/hm^2 and 3.38 t/hm^2 respectively, which indicated that the cultivated land has the highest productivity. Although forest has high carbon storage, the annual carbon sink of forest is lower than that of the cultivated land because the respiration rate of forest is much higher than that of crops. According to the NEP of each vegetation type, the area of each type in absorbing per unit carbon emissions (1t) could be calculated. Because the difference of NEP, the area of each vegetation type needed to absorb 1 t carbon is quite different among farmland, forest, grassland and urban greenbelt (the area was 0.21 hm^2, 0.26 hm^2, 1.05 hm^2 and 0.30 hm^2 respectively for them). We found that because the NEP of grassland was the lowest, the area of grassland required to absorb carbon was the largest.

According to the total carbon sinks, the proportion of carbon sink and NEP of each vegetation type and the carbon footprint of anthropogenic carbon emissions could be estimated. Because the carbon footprint was measured by the land areas of several vegetation types, here, the water body was not considered in the estimation of total carbon footprint. In the four vegetation types, the carbon sink of cultivated land was the main part (67.79% in 2009), urban greenbelt next (16.16%), then the forest (16.05%) (Table 3). Based on the annual proportion of carbon sinks of each vegetation type, the annual land area of them in absorbing total 1 t carbon emission could be estimated (Table 3). Then the total vegetation areas (total carbon footprint) required in absorbing total anthropogenic carbon emissions could be calculated.

Table 3 Carbon footprint of anthropogenic carbon emissions in Nanjing city

Year	The proportion of carbon sinks (%)				Land area required in absorbing total 1t carbon emission (hm^2)				Total anthropogenic carbon emissions (10^4 tC)	Total carbon footprint (10^4 hm^2)
	Forest	Grassland	Urban greenbelt	Cultivated land	Forest	Grassland	Urban greenbelt	Cultivated land		
2000	12.85	0.0982	2.09	84.97	0.0337	0.00104	0.0062	0.1736	1229.28	263.66
2001	13.10	0.0934	6.96	79.85	0.0344	0.00098	0.0206	0.1679	1257.91	281.55
2002	14.66	0.0375	12.73	72.57	0.0385	0.00040	0.0377	0.1455	1391.06	308.88
2003	16.39	0.0028	14.24	69.37	0.0430	0.00003	0.0422	0.1543	1613.33	386.46
2004	15.72	0.0027	13.80	70.47	0.0413	0.00003	0.0409	0.1419	1911.82	428.36
2005	16.07	0.0027	14.50	69.43	0.0422	0.00003	0.0429	0.1455	2363.02	544.99
2006	16.14	0.0026	15.28	68.58	0.0424	0.00003	0.0452	0.1451	2532.67	589.36
2007	17.08	0.0027	16.69	66.23	0.0448	0.00003	0.0494	0.1535	2755.75	682.68
2008	15.82	0.0025	15.71	68.46	0.0415	0.00003	0.0465	0.1424	2796.54	644.42
2009	16.05	0.0025	16.16	67.79	0.0421	0.00003	0.0478	0.1443	3069.39	719.08

Through the results, we found that the total carbon footprint of Nanjing increased rapidly from 263.66×10^4 hm^2 in 2000 to 719.08×10^4 hm^2 in 2009, in which the cultivated area was the biggest (442.87×10^4 hm^2 in 2009) with 61.59% in the total carbon footprint (Figure 5).

Compared with total carbon footprint, Nanjing has less productive land. For example, the total carbon footprint and productive land was 719.08×10^4 hm^2 and 40.76×10^4 hm^2 respectively in 2009. So the carbon deficit of Nanjing was 678.33×10^4 hm^2 (Figure 6), which is more than ten times of the total land area of Nanjing (65.82×10^4 hm^2). This means that vegetation areas of total 719.08×10^4 hm^2 were required in absorbing the total anthropogenic

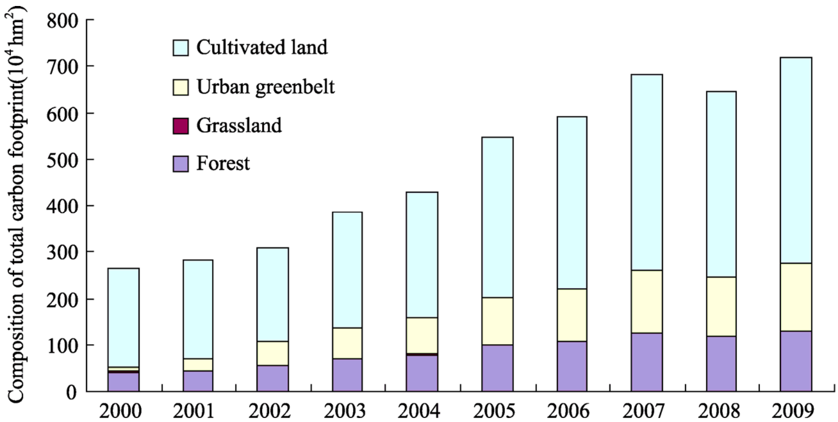

Figure 5 Composition of total carbon footprint of Nanjing city

carbon emissions of Nanjing. We also found that the total carbon deficit rapidly increased from 2000 (225.07×10^4 hm^2) to 2009 (678.33×10^4 hm^2), with an increase of carbon deficit of Nanjing by two times, indicated that the energy consumption and total carbon emissions increased rapidly since 2000, and the human impact on environment of Nanjing increased gradually. With the increase of total carbon emissions, carbon footprint and carbon deficit will further increase in the future.

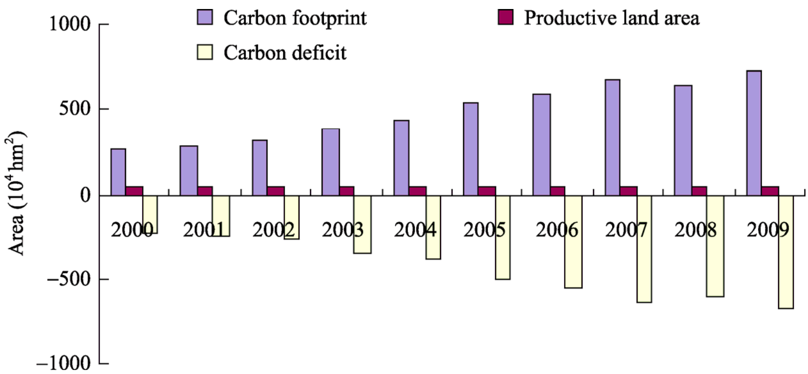

Figure 6 Carbon footprint, productive land and carbon deficit of Nanjing city

Although the carbon footprint and carbon deficit of Nanjing increased annually, if GDP was taken into account, we found that carbon footprint productivity appeared a fluctuating growth trend. It increased since 2000 and reached 4.36×10^4 yuan/hm^2 in 2002, then declined to about 4.00×10^4 yuan/hm^2 in 2003–2007, and rapidly increased after 2007 and reached 4.84×10^4 yuan/hm^2 in 2009 (Figure 7). Generally speaking, the economic productivity created by per unit carbon footprint of Nanjing was increasing, indicated that the carbon productivity, energy utilization rate and carbon efficiency of Nanjing were improved since 2000. With the increase of carbon footprint productivity, the carbon footprint intensity decreased since 2000, which was opposite to the trend of carbon footprint productivity. It decreased from 0.25 hm^2/10^4 yuan in 2000 to 0.21 hm^2/10^4 yuan in 2009 (Figure 7). This indicated that the productive land required in absorbing the carbon emissions created by per unit GDP was on decrease, which revealed that the energy conservation and emission reduction policy in Nanjing received better effect, and the impact of per unit economic production on environment decreased gradually since 2000.

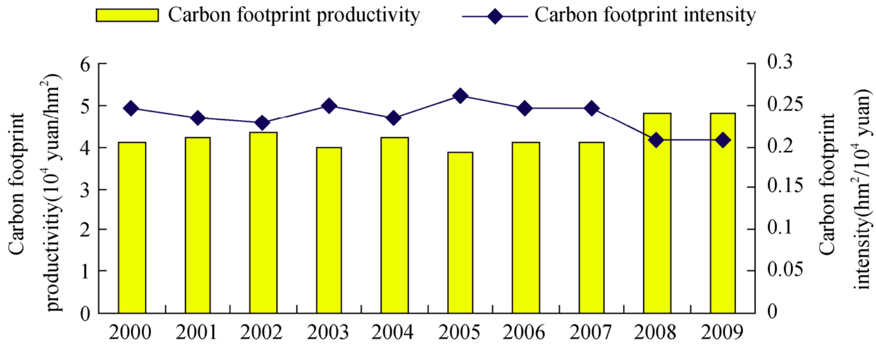

Figure 7 Carbon footprint productivity and carbon footprint intensity of Nanjing city

3.3 Decomposition analysis of carbon footprint

The influencing factors were decomposed into industrial carbon footprint intensity effect, industrial structural effect, economic development factor and population factor through LMDI model. And the annual contribution value and contribution rate was calculated. It should be noted that only the carbon footprint of fossil energy use was analyzed through LMDI model.

We see that the main positive factors promoting the rapid increase of urban carbon footprint during 2000–2009 in Nanjing were economic development factor and population factor, in which economic development factor was the most important prompting factor, the contribution value of which exceeded the whole change value of total carbon footprint during time span such as 2000–2002, 2003–2004, 2005–2006 and 2007–2008. This indicated that without inhibitory function of other factors, the increment of total carbon footprint of Nanjing will be much higher by the influence of economic development. Population factor was also a promoting factor, but its contribution value was much less than that of economic development factor (Table 4).

Table 4 Decomposition analysis of carbon footprint in Nanjing city

Year	Contribution value (10^4 hm^2)					Contribution rate (%)				
	Industrial carbon footprint intensity effect	Industrial structure effect	Economic development factor	Population factor	The whole	Industrial carbon footprint intensity effect	Industrial structure effect	Economic development factor	Population factor	The whole
	$\triangle C_{fi}$	$\triangle C_{si}$	$\triangle C_g$	$\triangle C_p$	$\triangle C$	D_f	D_s	D_g	D_p	D
2000–2001	–9.17	–4.23	19.76	3.22	9.58	0.96	0.98	1.10	1.01	1.05
2001–2002	–12.62	–2.62	23.23	4.18	12.16	0.95	0.99	1.11	1.02	1.05
2002–2003	27.61	3.48	33.11	4.21	68.35	1.11	1.01	1.13	1.02	1.29
2003–2004	–21.28	9.87	45.02	6.34	39.93	0.94	1.03	1.15	1.02	1.13
2004–2005	44.34	4.99	47.48	8.12	104.89	1.12	1.01	1.13	1.02	1.31
2005–2006	–28.64	1.73	56.27	8.86	38.22	0.94	1.00	1.13	1.02	1.09
2006–2007	3.16	6.85	66.64	8.56	85.21	1.01	1.01	1.13	1.02	1.18
2007–2008	–77.20	–8.40	56.41	6.57	–22.63	0.87	0.99	1.11	1.01	0.96
2008–2009	11.76	–8.68	58.93	4.92	66.93	1.02	0.99	1.11	1.01	1.12
2000–2009	–44.93	5.39	387.57	54.62	402.65	0.89	1.01	2.78	1.16	2.90

The main inhibitory factors were industrial carbon footprint intensity effect and industrial structure effect, in which the inhibitory effect of industrial carbon footprint intensity was the highest on the whole. Generally, the inhibitory effect of industrial carbon footprint intensity presented a fluctuating trend since 2000. The total contribution value was -44.93×10^4 hm^2. Before 2005, the inhibitory effect of industrial carbon footprint intensity was relatively weak, and it even presented a promoting effect in 2002–2003 and 2004–2005. After 2005, the inhibitory effect of industrial carbon footprint intensity became stronger and reached -77.20×10^4 hm^2 in 2007–2008. The industrial structure effect also presented a fluctuating trend. It appeared as promoting effect from 2002 to 2007, but presented as inhibitory factor in other time spans. Especially in 2008–2009, the inhibitory effect was the strongest (-8.68×10^4 hm^2). As a whole, the industrial structure appeared as a slightly promoting effect in 2000–2009, and the total contribution value was 5.39×10^4 hm^2. Therefore, the influencing factors of carbon footprint in Nanjing could be divided into promoting factors and inhibitory factors. The former were economic development, population factor and industrial structure effect, and the latter was industrial carbon footprint intensity effect. By sorting the contribution value of each factor during 2000–2009, we found that the total increasing value of carbon footprint was 402.65×10^4 hm^2. The order of each factor was: economic factor (387.57×10^4 hm^2), population factor (54.62×10^4 hm^2), industrial structure effect (5.39×10^4 hm^2) and industrial carbon footprint intensity effect (-44.93×10^4 hm^2) (Table 4).

As for the annual changing rate of total carbon footprint, the contribution rate of economic development was the highest. During 2000–2009, the whole changing rate (D) of carbon footprint of Nanjing was 2.90. The order of contribution rate of each factor was: economic development factor (2.78), population factor (1.16), industrial structure effect (1.01) and industrial carbon footprint intensity effect (0.89). This indicated that the promoting function of economic development factor was the highest, which even exceeded the increasing rate of the whole carbon footprint in certain year.

3.4 Urban carbon cycle pressure of Nanjing

In 2009, the anthropogenic carbon emissions accounted for 93.16% (it is also called “human carbon effect index”) in the total, and presented an increasing trend since 2000 (Table 5). This suggested that with social and economic development, the impact of human activities on urban carbon cycle processes was on increase, while the carbon emissions from natural processes basically kept stable. It just presented a slightly increasing trend, and the proportion of natural carbon emissions decreased since 2000 with the increase of human carbon effect index.

Nanjing is a rapidly developing city. Actually, with urban expansion, population growth and the increase of energy consumption and industrial production, human carbon effect will inevitably increase. Therefore, the total carbon footprint will increase certainly. But the natural process was quite different. If urban natural ecosystem was not disturbed seriously, the natural carbon productivity and carbon emission rate of vegetation and soil will not be changed highly.

The carbon compensation rate decreased from 15.54% in 2000 to 6.07% in 2009, suggesting that the carbon sink function of terrestrial ecosystems was not enough to compensate urban anthropogenic carbon emissions. Furthermore, with the decrease of carbon sink capacity, the urban carbon cycle pressure increased gradually. In 2000, the carbon cycle pressure index of Nanjing was 6.43, but in 2009, it reached 16.48 (Table 6). This indicated that anthropogenic carbon emission was more than 16 times of carbon sinks. With the rapid urbanization process, this trend will be further strengthened.

Table 5 Annual natural and anthropogenic carbon emissions of Nanjing city

Year	Total carbon emissions (10^4 t)	Natural processes		Anthropogenic processes	
		Amount (10^4 t)	Proportion (%)	Amount (10^4 t)	Proportion (%)
2000	1429.78	200.49	14.02	1229.28	85.98
2001	1470.55	212.64	14.46	1257.91	85.54
2002	1623.32	232.27	14.31	1391.06	85.69
2003	1828.70	215.37	11.78	1613.33	88.22
2004	2139.72	227.90	10.65	1911.82	89.35
2005	2587.44	224.42	8.67	2363.02	91.33
2006	2757.38	224.71	8.15	2532.67	91.85
2007	2971.30	215.54	7.25	2755.75	92.75
2008	3024.31	227.77	7.53	2796.54	92.47
2009	3294.78	225.38	6.84	3069.39	93.16

Table 6 Carbon compensation rate and carbon cycle pressure index of Nanjing city

Year	Carbon sinks (10^4 tC)	Anthropogenic carbon emissions (10^4 tC)	Carbon compensation rate (%)	Carbon cycle pressure index
2000	191.04	1229.28	15.54	6.43
2001	193.17	1257.91	15.36	6.51
2002	199.12	1391.06	14.31	6.99
2003	180.84	1613.33	11.21	8.92
2004	192.04	1911.82	10.04	9.96
2005	187.51	2363.02	7.94	12.60
2006	186.75	2532.67	7.37	13.56
2007	176.87	2755.75	6.42	15.58
2008	189.20	2796.54	6.77	14.78
2009	186.28	3069.39	6.07	16.48

4 Discussion and policy implications

From the decomposition analysis of carbon footprint, we see that the decrease of industrial carbon footprint intensity was the main inhibitory factor. Actually, the industrial energy consumption, especially the energy consumption in petrochemical industry, iron and steel industry and power generation, was the main source of carbon emissions. Therefore, the industrial energy consumption intensity should be decreased, and the industrial structure should be adjusted.

The decrease of total carbon footprint was mainly caused by the declining of carbon footprint intensity of agriculture, industry and part of service industry. Oppositely, the carbon footprint intensity of construction and transportation industry increased since 2000, and became the main promoting factor for the increase of total carbon footprint. Therefore, the most important sectors in carbon emission reduction are manufacturing, construction and transportation industries. The carbon emission intensity of these industries should be controlled to realize the inhibitory function for the increase of total carbon footprint.

Essentially, reasonable reconstruction of industrial structure will promote carbon emission reduction. However, through LMDI analysis, we found that the industrial structure of Nanjing was a promoting factor of the total carbon footprint, which was mainly caused by the high proportion of heavy industry, and also by the high weight of industrial added value in the total GDP. Therefore, if the industrial structure will be further optimized, and the weight of service sector will be raised in the future, the industrial structure reconstruction will also bring better carbon emission reduction effect, and will turn into inhibitory factor in the long run.

Carbon footprint elasticity is also an important index that reflects urban carbon cycle pressure and carbon footprint efficiency. Through analysis, we see that carbon footprint elasticity of Nanjing presented a fluctuating trend since 2000. Especially, it reached 1.67 and 1.80 in 2003 and 2005 respectively (Figure 8), which indicated that the growth rate of carbon footprint exceeded that of GDP in the above two years. In spite that the carbon footprint elasticity of Nanjing was 0.85 during 2000–2009 as a whole, which is lower than 1, the total carbon emissions and carbon footprint will increase gradually along with economic development, energy consumption and urbanization. Therefore, the low-carbon development measures should be adopted to decrease the carbon cycle pressure of Nanjing in the future, especially to decrease the increasing rate of carbon footprint.

Without human impact, regional carbon cycle process will be an absolutely natural process, which mainly includes the carbon flux and circulation process of photosynthesis, respiration, decomposition, etc. However, in urban system, natural carbon processes was seriously disturbed by human activities such as manufacturing, transportation, household consumption, energy use and land use, which highly increased the carbon footprint intensity and urban carbon cycle pressure, and inevitably contributed to the global warming effect. Therefore, to decrease the net carbon emissions, we should both consider the carbon sources and sinks. Except for the decrease of carbon footprint intensity of industries, strengthening carbon sequestration should also be considered. On the one hand, we should try to add carbon sinks through afforestation and environmental protection, and raise the carbon seques-

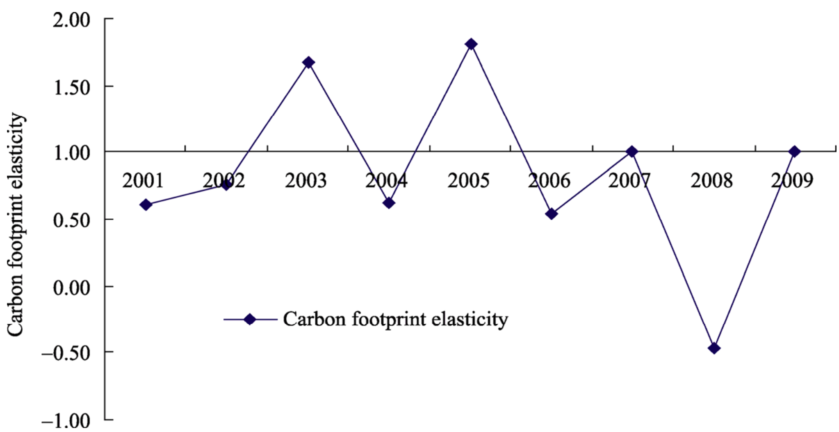

Figure 8 The carbon footprint elasticity of Nanjing city

tration efficiency of productive land. On the other hand, land use structure should be adjusted through controlling built-up areas, economical and intensive land use, returning farmland to forests or grassland. Through the above measures, the carbon sink capacity will be raised, and carbon emissions could be offset and the carbon cycle pressure will be decreased to some extent.

5 Conclusions

Through establishment of theoretical framework and estimation method of urban carbon footprint, this paper estimated the carbon emissions and carbon footprint, analyzed urban carbon footprint intensity and carbon cycle pressure of Nanjing city, and further discussed the influencing factors of carbon footprint through LMDI decomposition model. The main conclusions are as follows:

(1) The total carbon emissions of Nanjing increased rapidly since 2000, in which the carbon emission from the use of fossil energy was the largest. Meanwhile, carbon sinks of Nanjing presented a declining trend since 2000, which caused the decrease of carbon compensation rate and the increase of urban carbon cycle pressure.

(2) The total carbon footprint of Nanjing increased rapidly since 2000, and the carbon deficit was more than ten times of total land areas of Nanjing in 2009, which means Nanjing confronted high carbon cycle pressure.

(3) Generally, carbon footprint intensity of Nanjing was on decrease and the carbon footprint productivity was on increase. This indicated that energy utilization rate and carbon efficiency of Nanjing was improved since 2000, and the policy for energy conservation and emission reduction taken by Nanjing's government received better effects.

(4) Economic development, population and industrial structure are promoting factors for the increase of carbon footprint of Nanjing, while the industrial carbon footprint intensity was inhibitory factor.

(5) Several countermeasures should be taken to decrease urban carbon footprint and alleviate carbon cycle pressure, such as: improvement of the energy efficiency, industrial restructuring, afforestation and environmental protection and land use control. Generally, transition to low-carbon economy is essential for Chinese cities to realize sustainable development in the future.

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