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Temporospatial changes of carbon footprint based on energy consumption in China

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Abstract: Study on regional carbon emission is one of the hot topics under the background of global climate change and low-carbon economic development, and also help to establish different low-carbon strategies for different regions. On the basis of energy consumption and land use data of different regions in China from 1999 to 2008, this paper established carbon emission and carbon footprint models based on total energy consumption, and calculated the amount of carbon emissions and carbon footprint in different regions of China from 1999 to 2008. The author also analyzed carbon emission density and per unit area carbon footprint for each region. Finally, advices for decreasing carbon footprint were put forward. The main conclusions are as follows: (1) Carbon emissions from total energy consumption increased 129% from 1999 to 2008 in China, but its spatial distribution pattern among different regions just slightly changed, the sorting of carbon emission amount was: Eastern China > Northern China > Central and Southern China > Southwest China > Northwest China. (2) The sorting of carbon emission density was: Eastern China > Northeast China > Central and Southern China > Northern China > Southwest China > Northwest China from 1999 to 2003, but from 2004 Central and Southern China began to have higher carbon emission density than Northeast China, the order of other regions did not change. (3) Carbon footprint increased significantly since the rapid increasing of carbon emissions and less increasing area of productive land in different regions of China from 1999 to 2008. Northern China had the largest carbon footprint, and Northwest China, Eastern China, Northern China, Central and Southern China followed in turn, while Southwest China presented the lowest area of carbon footprint and the highest percentage of carbon absorption. (4) Mainly influenced by regional land area, Northern China presented the highest per unit area carbon footprint and followed by Eastern China, and Northeast China; Central and Southern China, and Northwest China had a similar

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medium per unit area carbon footprint; Southwest China always had the lowest per unit area carbon footprint. (5) China faced great ecological pressure brought by carbon emission. Some measures should be taken both from reducing carbon emission and increasing carbon absorption.

Keywords: carbon emissions; carbon sink; carbon footprint; temporospatial changes; China

1 Introduction

Anthropogenic carbon emission from traditional fossil-fuel energy consumption is one of the main causes of global warming, CO_2 emission in China increased more than 73% from 1990 to 2003 with the amount of 17 million tons and China has become the world's second largest carbon emitter (International Energy Agency, 1996; Zou *et al*., 2009). According to data from the Carbon Dioxide Information Analysis Center (CDIAC) (CDIAC, 2011), China is the largest emitter after the United States, with 13.7% of global energy-related carbon dioxide emissions. Under the situation of decreasing CO_2 emission, carbon emissions in China and its changes have become the focus of all countries around the world.

1.1 Researches on carbon emissions

Judging from recent researches, carbon emissions from energy consumption were mainly calculated on national and provincial scales: (1) National scale carbon emissions: Houghton (2008) made a comparison of carbon emissions between China and global from 1850 to 2005 and found China accounts for 5.9% to 18.4% of global energy-related carbon emissions in different years; BP (2010) and World Bank (2009) indicated that China has the highest CO_2 emissions at 6.468 billion tones in 2007 and accounts for 20.85% of the world's total carbon emissions; Li *et al*. (2010) calculated the total carbon emissions and analyzed the changes of the increasing rate from 1953 to 2007 in China and found there were a low growth stage during the period of 1953–1980, a steady growth stage during the period of 1981 to 1996 and a rapid growth stage during the period of 2001–2007, by using the relative statistic data of different industries and the method of IPCC greenhouse gas list, Sun *et al*. (2010) calculated carbon emissions from 1995 to 2005 in China. (2) Provincial level carbon emissions: Based on the method recommended by IPCC, Geng *et al*. (2011) estimated Beijing, Shanghai, Tianjin, and Chongqing's CO_2 emissions from energy consumption in 1990, 1995, 2000 and 2004–2007, and found coal combustion was the leading cause of total CO_2 emissions; by adopting the carbon emission calculating method for all kinds of energy proposed by IPCC in 2006, Hong (2011) calculated the amount of carbon emissions in Shandong Province, China, and found it increased 2.63 times from 1997 to 2008; by using fossil energy consumption data of different provinces and the carbon emission data announced by Oak Ridge national laboratory CO_2 information analysis center in America, Yue *et al*. (2010) calculated carbon emissions from 1995 to 2007 in China at provincial level.

Overall, carbon emissions in China have been widely studied but it was mainly focused on national and provincial scales, China can be divided into several different typical regions such as Northeast China, Northwest China and so on, among which there are quite different industry development and natural conditions, so researches of carbon emission based on regional scales are still needed.

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 emissions of human activities (Wiedmann *et al*., 2008; Lee, 2011), that is to measure it with emission amount. In this view, Christopher *et al*. (2008) calculated household carbon footprint in USA by using the input-output model; Gary *et al*. (2008) founded that carbon footprint produced at Christmas days accounted for 5.5% of the whole year in England of each year; Jeffrey *et al*. (2007) evaluated Hurricane Katrina's carbon footprint on U.S. gulf coast forest; based on apparent consumption, Qi *et al*. (2010) estimated carbon footprint in China from 1992 to 2007 and found it increased nearly 2 times.

The other one regards carbon footprint as part of ecological footprint: that is the ecological carrying capacity required in absorbing CO_2 emissions from fossil fuel combustion (Wiedmann *et al*., 2007; Global Footprint Network, 2003–2009), which measures in area. In this view, Kenny *et al*. (2009) compared and analyzed the performance of six carbon footprint models for use in Ireland; based on global average net ecosystem production (NEP) of forest and grass, Xie *et al*. (2008) made an analysis of ecological footprint (carbon footprint) brought by fossil energy and electricity consumption in China; Zhao *et al*. (2011) calculated carbon footprint of different industrial spaces based on energy consumption in China in 2007 and found that the productive lands were not sufficient to compensate for carbon footprint of industrial activities.

Overall, carbon footprint research is still in its early days and further development is needed, especially when carbon footprint is regarded as part of ecological footprint, carbon sink seems crucial to the calculation of carbon footprint, unlike carbon emissions, the studies of carbon sink were usually carried out on small scale and the research results were quite different from each other. In China, some researches were done on national scale but merely by adopting the global average carbon sink value (Xie *et al*., 2008; Zhao *et al*., 2011) which can not precisely represent the actual situation of different regions in China, then how to precisely evaluate the ecological carrying capacity of absorbing CO_2 emission measured in area still needs further researches.

Based on energy consumption data, land use data and the research results about terrestrial ecosystems carbon sink made by some scholars in China, this paper established carbon emission model and carbon footprint model on regional scale. The objectives of this study were: (1) to calculate and compare carbon emissions from total energy consumption in different regions and different years in China; (2) to calculate the amount of carbon sink absorbed by main terrestrial ecosystems such as forest and grassland in different regions; (3) to calculate and compare carbon footprint based on carbon emissions and carbon sink in different regions and its temporal changes; (4) to explore the way to reduce carbon footprint.

2 Materials and methods

2.1 Study area

Study on carbon emission and carbon footprint of regional scale of China's mainland was made in this paper. China is well known for her massive land and the mainland can usually be divided into six regions. Due to the lack of relevant energy consumption data in Tibet Autonomous Region, Taiwan Province, Hong Kong and Macao Special Administrative Regions, the study area in this paper did not include these areas. As indicated in Figure 1, the studied six areas include Northern China with an area of 152.88×10^6 hm^2, including Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia; Northeast China with an area of 79.18×10^6 hm^2, including Heilongjiang, Jilin, and Liaoning; Eastern China with an area of 80.86×10^6 hm^2, including Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, and Shandong; Central and Southern China with an area of 101.59×10^6 hm^2, including Henan, Hubei, Hunan, Guangxi, Guangdong, and Hainan; Southwest China with an area of 112.56×10^6 hm^2, including Chongqing, Sichuan, Guizhou, and Yunnan; and Northwest China with an area of 304.42×10^6 hm^2, including Shanxi, Gansu, Qinghai, Ningxia, and Xinjiang.

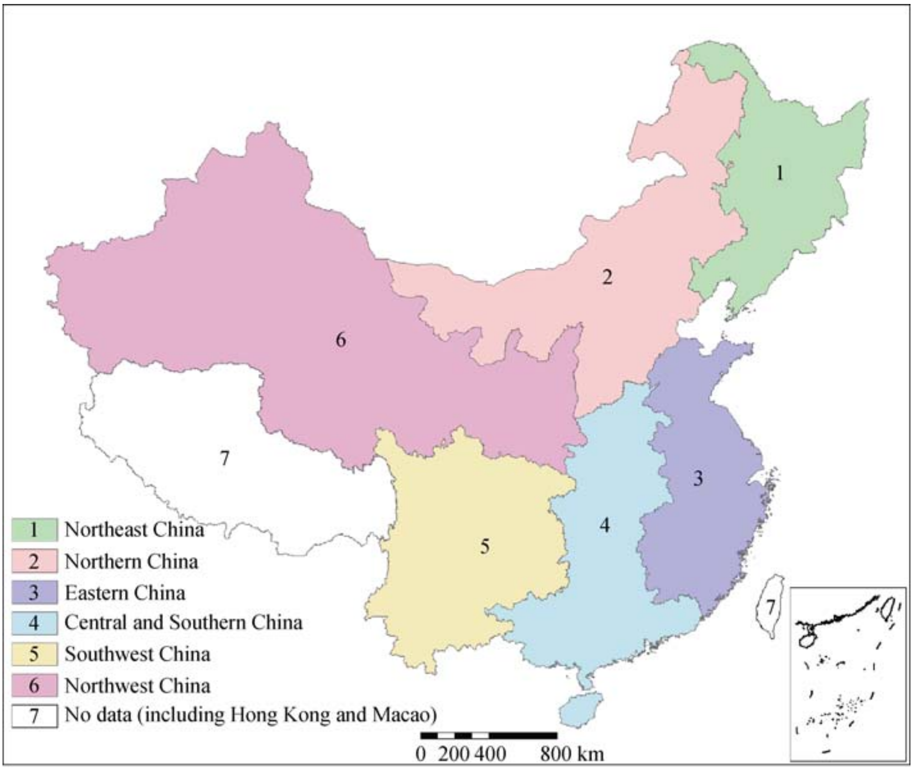

Figure 1 Different regions of China's mainland

2.2 Data sources

At present the main sources of energy are fossil energy, electricity, biomass, solar, hydraulic, wind and nuclear energy, and in traditional energy, fossil energy is the representative and the main cause of carbon emissions. Thus this paper only calculated the carbon emissions from major fossil energy. The data of coal (coal, coke), oil (crude oil, gasoline, diesel, kerosene, fuel oil), natural gas, land use data, GDP from 1999 to 2008 were adopted. Among them, energy consumption data was obtained from "China Energy Statistical Yearbook" (1998–2009), and land use data was obtained from "China Statistical Yearbook"

(2000–2009). 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.

2.3 Carbon emissions from energy consumption

By establishing energy carbon emission model we can calculate annual carbon emissions from major energy consumption in different regions (Formula 1):

$$C = \sum C_t = \sum M_t E_t V_t \tag{1}$$

where C is the total amount of carbon emissions; C_t is carbon emission from energy belonging to type t; M_t is the amount of energy (type t) consumption; E_t is carbon emissions coefficient of energy (type t). The average of coal and natural carbon emissions coefficient from existing researches is adopted here, such as the researches from DOE/EIA, Japan Energy Economy Research Institute, National Science and Technology Commission Climate Change Programs, the Chinese Academy of Engineering, Greenhouse Gas Control Project from National Environmental Protection Administration and so on (Zhao *et al*., 2010) and carbon emission coefficient of other energy types were obtained from IPCC; V_t is the standard coal coefficient of energy (type t). Carbon emission coefficients and standard coal coefficients of main energies are indicated in Table 1.

Table 1 Carbon emission coefficient and standard coal coefficient of main energy

Level 1	Level 2	Carbon emission coefficient (t/t)	Standard coal coefficient (kg/kg)
Coal	Coal	0.7105	0.7143
	Coke	0.855	0.9714
Oil	Oil	0.5857	1.4286
Natural gas	Natural gas	0.4175	1.33(kg/m^3)

2.4 Carbon footprint of different regions

This paper defines carbon footprint as the productive land area needed in absorbing carbon emissions, which means the ecological footprint of carbon emissions (Zhao *et al*., 2011). The productive land mainly includes woodland, grassland and agricultural land. But since carbon emissions absorbed by agricultural vegetation will be decomposed in short term and released into atmosphere (Fang *et al*., 2007) and in this paper the energy carbon emission calculation did not include the carbon emissions from rural biomass energy, thus here carbon absorption from agricultural ecosystem was not considered.

It can be seen that the calculation of carbon footprint is greatly affected by carbon absorption from the productive land, the productive land carbon sink includes carbon absorption both from vegetation and soil covered by vegetation (Fang *et al*., 2007; Pan *et al*., 2003; Lal *et al*., 2002). So it is crucial to determine the value of carbon sink from vegetation and soil before calculating carbon footprint.

As to vegetation, many scholars have made studies of carbon sink (the ability to absorb carbon) from vegetation in different regions of China and Lai (2009) collected more than 800 related researched achievement in recent years which can cover almost all kinds of vegetation in China, according to the comprehensive analysis (Lai, 2009), the values of carbon sink for different vegetation types in China are indicated in Table 2.

Table 2 Carbon sink values for different vegetation types in China

Vegetation	Annual carbon sink (t/hm^2)	Vegetation	Annual carbon sink (t/hm^2)
Boreal, temperate mountain deciduous coniferous forests	0.271	Tropical evergreen broadleaf sclerophyllous coastal scrub, coppice	0.082
Temperate mountain evergreen coniferous forest	0.428	Tropical evergreen broadleaf shrub succulent coral reefs, coppice	0.211
Temperate steppe sandy evergreen coniferous woodland	0.178	Sub-tropical mountains, sub-alpine evergreen scoriaceous scrub, coppice	0.162
Temperate evergreen coniferous forest	0.229	Temperate, subtropical sub-alpine deciduous scrub	0.062
Subtropical and tropical evergreen coniferous forest	0.442	Temperate alpine dwarf shrub tundra	0.063
Subtropical and tropical mountain evergreen coniferous forest	0.428	Temperate, subtropical subalpine cushion-shaped dwarf shrubs, herbaceous vegetation	0.090
Temperate deciduous broadleaf-evergreen conifer mixed forest	0.585	Temperate grass and forb steppe	0.021
Temperate, subtropical deciduous broadleaf forest	0.407	Temperate needlegrass steppe	0.021
Temperate, subtropical deciduous microphylla forest	0.585	Temperate mountain needlegrass steppe	0.021
Temperate deciduous microphylla woodland	0.324	Temperate dwarf needlegrass, semi-dwarf shrub steppe	0.021
Sub-tropical limestone deciduous-evergreen broadleaf mixed forest	0.729	Temperate mountain dwarf grass, semi-dwarf shrub steppe	0.021
Subtropical mountain yellow-soil evergreen-deciduous broadleaf mixed forest	0.729	Temperate, subtropical alpine steppe	0.021
Subtropical evergreen broadleaf forest	0.729	Subtropical and tropical shrub savanna	0.060
Tropical rain forest of evergreen broadleaf forest	0.729	Temperate meadow	0.077
Subtropical evergreen sclerophyllous broadleaf forest	0.624	Temperate and sub-tropical alpline meadow	0.077
Subtropical Bamboo	0.883	Temperate herbaceous swamp	0.389
Tropical semi-evergreen broadleaf forests	0.762	Temperate alpine herbaceous swamp	0.389
Tropical evergreen broadleaf forests and secondary vegetation	0.271	Cultivated vegetation	0.000
Temperate, subtropical deciduous shrub, coppice	0.174	Bare land/Ice/desert	0.000
Subtropical and tropical acid soil evergreen, deciduous broadleaf shrubs, coppice and meadow	0.418	Desert	0.000
Subtropical and tropical limestone evergreen, deciduous shrubs, coppice	0.195		

According to carbon sink value of different vegetation types in Table 2 and Vegetation Type Map of China compiled in the 1980s, we produced vegetation carbon sink map of China as indicated in Figure 2.

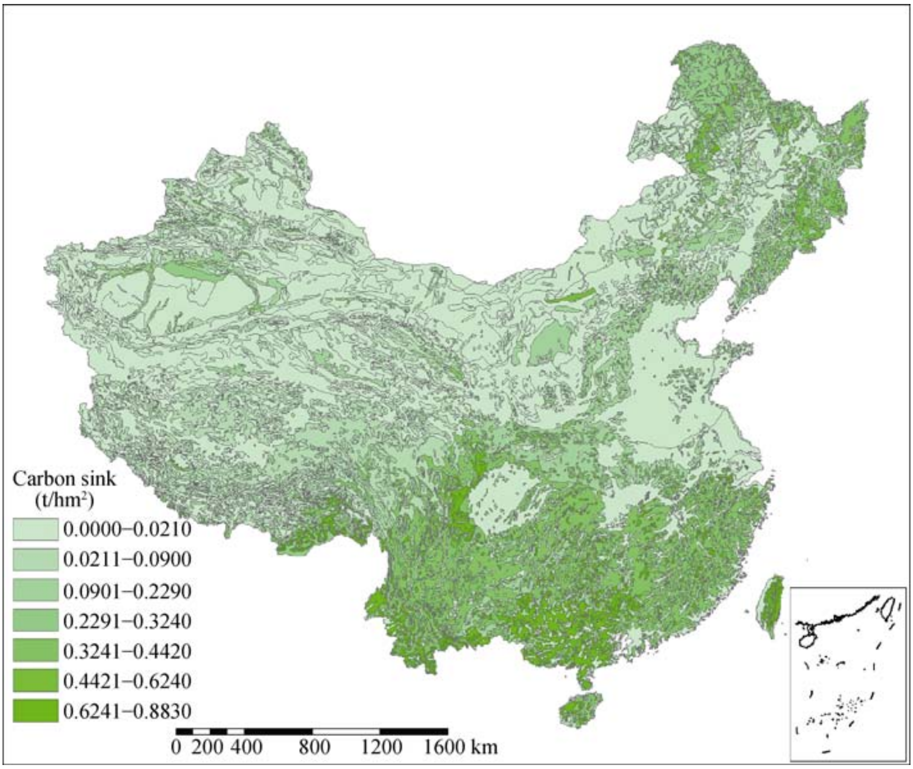

Figure 2 Distribution of annual carbon sink of different vegetations in China

Different vegetations can be classified into different land uses such as woodland and grassland, and by making intersect analysis between Figures 1 and 2 in software ArcGIS9.3, average vegetation carbon sink value of woodland and grassland in different regions can be calculated (Table 3). Since the distribution of vegetations did not change significantly from the 1980s to 2000s, carbon sink values of woodland and grassland in Table 3 can well be used in different years in this paper.

Table 3 Mean carbon sink values of woodland and grassland in different regions of China

Region	Mean annual carbon sink value (t/hm^2)	
	Woodland vegetation	Grassland vegetation
Northern China	0.25	0.03
Northeast China	0.30	0.15
Eastern China	0.42	0.08
Central and Southern China	0.46	0.06
Southwest China	0.35	0.05
Northwest China	0.19	0.04
Total studied area of China	0.34	0.05

Unlike vegetation carbon sink, there is rare detected data of soil carbon sink in China, so it is hard to make a relatively accurate assessment to soil carbon sink. Pacala *et al*. (2001) evaluated that soil carbon sink accounts for about 2/3 of vegetation carbon sink in the United

States. And in Europe soil carbon sink accounts for about 30% of the whole ecosystem (Janssens *et al*., 2003); Piao *et al*. (2009) calculated soil carbon sink in China was 75.4 $Tg.yr^{-1}$ while vegetation (forest, shrub, grass) carbon sink was 105.2 $Tg.yr^{-1}$ from 1980 to 2000; Fang *et al*. (2007) calculated soil carbon sink in China was 41.2–70.8 $Tg.yr^{-1}$ while vegetation (forest, shrub, grass) carbon sink was 96.1–106.1 $Tg.yr^{-1}$ from 1981 to 2000. According to their studies, this paper adopted the average value and regarded soil carbon sink accounting for 65% of vegetation carbon sink.

As analyzed above, the method to calculate carbon footprint is as follows:

$$CF = Ct \times \left(\frac{P_f}{V_f} + \frac{P_g}{V_g}\right) / (1 + 65\%) \quad (2)$$

where CF is carbon footprint (hm^2) brought by the total amount of carbon emissions C_t (t); P_f and P_g are the total carbon absorption proportion of woodland and grassland respectively; V_f and V_g are the annual amount carbon (t/hm^2) absorbed by vegetation of woodland and grassland ecosystem respectively. 65% is the percentage of soil carbon sink accounting for vegetation carbon sink.

3 Results

3.1 Changes of carbon emissions in different regions

As indicated in Figure 3, the amount of carbon emissions in the 6 different regions are much different from 1999 to 2008, Eastern China always had the largest amount of carbon emissions and increased from 236.77×10^6 t in 1999 to 603.47×10^6 t in 2008, which increased nearly 155%. Following Eastern China, Northern China, Central and Southern China also had large amount of carbon emissions with 201.02×10^6 t in 1999 to 451.13×10^6 t in 2008 which increased nearly 124%, and 157.64×10^6 t in 1999 to 377.77×10^6 t in 2008 which increased more than 140%. Northeast China had a medium carbon emissions and the increasing rate was lower compared with other regions, it increased from 142.55×10^6 t in 1999 to 252.56×10^6 t in 2008 with the increasing rate 77%. Carbon emissions in Southwest and Northwest China were low but the increasing rates here were high which increased 110% and 156% respectively.

Overall, carbon emissions from energy consumption in the total 6 regions of China increased obviously. The spatial distribution pattern of carbon emissions among the 6 regions did not change greatly from 1999 to 2008, Eastern China always had the largest amount of carbon emissions, carbon emissions in Northern China, Central and Southern China were

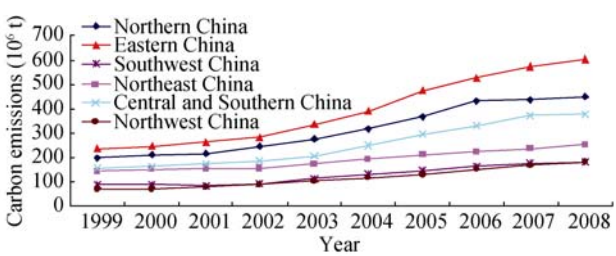

Figure 3 Carbon emissions in different regions of China from 1999 to 2008

also high and also with high increasing rate, carbon emissions in Southwest China and Northwest China were low but with a high increasing rate.

Since the area of each region is different and this can greatly influence its total amount of carbon emissions, in order to make the comparison among different regions more scientifically and precisely, this paper also made a study of carbon emission density from 1999 to 2008 as indicated in Figure 4. The same as the amount of carbon emissions, carbon emission density in Eastern China was also much higher than other regions, the density increased from 2.93 t/hm^2 in 1999 to 7.46 t/hm^2 in 2008. Except Eastern China, carbon emission density in Northeast China was higher than other regions from 1999 (1.8 t/hm^2) to 2003 (2.2 t/hm^2), but from 2004 carbon emissions in Central and Southern China began to increase rapidly and it began to be higher than other regions except Eastern China, and reached 3.72 t/hm^2 in 2008. Following Northeast China, Central and Southern China, carbon emissions in Northern China were higher than in Southwest China and Northwest China, and its carbon emission density increased from 1.31 t/hm^2 in 1999 to 2.95 t/hm^2 in 2008. Carbon emission density in Southwest China was only higher than in Northwest China, its density increased from 1.08 t/hm^2 in 1999 to 2.46 t/hm^2 in 2008 while in Northwest China the density was only 0.23 t/hm^2 in 1999 and 0.59 t/hm^2 in 2008.

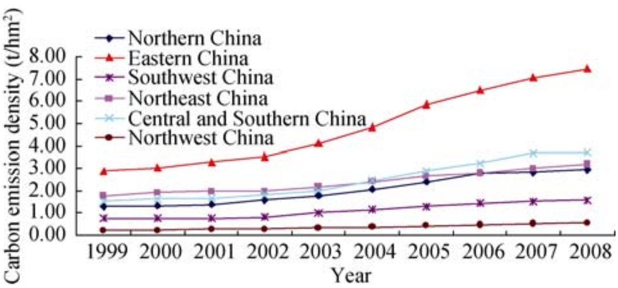

Figure 4 Carbon emission density in different regions of China from 1999 to 2008

Overall, the developed regions usually had high carbon emission density. The average carbon emission density in China's mainland increased rapidly from 1999 to 2008. It can be seen that energy consumption accelerated the growth of economy and also led to high carbon emissions in China.

3.2 Changes of carbon footprint in different regions

Carbon footprint caused by energy consumption increased greatly, but the productive land did increase significantly (woodland and grassland) in different regions of China. As indicated in Table 4, the productive land only increased between 0.22% (Northeast China) and 2.03% (Southwest China) from 1999 to 2008 while energy consumption increased from 77% (Northeast China) to 156% (Northwest China). This led to a great increase of carbon footprint from 1999 to 2008. Northern China had the largest carbon footprint with an area of 1267.82×10^6 hm^2 in 1999 and increased to 2697.67×10^6 hm^2 in 2008, according to the area of its productive land, Northern China can only absorb 7.65%–3.65% of its carbon emissions from 1999 to 2008. Southwest China had the lowest largest carbon footprint with an area of 190.45×10^6 hm^2 in 1999 and increased to 396.52×10^6 hm^2 in 2008, the vegetation (forest, shrub, grass) and soil in this region can only absorb 35.66%–17.48% of its carbon emissions from 1999 to 2008. Though carbon emissions were the lowest in Northwest China where there is the highest area of productive land, the value of carbon sink is much lower than other regions (Table 3). This made it also have large area of carbon footprint, with the area of 616.93×10^6 hm^2 in 1999 and 1531.45×10^6 hm^2 in 2008, productive land in this region can absorb 21.66%–8.82% of its carbon emissions from 1999 to 2008. Carbon emissions in Eastern China was the highest and it had the lowest area of productive land compared with

Table 4 Comparison of carbon footprint and productive land in different regions of China from 1999 to 2008

Item	Year	Region						
		Northern China	Northeast China	Eastern China	Central and Southern China	South-west China	Northwest China	Total studied area
Productive land area (10^6 hm^2)	1999	96.94	41.33	29.25	46.44	67.92	133.65	415.54
	2000	96.78	41.33	29.25	46.42	68.09	133.56	415.43
	2001	96.93	41.32	29.24	46.45	68.15	133.83	415.91
	2002	97.42	41.35	29.29	46.58	68.36	134.12	417.12
	2003	98.20	41.50	29.55	46.95	68.97	134.78	419.96
	2004	98.46	41.46	29.59	47.01	69.22	134.90	420.63
	2005	98.39	41.44	29.63	47.04	69.29	135.01	420.81
	2006	98.48	41.42	29.68	47.05	69.35	135.01	420.99
	2007	98.46	41.42	29.63	47.02	69.33	135.00	420.86
	2008	98.46	41.42	29.57	47.00	69.30	135.00	420.76
Increasing rate (%)	–	1.57	0.22	1.10	1.22	2.03	1.01	1.26
Carbon footprint (10^6 hm^2)	1999	1267.82	300.04	346.90	212.85	190.45	616.93	2529.61
	2000	1324.80	324.72	363.27	225.98	191.51	628.44	2652.21
	2001	1366.90	328.94	387.97	235.24	187.50	713.76	2767.08
	2002	1517.30	328.74	418.49	251.40	203.25	785.46	2973.78
	2003	1691.51	365.59	487.98	279.46	250.70	889.74	3389.05
	2004	1912.75	406.12	574.28	340.09	290.29	995.65	3920.87
	2005	2208.97	444.04	696.84	398.50	320.34	1126.87	4546.01
	2006	2581.28	469.07	768.43	446.00	356.56	1291.98	5087.49
	2007	2618.13	499.23	837.95	501.65	382.76	1418.95	5467.76
	2008	2697.67	530.38	883.00	509.14	396.52	1531.45	5703.19
Increasing rate (%)	–	112.78	76.77	154.54	139.21	108.20	148.24	125.46
The percentage of carbon absorption accounting for carbon emissions (%)	1999	7.65	13.78	8.43	21.82	35.66	21.66	16.43
	2000	7.31	12.73	8.05	20.54	35.55	21.25	15.66
	2001	7.09	12.56	7.54	19.74	36.34	18.75	15.03
	2002	6.42	12.58	7.00	18.53	33.63	17.08	14.03
	2003	5.81	11.35	6.06	16.80	27.51	15.15	12.39
	2004	5.15	10.21	5.15	13.82	23.84	13.55	10.73
	2005	4.45	9.33	4.25	11.81	21.63	11.98	9.26
	2006	3.82	8.83	3.86	10.55	19.45	10.45	8.27
	2007	3.76	8.30	3.54	9.37	18.11	9.51	7.70
	2008	3.65	7.81	3.35	9.23	17.48	8.82	7.38

others, but since value of carbon sink is high, carbon footprint here was much lower than in Northwest China with the area of 346.9×10^6 hm^2 in 1999 and 883×10^6 hm^2 in 2008, but the productive land here can only absorb 8.43%–3.35% of its carbon emissions. The area of productive land in Central and Southern China differed not much compared with that in Northeast China and carbon emissions here were much higher than in Northeast China (Figure 3), but since the value of carbon sink is much higher (Table 3), the area of carbon footprint in the two regions differed not too much, the vegetation (forest, shrub, grass) and soil in the two regions can absorb 13.78%–7.81% and 21.82%–9.23% of their carbon emissions from1999 to 2008 respectively.

Overall, carbon footprint in China increased 125.46% from 1999 (2529.61×10^6 hm^2) to 2008 (5703.19×10^6 hm^2), vegetation (forest, shrub, grass) and soil in China can absorb 16.43% of its carbon emissions from energy consumption but it decreased to 7.38% in 2008. Northern China had the largest carbon footprint and the lowest percentage of carbon absorption, which is the region under the maximum ecological pressure. Following Northern China, Northwest China, Eastern China, Northern China, Central and Southern China also face a great and increasing ecological pressure from 1999 to 2008. Southwest China presented less ecological pressure with the lowest area of carbon footprint and the highest percentage of carbon absorption compared with others.

As indicated in Table 5, per unit area carbon footprint caused by energy consumption in the studied area of China was 3.04 hm^2/hm^2 in 1999 and increased to 6.86 hm^2/hm^2 in 2008. There were significant regional differences. From 1999 to 2008, Northern China had the highest per unit area carbon footprint of 8.29–17.65 hm^2/hm^2. Following Northern China, per unit area carbon footprint in Eastern China and Eastern China were also high with the value between 4.29 and 10.92 hm^2/hm^2 and between 3.79 and 6.7 hm^2/hm^2, while Southwest China always had the lowest per unit area carbon footprint of 1.69–17.65 hm^2/hm^2. Compared with other regions, Central and Southern China, Northwest China had a similar medium per unit area carbon footprint from 1999 to 2008.

The results indicated that per unit area carbon footprint was determined not only by the amount of carbon emissions but also by its land area and the ability of carbon absorption brought by vegetation and soil. Mainly influenced by the three factors, Northern China

Table 5 Comparison of per unit area carbon footprint in different regions of China from 1999 to 2008

Item	Year	Region						
		Northern China	Northeast China	Eastern China	Central and Southern China	Southwest China	Northwest China	Total studied area
Regional land area (10^6 hm^2)	–	152.88	79.18	80.86	101.59	112.57	304.42	831.51
Per unit area carbon footprint (hm^2/hm^2)	1999	8.29	3.79	4.29	2.09	1.69	2.03	3.04
	2000	8.67	4.10	4.49	2.22	1.70	2.06	3.19
	2001	8.94	4.15	4.80	2.32	1.67	2.34	3.33
	2002	9.92	4.15	5.18	2.47	1.81	2.58	3.58
	2003	11.06	4.62	6.03	2.75	2.23	2.92	4.08
	2004	12.51	5.13	7.10	3.35	2.58	3.27	4.72
	2005	14.45	5.61	8.62	3.92	2.85	3.70	5.47
	2006	16.88	5.92	9.50	4.39	3.17	4.24	6.12
	2007	17.13	6.30	10.36	4.94	3.40	4.66	6.58
	2008	17.65	6.70	10.92	5.01	3.52	5.03	6.86

presented the highest per unit area carbon footprint and was followed by Eastern China, Northern China. Central and Southern China, Northwest China had a similar medium per unit area carbon footprint and Southwest China always had the lowest per unit area carbon footprint.

4 Discussion

4.1 Carbon emissions

Carbon emissions from energy consumption calculated in this paper increased from 895.68×10^6 t (0.90 Gt) in 1999 to 204.84×10^6 t (2.05 Gt) in 2008 which increased nearly 129%, and this result was slightly higher than that of other Chinese scholars in recent years (Table 6). The main reason was that energy consumption in this paper refers to the total energy, it not only includes the final energy consumption studied by other scholars (Zhao *et al*., 2011; Hu *et al*., 2008; Xiao, 2008; Liu *et al*., 2008; Wei *et al*., 2008) but also includes the loss during energy transformation and the course of transformation, distribution, storage and the loss caused by any objective reason in a given period of time.

Table 6 Comparison of results with other authors

Year	Carbon emissions of this paper (Gt)	Carbon emissions of other authors (Gt)
1999	0.90	0.79 (Chunbo *et al*.); 0.82 (Houghton *et al*.);
2000	0.94	0.85 (Chunbo *et al*.); 0.79 (Houghton *et al*.)
2001	0.98	1.1 (Chunbo *et al*.)
2002	1.06	0.98 (Hu *et al*., 2008)
2003	1.21	1.13 (Xiao, 2008)
2004	1.40	1.28 (Xu *et al*., 2006); 1.37 (Wei *et al*., 2008)
2005	1.63	1.5 (Lai, 2009); 1.51 (Liu *et al*., 2008)
2006	1.83	1.66 (Xu, 2010)
2007	1.96	1.78 (CDIAC, 2010); 1.46 (Zhao *et al*., 2011)
2008	2.05	–

4.2 Carbon footprint

Carbon footprint was greatly affected by carbon emissions and the value of carbon sink brought by vegetation and soil. As discussed above, carbon emissions in this paper were slightly higher than that of other Chinese scholars. As for the value of vegetation carbon sink, according to the actual situation of China, this paper quoted the study of Lai (2009) who have made a summary of related researches in recent years, about carbon sink value of different vegetations. But the vegetation carbon sink values were much lower than the study of Xie *et al*. (2008) and Zhao *et al*. (2011) who used the average global NEP (net ecosystem production) value of forest and grass to describe the ability to absorb carbon. Due to slightly higher carbon emissions and much lower vegetation carbon sink value, carbon footprint in this paper was much higher than in the study of Xie *et al*. (2008) and Zhao *et al*. (2011), but the calculated results in this paper should be much more accurate because it considered the characters of vegetation types, its distribution and its actual net ecosystem production in China, and what is more, this paper also considered carbon sink brought by soil. In this way, the amount of carbon absorbed by vegetation and soil was 135.7–139.2 $Tg.yr^{-1}$ from 1999 to

2008 and this result is very close to the study of Fang *et al*. (2007) and Lai (2009).

Since land area in the 6 regions differed much, the sorting of per unit area carbon footprint did not totally agree with the sorting of carbon footprint, for example, Northwest China had the second largest area of carbon footprint among the 6 regions, but since it has large region area, the per unit area carbon footprint in this region was low. This indicated that the large land area can decrease the ecological pressure it faced.

4.3 Policy recommendations

As analyzed above, carbon footprint was determined by carbon emissions and carbon sink value. In order to reduce regional carbon footprint, some measures should be taken from two aspects of how to reduce carbon emissions and how to increase carbon absorption.

Since the use of fossil energy is the primary reason causing carbon emissions and especially coal was the main energy consumption in China which can lead to great carbon emissions, the traditional energy structure must be innovated and the use of clean energy should be increased. Energy consumption in different industries differed much and that made most of carbon emissions focus on some energy-intensive industries such as steel and non-ferrous metal industry, cement industry and so on. So China should adjust its industrial structure, not only adjust the structure among the primary industry, the secondary industry and the tertiary industry, but also adjust the specific industries structure of the three industries. Such as decrease some energy-intensive industries and increase some low pollution industries. What is more, the efficiency of energy use in China is low, then how to improve energy efficiency seems an effective way to reduce carbon emissions, which is also a challenge to China.

In terrestrial ecosystem, carbon emissions will mainly be absorbed by vegetation (especially forest and grass) and its covered soil as discussed in this paper, some measures should be taken to increase the carbon absorption. Firstly, the area of productive land should be protected, especially the woodland which has the highest production compared with other land use types. Secondly, ecological management should be strengthened to enhance the carbon fixation efficiency of productive land, such as to prohibit the behavior of deforestation and over-grazing, to make soil less disturbed and so on. Thirdly, according to the local climatic and soil environment, plant more vegetation which can adapt to its local natural environment and can absorb carbon more effectively.

5 Conclusions

Based on energy consumption data, land use data and carbon sink values of different vegetations in the main 6 regions of China from 1999 to 2008, by establishing energy carbon emission and carbon footprint models, this paper carried out studies on the amount of carbon emissions from total energy consumption and carbon footprint in different regions of China, and also analyzed carbon emission density, per unit area carbon footprint in different regions. The results showed:

1) Carbon emissions from energy consumption in different regions of China all increased significantly from 1999 to 2008. Eastern China always had the largest amount of carbon emissions, and in Northern China, Central and Southern China it was also high. There was also high increasing rate, while carbon emissions in Southwest China and Northwest China were low but the increasing rate was high from 1999 to 2008. The sorting of carbon emis-

sion density was: Eastern China > Northeast China > Central and Southern China > Northern China > Southwest China > Northwest China from 1999 to 2003, but from 2004 Central and Southern China began to have higher carbon emission density than Northeast China while the sorting of other regions did not change.

2) Carbon footprint increased significantly since the rapid increasing of carbon emissions, but not significantly changed area of productive land in different regions of China. Northern China had the largest carbon footprint and the lowest percentage of carbon absorption. Following Northern China, Northwest China, Eastern China, Northern China, Central and Southern China also faced a great and increasing ecological pressure from 1999 to 2008; Southwest China presented less ecological pressure with the lowest area of carbon footprint and the highest percentage of carbon absorption compared with others. Mainly influenced by regional land area, Northern China presented the highest per unit area carbon footprint and was followed by Eastern China, Northern China in turn; Central and Southern China, Northwest China with a similar medium per unit area carbon footprint; Southwest China always had the lowest per unit area carbon footprint.

3) China faced great ecological pressure brought by carbon emissions. Some measures should be taken both from reducing carbon emissions and increasing carbon absorption. That includes adjusting the structure of industries, improving energy efficiency, increasing or at least not decreasing the area of productive land, prohibiting the behavior of deforestation and over-grazing, making soil less disturbed and so on.

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