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Carbon Emission of Regional Land Use and Its Decomposition Analysis: Case Study of Nanjing City, China

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Abstract: Through the matching relationship between land use types and carbon emission items, this paper estimated carbon emissions of different land use types in Nanjing City, China and analyzed the influencing factors of carbon emissions by Logarithmic Mean Divisia Index (LMDI) model. The main conclusions are as follows: 1) Total anthropogenic carbon emission of Nanjing increased from 1.22928×10^7 t in 2000 to 3.06939×10^7 t in 2009, in which the carbon emission of Inhabitation, mining & manufacturing land accounted for 93% of the total. 2) The average land use carbon emission intensity of Nanjing in 2009 was 46.63 t/ha, in which carbon emission intensity of Inhabitation, mining & manufacturing land was the highest (200.52 t/ha), which was much higher than that of other land use types. 3) The average carbon source intensity in Nanjing was 16 times of the average carbon sink intensity (2.83 t/ha) in 2009, indicating that Nanjing was confronted with serious carbon deficit and huge carbon cycle pressure. 4) Land use area per unit GDP was an inhibitory factor for the increase of carbon emissions, while the other factors were all contributing factors. 5) Carbon emission effect evaluation should be introduced into land use activities to formulate low-carbon land use strategies in regional development.

Keywords: carbon emission; land use; intensity; Logarithmic Mean Divisia Index (LMDI) model; decomposition analysis; Nanjing City

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1 Introduction

To explore the impact of human activities on global carbon cycle, anthropogenic carbon emission has become one of the major concerns in academic circles (Soytasa *et al.*, 2007). The most important anthropogenic influences on climate are greenhouse gas emission and land use change (Kalnay and Cai, 2003). Land use change will directly influence the carbon storage and fluxes of terrestrial ecosystems. It has been one of the main factors that caused the rapid growth of CO_2 concentration in the atmosphere (Quay *et al.*, 1992; DeFries *et al.*, 1999; Houghton *et al.*, 1999; McGuire *et al.*, 2001; Houghton and Hackler, 2003). Recently, there appeared some studies about the impact of land use change on regional carbon cycle. For example, Houghton (1999) found that changes in land use have added 124 Pg C to the atmosphere, about half as much as the carbon released from fossil fuels during 1850–1990. While, the net carbon fluxes attributable to land use management offset 10%–30% of US fossil fuel emissions during the 1980s (Houghten, 1999). Fang *et al.*

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(2001) concluded that planted forests in China have sequestered 0.45 Pg C since the mid-1970s, suggesting that the carbon sequestered by forest management practices could offset human carbon emissions. In the past 200 years, carbon emissions from land use changes in China′s terrestrial ecosystems were about 4.50–9.54 Pg C (Ge *et al.*, 2008). Due to the complexity of human activities, carbon flux of different land use types is quite different from one another. Therefore, it also remains uncertainty about the impacting extent of land use on carbon cycle, regional differences and carbon emission intensity, *etc*. (Schindler, 1999).

Recently, there appeared some studies on carbon emissions of regional land use, which mainly include two aspects: 1) Carbon emission from land use changes and its driving forces. Some studies suggested that carbon emissions and carbon sequestration rate was drastically influenced by land use changes (Koemer and Klopatek, 2002; Zhang *et al.*, 2012), especially by the urbanization (urban expansion) processes (Zhang *et al.*, 2012; Ali and Nitivattananon, 2012) and the corresponding energy consumption (Araujo *et al.*, 2009) and bio-fuel feedstock production (Kwon *et al.*, 2013). Based on land use perspective, the spatial distribution of carbon emissions could be simulated on certain scale of areas (Christen *et al.*, 2010). Those studies mainly discussed the natural carbon processes of land use change and the impact of land use change on human carbon emissions, which gave us different views on the relationship between carbon emissions and land use. 2) Carbon emissions of different land use types based on energy consumption. The carbon dynamics caused by land use changes could be studied by the division of different land use types, through which we could accurately explore the carbon emission effect of different land use types. For examples, Svirejeva-Hopkins and Schellnhuber (2006) simulated the carbon dynamics and carbon input and output caused by urban land use changes. Lai and Huang (2011) and Zhao *et al.* (2011) estimated carbon emissions of different land use types and industrial spaces in each province of China respectively. The above studies were mainly focused on the carbon emissions from energy consumption, but the other carbon sources such as carbon emissions from natural process, respiration, industrial or agricultural activities and wastes was not involved, and the whole carbon estimation system based on land use was not established. Further, the land use division in the above studies was not suitable for the land classification system of China. Therefore, studies on carbon emissions of regional land use should be further enhanced for raising the estimation accuracy. Generally, energy consumption, population increase, urbanization, industrial structure and land use are main factors that influence regional carbon emissions. Therefore, the influencing factors of regional carbon emissions should be further discussed to analyze the driving forces of carbon emission.

Decomposition analysis is one of the most effective and widely applied tools for investigating the mechanisms influencing energy consumption and its environmental side-effects. There are two commonly used decomposition methods in the literature: Index Decomposition Analysis (IDA) and Structural Decomposition Analysis (SDA) (Malla, 2009)˙ Ang (2004) recommended Logarithmic Mean Divisia Index (LMDI) method over other IDA methods because this method has several desirable advantages including time independence, ability to handle zero values and consistency in aggregation. Since then, LMDI method was widely used in the researches on carbon emissions. For instance, Tunc *et al.* (2009) studied the influencing factors that contributing to the changes in carbon emissions for the Turkish economy by using LMDI method. Ma and Stern (2008) investigated China's carbon emissions during 1971–2003, with particular focus on the role of biomass, by using LMDI model. Zhao *et al.* (2010) studied the influencing factors of industrial carbon emissions in Shanghai through LMDI model. Xu *et al.* (2006), Liu and Liu (2009) and Liu *et al.* (2007) studied the per capita carbon emissions and industrial carbon emissions respectively by LMDI model. Tian *et al.* (2012) and Shao *et al.* (2014) discussed the changes of carbon emissions of Beijing and Tianjin by Structural decomposition analysis and LMDI decomposition model respectively. The above studies mostly focused on influencing factors of carbon emission from energy consumption, and mainly discussed the impacts of economic development, industrial structure and energy efficiency on carbon emissions. Actually, land use is one of the most important factors that influence regional carbon emission. The alteration of land use structure will change the pattern, structure of human energy consumptions, and further affect the natural or anthropogenic carbon emission intensity and regional carbon cycle efficiency. The impact of anthropogenic activities on regional carbon cycle is largely achieved by changing the land use structure and pattern. But the former studies rarely considered the land use indicators, and the decomposition analysis of carbon emissions based on land use has not yet been put forward.

Researches on carbon emission of regional land use helps to understand the interaction mechanism between land use and carbon emissions, and will provide suggestions on regional carbon emission reduction for policy-makers. Therefore, through comprehensively estimating the carbon emissions of Nanjing City, Jiangsu Province, China, this paper established the matching relationship between land use types and carbon emission items according to land use classification system of China and analyzed the carbon sources and sinks of different land use types. Then, the influencing factors of regional carbon emissions were analyzed through LMDI decomposition method by introducing land use indicators into the model. This study will not only provide a new thought for study regional carbon emission based on land use, but also help to guide the carbon emission effect evaluation of regional land use.

2 Materials and Methods

2.1 Study area and data sources

Because China's statistical system was divided by administrative regions, Nanjing City in this paper means Nanjing administrative region, which includes 11 urban districts (Gulou, Xuanwu, Qixia, Qinhuai, Jianye, Yuhuatai, Liuhe, Pukou, Jiangning, Lishui and Gaochun) (Fig. 1). The total area of Nanjing City is 6582.31 km^2 and the time span of this study was 2000–2009.

Population, GDP, urban waste, crop yield, livestock, rice field area and industrial production were from the *Statistical Yearbook of Nanjing City* (Nanjing Statistical Bureau, 2010a) and *Statistical Yearbook of Jiangsu Province* (Statistical Bureau of Jiangsu Province, 2010); energy consumption data were derived from the *Environmental Report of Jiangsu Province*①, *Statistical Yearbook of Nanjing City* (Nanjing Statistical Bureau,

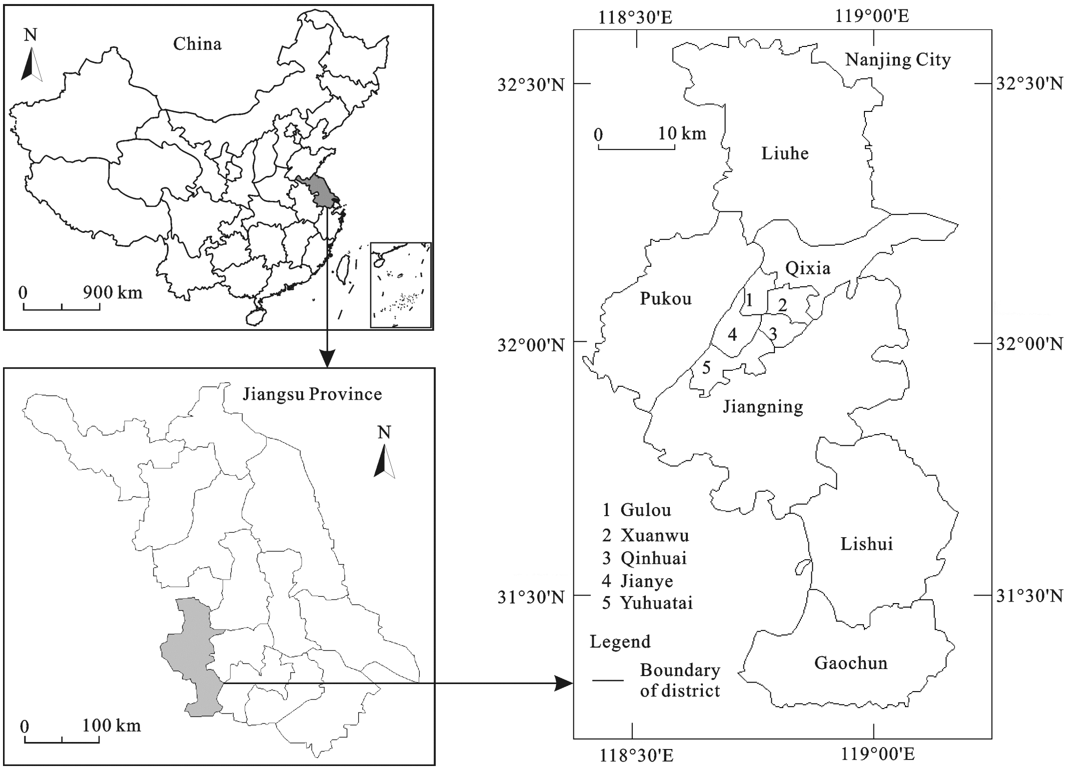

Fig. 1 Location and administrative divisions of Nanjing City

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① Department of Housing and Urban-rural Development of Jiangsu Province. *Urban Construction Statistical Report of Jiangsu Province, 2000–2009*.

2010a) and *General Economic Surveying Yearbook of Nanjing* (Nanjing Statistical Bureau, 2010b); living energy consumption data of Nanjing were from the *2009 China Urban Construction Statistical Yearbook* (Ministry of Housing and Urban-rural Development of China, 2010) and *Urban Construction Statistical Report of Jiangsu Province*①; soil data were derived from the sampling data (100 cm 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.

2.2 Mechanism and framework of carbon emission from land use

With different natural processes and anthropogenic activities, each land use type has different carbon emission intensity. In this paper, land use was divided into eight types (Fig. 2) according to Land Use Classification System of China. In essence, each land use type are both carbon source and carbon sink, but the intensity of carbon source/sink of different land use types were quite different. Generally speaking, carbon emissions from energy consumption and industrial activities on Inhabitation, mining & manufacturing land and Transportation land are the main carbon sources, while there is also carbon emitted from living energy consumptions, human wastes and cultivation activities on Cultivated land, Garden land, Forest land and Water body. On the opposite, the carbon absorption of Cultivated land, Garden land, Forest land, Grazing & pasture land and Water body are the main carbon sinks, while there is also carbon sinks by photosynthesis of urban greenbelt on Inhabitation, mining & manufacturing land. The detailed processes of carbon sources/sinks of each land use type were shown in Fig. 2.

Here, several explanations about Fig. 2 should be noted: 1) Inhabitation, mining & manufacturing land is both carbon source and carbon sink, but the intensity of carbon source is much stronger than that of carbon sink. 2) Cultivated land, Garden land, Forest land, Grazing & pasture land and Water body are both carbon sinks and carbon sources, but the intensity of carbon sink of those land use types are generally higher than that of carbon source. 3) For few human activities, carbon emission of Unused land could be neglected. But there exists carbon absorption processes by photosynthesis of natural vegetation on unused land. 4) Transportation land is just shown as a carbon source but not carbon sink. 5) Carbon emissions of different land uses could be divided into natural and anthropogenic processes. Carbon emissions from vegetation, soil and water belong to natural processes, while carbon emissions from anthropogenic activities belong to anthropogenic processes. Therefore, in order to establish a comprehensive carbon emission estimation model, the natural and anthropogenic carbon sources/sinks should be both involved.

2.3 Methods for carbon emission estimation

2.3.1 Carbon emissions from energy consumption

Energy consumption is the most important carbon sources, which has been studied by many researchers. Based on the calculation method of the IPCC (2006),

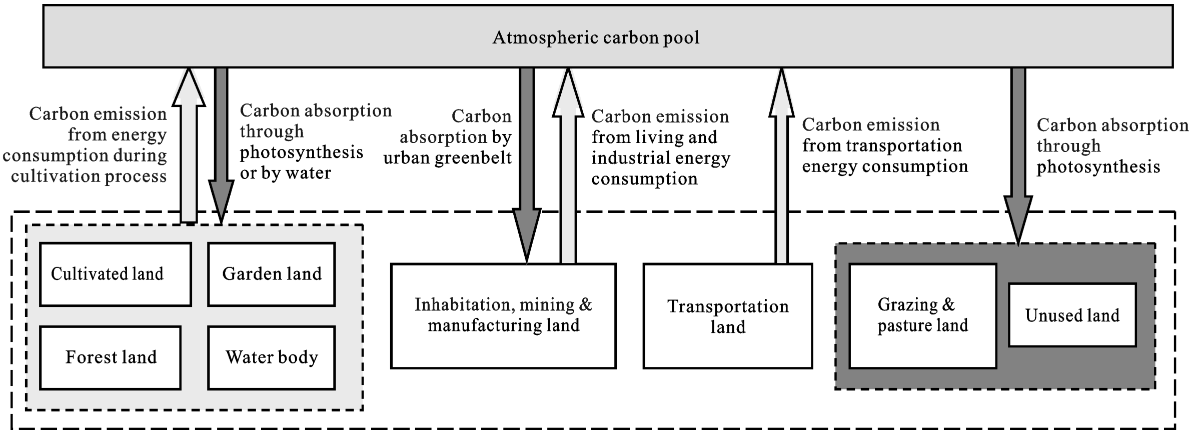

Fig. 2 Main processes of carbon sources/sinks of different land use types

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① Environmental Protection Department of Jiangsu Province. *Environmental Report of Jiangsu Province, 2000–2009*.

carbon emission from energy consumptions (which includes fossil energy, electricity and biomass energy) was estimated by Equation (1).

$$CE_{\text{energy-}i} = Q_{\text{energy-}i} \times H_{\text{energy-}i} \times (C_{\text{energy-}i} + M_{\text{energy-}i}) \tag{1}$$

where $CE_{\text{energy-}i}$ is carbon emission from energy consumption type i; $Q_{\text{energy-}i}$ is the consumption of energy type i; $H_{energy\text{-}i}$ is net calorific value of energy type i; $C_{\text{energy-}i}$ is CO_2 emission factor of energy type i; and $M_{\text{energy-}i}$ is CH_4 emission factor of energy type i. $H_{\text{energy-}i}$ was derived from the *China Energy Statistical Yearbook* (National Bureau of Statistics of China, 2008), and carbon emission factors ($C_{\text{energy-}i}$ and $M_{\text{energy-}i}$) of each energy type were derived from IPCC (2006).

2.3.2 Carbon emission from industrial production processes

Carbon will be emitted from the production processes (except for fossil fuel combustion) of several industrial products. For example, during the production of cement, CO_2 will be emitted from the lime combustion process. In this paper, carbon emission factors of 0.136 t CO_2/t (Fang *et al.*, 1996), 1.06 t CO_2/t, 0.687 t CO_2/t, 0.21 t CO_2/t, 3.273 t CO_2/t (Cai *et al.*, 2009) were used to estimate the carbon emissions from the production of cement, steel, lime, glass and synthesis ammonia, respectively.

2.3.3 Carbon emission from agricultural activities

Carbon emissions from agricultural activities include CH_4 emission from paddies and ruminant animals and CO_2 emission from straw combustion. According to IPCC (2006), methane emission from rice production was estimated by paddy area, rice production cycle and carbon emission factor. Here, the parameters of carbon emission factor of paddies in Jiangsu Province were adopted, which were derived from Tang *et al.* (2009). CH_4 emission from ruminant animals was estimated by CH_4 emission factors of each animal (IPCC, 2006; Cai *et al.*, 2009). Carbon emission from straw combustion was estimated through Formula (1) by using straw yield of Nanjing and the combustion ratio of straw (10%, which was get from Nanjing Committee of Development and Reform).

2.3.4 Carbon emission by respiration

Carbon emission by respiration was estimated by population and animal numbers. Per capita annual respiration rate is 0.079 t C (Fang *et al.*, 1996). Annual carbon emission factor of respiration by pig and cattle was 0.082 t C and 0.796 t C (Kuang *et al.*, 2010) respectively. For lack of carbon emission factor, carbon emitted from respiration of other animals was ignored.

2.3.5 Carbon emission from solid wastes

According to IPCC (2006), the two main final disposal ways of solid wastes are burning and burying. Carbon emission from the two processes can be estimated by the following methods:

$$CE_{\text{waste-burn}} = Q_{\text{waster-burn}} \times C_{\text{waste}} \times P_{\text{waste}} \times EF_{\text{waste}} \tag{2}$$

$$CE_{\text{waste-fill}} = Q_{\text{waste-fill}} \times 0.167 \times (1 - 71.5\%) \tag{3}$$

where $CE_{\text{waste-burn}}$ is the total carbon emission from burning process of solid wastes; $Q_{\text{waste-burn}}$ is the amount of solid wastes that were burned; C_{waste} is the carbon content rate of solid wastes (default value is 40%,) (IPCC, 2006); P_{waste} is the mineral carbon content rate of solid wastes (default value is 40%); EF_{waste} is the burning efficiency (default value is 95%) (Cai *et al.*, 2009); $CE_{\text{waste-fill}}$ is the total CH_4 emission from buried solid wastes; $Q_{\text{waste-fill}}$ is the amount of solid wastes that were buried. The default CH_4 emission factor of buried solid wastes is 0.167 t/t (IPCC,2006), and the water content of solid wastes is 71.5% (Guo, 2009).

2.3.6 Carbon emission from waste water

Carbon emissions from waste water include carbon emissions from life waste water and industrial waste water. The estimation methods are as follows (IPCC, 2006):

$$CE_{\text{liv-water}} = Num_{\text{people}} \times BOD_{\text{capita}} \times SBF \times C_{\text{BOD}} \times 0.8 \times 365 \tag{4}$$

$$CE_{\text{ind-water}} = Q_{\text{ind-water}} \times COD_{\text{ind-water}} \times C_{\text{COD}} \tag{5}$$

where $CE_{\text{liv-water}}$ is annual CH_4 emissions from life waste water; Num_{people} is population number; BOD_{capita} is per capita content of Biochemical Oxygen Demand (BOD) in life waste water (60 g BOD/d); SBF is the ratio of deposited BOD (50%); C_{BOD} is CH_4 emission factor of BOD (0.6 g CH_4/g BOD); $CE_{\text{ind-water}}$ is CH_4 emissions from industrial waste water; $Q_{\text{ind-water}}$ is the yield of industrial waste water; $COD_{\text{ind-water}}$ is the content of Chemical Oxygen Demand (COD) in industrial waste water (kg COD/m^3); C_{COD} is the CH_4 emission factor of industrial waste water (the default value is 0.25 kg CH_4/kg COD) (IPCC, 2006).

2.3.7 Carbon emission from natural processes

Natural carbon emissions include carbon from respiration by vegetation and soil and the carbon emission from water volatility. Carbon emission from vegetation respiration was estimated by per unit area carbon emission factors of different vegetation types, which were determined by Net Primary Productivity (NPP) and derived from Xie *et al.* (2008) and Fang *et al.* (1996). Carbon emission from soil respiration was calculated by the average respiration rate of different soil types, which was determined by the litter ratio of different vegetation types (Fang *et al.*, 1996). Carbon emission from water volatility was estimated by carbon emission factor of river and lake, which is 0.026 t/(km^2·yr) (the value for the Changjiang (Yangtze) River) and 0.041 t/(km^2·yr) (the value for East China Plain) respectively (Ye and Chen, 1992).

2.4 Methods for carbon sink estimation

The carbon sinks mainly include that of vegetation and water body. The former include carbon sink of different vegetation types, while the latter include the carbon sequestration and the dry & wet deposition of water body. The carbon sink of forest, grassland and urban greenbelt was estimated by their areas and the corresponding NPP factors. Here, the average NPP factor of forest, grassland and urban greenbelt is 3.810 t/(ha·yr), 0.948 t/(ha·yr) (Xie *et al.*, 2008) and 3.378 t/(ha·yr) (Guan *et al.*, 1998) respectively. Carbon sink of Cultivated land was estimated by the method of Li (2000) and Fang *et al.* (2007), which was calculated by the crop yield, economic coefficient, carbon absorption rate and moisture content of each crop type. The carbon sequestration of Water body was estimated by the carbon sequestration rate and the area of water body. Here, the carbon sequestration rate of river (lake) and shallows is 0.567 t/(ha·yr) and 2.356 t/(ha·yr) respectively (the value of East China Plain) (Duan *et al.*, 2008). The carbon sinks of dry & wet deposition was estimated by the regional area and the dry & wet deposition factor (5.208 t/(km^2·yr)) (the value of Jiangsu Province) (Ye and Chen, 1992).

2.5 Matching relationship between different land use types and carbon emissions

According to the theoretical framework of Fig. 2, the matching relationship between land use types and carbon emissions was established according to Land Use Classification System and Energy Balance Table of China (National Bureau of Statistics of China, 2008), as shown in Table 1.

It should be noted that: 1) Actually, there also exsits carbon fluxes on unused land, but it was ignored in this paper because there is few Unu sed land in Nanjing. 2) Considering most of transportation land surface was indurated, the respiration of soil under transportation land was ignored in this paper. 3) As for the detailed industrial energy consumption, this paper adopted the

Table 1 Matching relationship between different land use types and carbon source/sink

Land use type	Carbon sink	Carbon source	
		Natural carbon emission	Anthropogenic carbon emission
Cultivated land	Photosynthesis of cropland	Respiration of crops and soil	(1) Carbon emissions from fossil energy, electricity, biomass energy, straw combustion and other agricultural activities (2) CH$_4$ emission from paddies
Garden land	Photosynthesis of vegetables, fruit trees, *etc*.	Respiration of vegetables, fruit trees and soil	Carbon emission from energy use in cultivation
Forest land	Photosynthesis of forests	Respiration of trees and soil	Carbon emission from energy use in felling
Grazing & pasture land	Photosynthesis of grasses	Respiration of grasses and soil	Carbon emission from energy use in grazing
Inhabitation, mining & manufacturing land	Photosynthesis of urban greenbelts	Respiration of greenbelts and soil	(1) Carbon emission from living energy and biomass energy, industrial production, human respiration, solid waste, waste water (2) CH$_4$ emission from ruminant animals
Transportation land	None	Respiration of soil*	Carbon emission from energy use in transportation
Water body	Carbon sequestration and dry & wet deposition of water and shallows	Carbon emission from water volatility	Carbon emission from energy use in fishery
Unused land	Photosynthesis of natural vegetation*	Respiration of vegetation and soil*	None

Note: Items marked * are ignored items in this paper method of Zhao *et al.* (2011) and Energy Balance Table of China to establish the relationship between land use types and detailed energy consumptions. 4) In the Energy Balance Table of China, Other Energy Consumption means the energy use by some special activities (such as military facilities), which was incorporated into Inhabitation, mining & manufacturing land. 5) Carbon emission from Farming, Forestry, Animal Husbandry, and Fishery & Water Conservancy was subdivided according to their production value and incorporated into Cultivated land, Garden land, Forest land, Grazing & pasture land and Water body respectively. 6) Considering the animal husbandry in Nanjing was mainly managed in rural residential areas, so carbon emission from animal husbandry was incorporated into Inhabitation, mining & manufacturing land.

Carbon emission intensity of land use means the carbon emission of per unit land area, which was used for measuring the density of carbon missions from anthropogenic activities on certain land use type. Here, it was calculated by the following method:

$$Cp_i = Ct_i / S_i \tag{6}$$

where Cp_i is the carbon emission intensity of land use type i (t/ha); S_i is the area of land use type i; Ct_i is the carbon emission of land use type i. The method for carbon sink intensity estimation is similar to Formula (6).

2.6 Decomposition analysis of carbon emission from land use based on LMDI model

In order to analyze the influencing extent of different factors on carbon emissions, according to Kaya Equation, this paper built the formula for carbon emission through introducing land use factors to the equation. Therefore, regional carbon emissions can be expressed as follows:

$$C = \sum_i \frac{C_i}{L_i} \times \frac{L_i}{L} \times \frac{L}{G} \times \frac{G}{P} \times P \tag{7}$$

where C is the total regional carbon emission; C_i is the carbon emission of land use type i; L_i is the area of land use type i; L is the total land use area; G is GDP; P is population. Here, we assume that:

$$f_i = \frac{C_i}{L_i};\quad s_i = \frac{L_i}{L};\quad q = \frac{L}{G};\quad g = \frac{G}{P} \tag{8}$$

then the total regional carbon emission could be expressed as the product of several factors, as follows:

$$C = \sum_i f_i \times s_i \times q \times g \times p \tag{9}$$

where f_i, s_i, q, g and p represents carbon emission intensity of land use, structure effect of land use, land use area per unit GDP, economic development factor and population factor respectively. According to Formula (9), contribution value and contribution rate of each factor could be decomposed by LMDI model. Here, we assume that the carbon emission of start year is C^0 and the carbon emission of year T is C^T. Then, the change of carbon emissions during study period (0–T) could be expressed as follows:

$$\begin{aligned}\Delta C = C^T - C^0 &= \sum_i f_i^T \times s_i^{\ T} \times q^T \times \\ &\quad g^T \times p^T - \sum_i f_i^0 \times s_i^{\ 0} \times q^0 \times g^0 \times p^0 \\ &= \Delta C_{f_i} + \Delta C_{S_i} + \Delta C_q + \Delta C_g + \Delta C_p + \Delta C_{rsd}\end{aligned} \tag{10}$$

$$D = \frac{C^T}{C^0} = D_f D_s D_q D_g D_p D_{rsd} \tag{11}$$

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

$$\begin{aligned}\Delta C_{f_i} &= \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \times \ln \frac{f_i^T}{f_i^0};\\ \Delta C_{S_i} &= \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \times \ln \frac{s_i^T}{s_i^0};\\ \Delta C_q &= \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \times \ln \frac{q^T}{q^0};\\ \Delta C_g &= \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \times \ln \frac{g^T}{g^0};\\ \Delta C_p &= \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^0} \times \ln \frac{p^T}{p^0};\ \Delta C_{rsd} = 0\end{aligned} \tag{12}$$

$$\begin{aligned}&D_f = \exp(W\Delta C_{f_i});\\ &D_s = \exp(W\Delta C_{s_i});\ D_q = \exp(W\Delta C_q);\\ &D_g = \exp(W\Delta C_g);\ D_p = \exp(W\Delta C_p);\end{aligned}$$

$$D_{rsd} = 1;\quad W = \frac{\ln D}{\Delta C} \tag{13}$$

3 Results

3.1 Carbon emission of different land use types

Through the above estimation method of carbon emissions, we concluded that the anthropogenic carbon emission of Nanjing in 2009 was 3.069 39 × 10^7 t, which was more than two times of that in 2000 (1.229 28 × 10^7 t). Through the matching relationship (Table 1), the anthropogenic carbon emissions of different land use types could be obtained (Table 2). As for each land use type, carbon emission of Inhabitation, mining & manufacturing land was the highest (2.86762 × 10^7 t), which accounted for 93% of the total, the next was Transportation land (1.3886 × 10^6 t), then the cultivated land (5.259 × 10^5 t), and the carbon emission of other land use types was relatively low. For the temporal changes, the carbon emission of construction land was obviously on increase, in which that of Transportation land increased from 4.122 × 10^5 t to 1.3886 × 10^6 t with the highest increasing rate. Compared with the construction land, carbon emission of Cultivated land, Garden land and Forest land was on decrease, which indicated that the environmental impact of those land use activities was alleviated since 2000. The declining rate of carbon emission of Forest land was the highest (decreased from 1.04 × 10^4 t to 0.57 × 10^4 t), which was caused by the decrease of human energy activities on Forest land. For example, the energy consumption of forestry in Nanjing decreased from 9.05 × 10^4 tec (tons equivalent coal) in 2000 to 5.18 × 10^4 tec in 2009. It should be noted that Grazing and pasture land and Unused land was not listed in table 2 and table 3 because there was no anthropogenic carbon fluxes emitted from Grazing and pasture land and Unused land.

The average anthropogenic carbon emission intensity of Nanjing was 46.63 t/ha in 2009, in which the anthropogenic carbon emission intensity of Inhabitation, mining & manufacturing land (200.52 t/ha) was much

Table 2 Anthropogenic carbon emissions of different land use types of Nanjing City (10^4 t C)

Year	Cultivated land	Garden land	Forest land	Inhabitation, mining & manufacturing land	Transportation land	Water body	Average carbon emission intensity
2000	66.80	0.89	1.04	1111.99	41.22	7.34	1229.28
2001	64.11	0.87	0.88	1141.61	41.95	8.50	1257.91
2002	62.76	0.92	0.82	1271.46	45.31	9.78	1391.06
2003	52.95	0.75	0.62	1468.67	82.14	8.20	1613.33
2004	56.29	0.77	0.57	1747.99	98.37	7.82	1911.82
2005	52.97	0.69	0.47	2200.20	101.61	7.08	2363.02
2006	51.73	0.69	0.47	2365.44	106.53	7.81	2532.67
2007	48.19	0.68	0.49	2581.96	116.43	8.01	2755.75
2008	50.54	0.66	0.46	2608.74	128.56	7.57	2796.54
2009	52.59	0.77	0.57	2867.62	138.86	8.98	3069.39

Table 3 Anthropogenic carbon emission intensity of different land use types of Nanjing City (t/ha)

Year	Cultivated land	Garden land	Forest land	Inhabitation, mining & manufacturing land	Transportation land	Water body	Average carbon emission intensity
2000	2.22	0.79	0.17	109.08	28.48	0.50	18.68
2001	2.17	0.84	0.14	108.94	28.09	0.58	19.11
2002	2.40	0.91	0.11	105.34	30.47	0.65	21.13
2003	2.11	0.79	0.09	117.14	49.06	0.53	24.51
2004	2.29	0.82	0.08	134.90	58.18	0.51	29.04
2005	2.16	0.73	0.06	167.43	58.76	0.46	35.90
2006	2.12	0.72	0.06	177.25	59.57	0.51	38.48
2007	1.98	0.69	0.07	188.97	62.47	0.53	41.87
2008	2.09	0.68	0.06	186.57	66.30	0.50	42.49
2009	2.18	0.79	0.08	200.52	68.93	0.59	46.63

meant that the increasing rate of carbon emission obviously exceeded that of land use area with the increasing of human energy activities on Inhabitation, mining & manufacturing land. Also, Transportation land in Nanjing has high anthropogenic carbon emission intensity (68.93 t/ha in 2009). Especially, some additional carbon emissions were brought by agricultural cultivation activities (such as agricultural machines and irrigation processes), which caused the carbon emission intensity of Cultivated land was higher than that of Garden land, Forest land and Water body. Furthermore, it should be noted that the anthropogenic carbon emission intensity of Forest land decreased from 0.17 t/ha to 0.08 t/ha, indicating that the energy efficiency of Forest land was improved. In contrast, total carbon emission of Cultivated land and Garden land declined since 2000.

In 2009, the order of anthropogenic carbon emission intensity of each land use type was: Inhabitation, mining & manufacturing land (200.52 t/ha) > Transportation land (68.93 t/ha) > Cultivated land (2.18 t/ha) > Garden land (0.79 t/ha) > Water body(0.59 t/ha) > Forest land (0.08 t/ha), indicating that Inhabitation, mining & manufacturing land and Transportation land were main carbon sources among others because of huge energy consumption and intensive industrial activities. Therefore, for the aim of low-carbon land use control and carbon emission reduction, Inhabitation, mining & manufacturing land and transportation land should be highly controlled and regulated to decrease the carbon emission intensity.

If considering the natural carbon emission processes, total carbon emissions of land use include three parts (Table 4): natural carbon emission, fossil energy carbon emission and other human carbon emission (which represents human carbon emissions without fossil energy sources). The proportions of the above three carbon emission types of different land use types were quite different from one another. Natural carbon emission was determined by the respiration rate of vegetation and soil and the area of each land use type. The average natural carbon emission intensity of Nanjing City was 3.42 t/ha in 2009 (Table 4). For each land use type, natural carbon emission intensity of Forest land and Water body was the highest (7.64 t/ha) and the lowest (0.001 t/ha) respectively. The average anthropogenic carbon emission intensity of Nanjing was 46.63 t/ha (in which the fossil energy carbon emission intensity and other human carbon emission intensity was 39.88 t/ha and 6.75 t/ha respectively), which account for 93 % of the total carbon emission intensity. This indicated that the human activities were the main source of carbon emissions. Fossil energy carbon emission intensity of Inhabitation, mining & manufacturing land was the highest (171.57 t/ha), and that of Water body was the lowest (0.59 t/ha). From the above analysis, we see that the natural carbon emission was much more than human energy carbon emissions for land use types with stronger carbon sink function (such as Cultivated land, Garden land, Forest land), while the fossil energy carbon emission was much higher than natural carbon emissions for land use types with stronger carbon source function (such as Inhabitation, mining & manufacturing land, Transportation land). Other human carbon emission was just involved in Cultivated land and Inhabitation, mining & manufacturing land.

Generally, the average anthropogenic carbon emission intensity of Nanjing City increased from 18.68 t/ha to

Table 4 Total carbon emission intensity of different land use types of Nanjing City in 2009 (t/ha)

Land use type	Natural carbon emission	Fossil energy carbon emission	Other human carbon emission	Total
Cultivated land	4.54	0.93	1.25	6.72
Garden land	3.86	0.79		4.65
Forest land	7.64	0.08		7.72
Grazing & pasture land	1.67			1.67
Inhabitation, mining & manufacturing land	3.92	171.57	28.95	204.44
Transportation land		68.93		68.93
Water body	0.001	0.59		0.59
Unused land				0.00
Total	3.42	39.88	6.75	50.05

46.63 t/ha with the increasing rate of about 150% during 2000–2009, which indicated that the environmental impact of land use activities was increasing. The increasing rates of human carbon emission intensity of different land use types were quite different from one another. The anthropogenic carbon emission intensity of Transportation land, Inhabitation, mining & manufacturing land and Water body was on increase during 2000–2009 with the increasing rate of 142.0%, 84.0% and 17.8% respectively, which suggested that the energy consumption intensity in the field of industry, life and transportation increased drastically, and also the energy consumption by aquaculture was also increasing. Comparatively, the anthropogenic carbon emission intensity of Cultivated land, Garden land and Forest land decreased during 2000–2009 with the decreasing rate of 1.76%, 0.38% and 54.39% respectively, which was caused by the increase of energy efficiency and the decrease of human activities on those land use types. For Nanjing City as a whole, the total land area was constant, so the carbon emission intensity of Nanjing will tend to increase inevitably with the increasing of total carbon emissions unless it will decrease in the future.

3.2 Carbon source/sink characteristics of different land use types

Analysis of carbon source/sink characteristics of different land use types helps to understand the carbon cycle pressure of each land use type. We see that the carbon source/sink intensity of different land use types was quite different from one another (Table 5). The carbon source intensity (anthropogenic carbon emission intensity) of Inhabitation, mining & manufacturing land was the highest (200.52 t/ha) in 2009, the Transportation land next (68.93 t/ha), and that of other land use types was relatively low. The carbon sink intensity of Cultivated land is the highest (4.73 t/ha), the Garden land the next. The carbon sink intensity of Grazing & pasture land and Water body was relatively low (less than 1 t/ha).

The carbon source and sink intensity of Inhabitation, mining & manufacturing land were both on increase during 2000–2009. But the carbon sink intensity of Inhabitation, mining & manufacturing land was much less than the carbon source intensity. Carbon source intensity of Inhabitation, mining & manufacturing land increased from 109.08 t/ha in 2000 to 200.52 t/ha in 2009, while carbon sink intensity increased from 0.37 t/ha to 1.97t/ha because of the increasing green coverage rate of the urban built-up area of Nanjing City. Further, carbon source intensity of Transportation land also increased drastically (from 28.48 t/ha to 68.93 t/ha) during 2000–2009. Generally speaking, except for Inhabitation, mining & manufacturing land, Forest land, Grazing & pasture land and Water body, carbon sink intensity of other land use types were on decrease, which caused that the average carbon sink intensity slightly deceased from 2.90 t/ha to 2.83 t/ha. Meanwhile, the average carbon source intensity increased drastically and reached 46.63 t/ha in 2009, which was 16 times of the average carbon sink intensity (2.83 t/ha) (Fig. 3). Thus, we see that Nanjing was confronted with serious carbon deficit and high carbon cycle pressure with the economic development, urban expansion and the increasing of energy consumption.

Table 5 Carbon source/sink characteristics of different land use types of Nanjing City

Land use type	2000				2009			
	Carbon sink (10^4 t C)	Carbon sink intensity (t/ha)	Carbon source (10^4 t C)	Carbon source intensity (t/ha)	Carbon sink (10^4 t C)	Carbon sink intensity (t/ha)	Carbon source (10^4 t C)	Carbon source intensity (t/ha)
Cultivated land	147.79	4.91	66.80	2.22	114.00	4.73	52.59	2.18
Garden land	5.10	4.53	0.89	0.79	3.93	4.01	0.77	0.79
Forest land	23.11	3.81	1.04	0.17	27.93	3.81	0.57	0.08
Grazing & pasture land	0.18	0.95	0.00	0.00	0.001	0.95	0.00	0.00
Inhabitation, mining & manufacturing land	3.76	0.37	1111.99	109.08	28.11	1.97	2867.62	200.52
Transportation land	0.00	0.00	41.22	28.48	0.00	0.00	138.86	68.93
Water body	11.11	0.76	7.34	0.50	12.30	0.81	8.98	0.59
Unused land	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	191.04	2.90	1229.28	18.68	186.28	2.83	3069.39	46.63

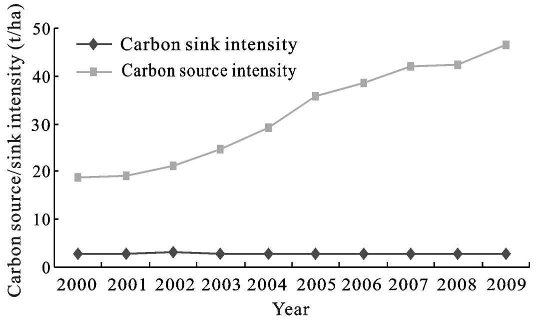

Fig. 3 Change of carbon source/sink intensity of Nanjing City

3.3 Decomposition analysis of carbon emission from land use

Using LMDI model, through introducing land use factors into the model, regional carbon emission can be expressed as the product of carbon emission intensity of land use (f_i), structure effect of land use (s_i), land use area per unit GDP (q), economic development factor (g) and population factor (p). Through decomposition analysis, the contribution value and contribution rate of each factor could be obtained (Table 6).

During 2000–2009, the total carbon emission of Nanjing increased 1.84011 × 10^7 t (Table 6). The economic development factor was the main factor contributing to the increase of total carbon emission from land use. The contribution value of economic development factor increased gradually and the total contribution value exceeded 2.000 × 10^7 t during 2000–2009, which indicated that the economic development factor was the most important positive factor for the increase of total carbon emission. Population factor was also contributing factor for the increase of total carbon emission. The contribution value of population factor was 2.9113 × 10^6 t during 2000–2009, but it was not the major contributing factor, and much less than the contribution value of economic development. In the factors that related to land use, the total contribution value of structure effect of land use was 6.4113 × 10^6 t, indicated that the change of land use structure of Nanjing was negative factor for the carbon emission reduction since 2000. The contribution value of carbon emission intensity of land use was on a fluctuating trend from 2000 to 2009, during which negative effect and positive effect both appeared, but it mainly appeared as positive factor except for the time span 2000–2002 and 2007–2008 (Table 6). Especially, it reached 4.2132 × 10^6 t during 2004–2005, which even exceeded the contribution value of economic development factor at the same time. Comparatively, land use area per unit GDP was an inhibitory factor for the increase of total carbon emission, and its total inhibitory effect on carbon emission reached 2.35673 × 10^7 t during 2000–2009, which suggested that land use area per unit GDP was the most important positive factor that contributing to carbon emission reduction.

Table 6 Contribution value of each factor of land use carbon emission in Nanjing (10^4 t C)

Year	f_i	s_i	q	g	p	whole
2000–2001	–2.43	31.05	–131.61	113.15	18.46	28.62
2001–2002	–29.73	162.88	–159.10	134.82	24.28	133.15
2002–2003	165.22	57.06	–209.70	186.06	23.64	222.27
2003–2004	245.87	52.62	–280.43	245.84	34.60	298.49
2004–2005	421.32	29.87	–301.63	257.57	44.06	451.20
2004–2006	131.49	38.16	–341.86	295.37	46.50	169.65
2006–2007	160.32	62.76	–377.11	334.20	42.91	223.08
2007–2008	–23.74	64.52	–312.58	279.98	32.60	40.78
2008–2009	206.30	66.56	–322.11	297.30	24.82	272.85
2000–2009	1198.98	641.13	–2356.73	2065.61	291.13	1840.11

The decomposition result showed that the contribution rate of economic development factor was obviously higher than that of other factors (Fig. 4). Take each factor during 2000–2009 as a whole, we can see that the order of contribution rate was: economic development factor (2.79) > carbon emission intensity of land use (1.82) > structure effect of land use (1.38) > population factor (1.16) > land use area per unit GDP (0.31). We can see that except for land use area per unit GDP, the contribution rate of other factors were all higher than 1, which suggested that land use area per unit GDP was an

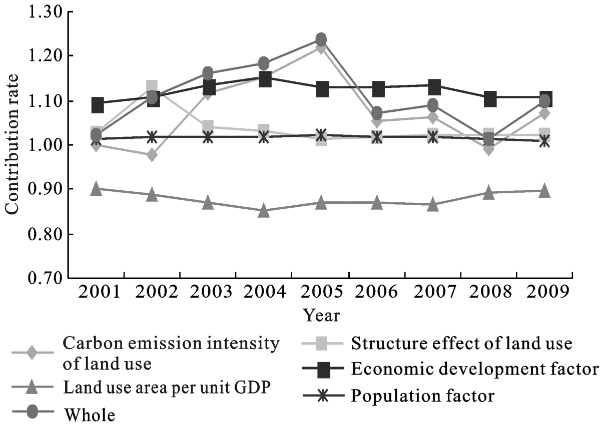

Fig. 4 Contribution rate of each factor of land use carbon emission in Nanjing City. 2001 represent the contribution rate of each factor from 2000 to 2001, and the rest means the similar meaning

inhibitory factor, but the other factors were all contributing factors for the increase of total carbon emission.

4 Discussion and Policy Implication

4.1 Discussion

The main deficiencies of this study are: 1) The division of land use types was based on energy carbon emission items of the China Energy Balance Table and Land Use Classification System. Since the correspondence relationship between them should be considered, some detailed land use types (such as commercial land use, residential land use, *etc.*) were not divided from Inhabitation, mining & manufacturing land. 2) Because the data of industrial division and the land use classification was not easy to match according to the statistic system of China, the industrial structure was not considered in the decomposition model. Therefore, the carbon emissions from different industrial land use types based on energy consumption should be considered to further accurately estimated the carbon emission from different land use activities in the future study. Also, the industrial structure is also one of the important factors that influence regional carbon emissions, so the industrial structure effect should be considered as well as land use factors in the next study.

The land use in other studies was just divided into five (Zhao *et al.*, 2011) or six (Lai and Huang, 2011) land use types, which was not suitable for the land classification system of China. Koemer and Klopatek (2002) divided the Phoenix metropolitan region into 13 land use types and analyzed the soil CO_2 efflux of each land use type, but the carbon emissions of human activities on each land use type was not discussed. In this paper, on the basis of matching relationship, we divided the land use into eight land use types according to the land use classification system of China, which is important for carbon emission effect evaluation in the future researches and practices.

Land use change, especially urban sprawl and constructive land expansion, is an important factor that influences regional carbon emission and its intensity. Land use change will not only influence energy consumption (Araujo *et al.*, 2009) and urbanization process (Zhang *et al.*, 2012), but also drastically affect the carbon emission intensity of human activities, which has been confirmed by the other studies (Svirejeva-Hopkins and Schellnhuber, 2006; Ali and Nitivattananon, 2012; Zhang *et al.*, 2012). According to the report of Svirejeva-Hopkins and Schellnhuber (2008), the carbon emission caused by urbanization in the world is 1.25 Gt C in 2005, in which China, Asia and Pacific are being active sources of carbon. Based on the result of this paper, the future carbon emission intensity of urbanization was predicted according to the constructive land expansion of Nanjing during 2000–2009. We see that the relationship between carbon emissions and built-up area of Nanjing had an exponential distribution during 2000–2009 (Fig. 5). This indicates that urban expansion will drastically impact urban carbon emission in the future. Per-unit area carbon emission from Nanjing′s built-up areas in 2009 was 4.63×10^4 t /km^2. According to the urban expansion rate during 2000–2009, the carbon emissions in Nanjing′s built-up areas will reach 6.659×10^7 t in 2020, and per-unit area carbon emission will attain 6.54×10^4 t/km^2. Urban expansion will not only occupy forest and cropland around the city, but also emit more carbon via road building, factory construction and energy consumption during land use activities. This will inevitably influence urban carbon cycle processes.

Urban area and construction land is the main sources of regional carbon emissions according to other studies (Churkina, 2008; Zhang *et al.*, 2012). According to this study, we found that except for Inhabitation, mining & manufacturing land and Transportation land, carbon sink of other land use types was enough to offset the human carbon emissions, indicating that the carbon emissions from human energy consumption on construction land was the main reason that caused the carbon deficit of Nanjing City. Therefore, in order to decrease regional carbon emission intensity and develop low-carbon city, we should not only control the expansion of urban built-up area and increase the energy efficiency, but also add the productive land area and enhance carbon fixa

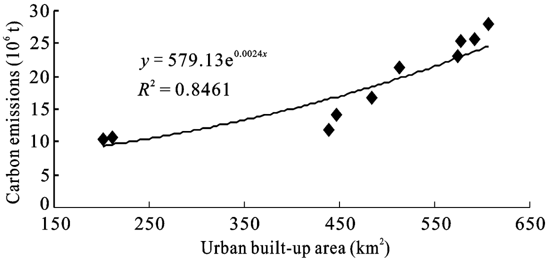

Fig. 5 Correlation of carbon emission and built-up area in Nanjing City

tion efficiency, which will effectively reduce regional-carbon emission intensity.

4.2 Policy implications

From the above analysis, we see that land use is an important factor that influences regional carbon cycle both on natural and anthropogenic processes. Therefore, land use regulation and management will basically guide the low-carbon transition through land use control, urban planning, industrial adjustment and regional renovation. In order to promote regional carbon emission reduction, several suggestions were put forward as follows:

(1) Energy innovation and industrial structure adjustment are important for the future low-carbon development. The proportion of carbon emissions from energy use was much higher than other emission sources. Therefore, the energy structure should be adjusted, and clean energy (such as solar and bio-energy) should be developed. Further, adjusting industrial structure, especially increasing the proportion of tertiary industries, should be included in economic development planning for the city. The adjustment of industrial structure would decrease the carbon emission intensity, and basically lead the low-carbon transition of Nanjing in the long run.

(2) Land use carbon emission intensity should be decreased through land use structure adjustment, land saving and intensive use and adding productive land. Through land use optimization, establishing low-carbon land use pattern, increasing carbon emission reduction potential, the carbon emission intensity of land use will be decreased, and the land use structure effect will turned into inhibitory factor in the long run.

(3) In the future, reasonable land use scale, intensity and structure should be considered in the future land use activities and urban development. Especially, the construction land should be controlled by rigidly management of urban expansion and cropland occupation. With rapid urbanization, per-unit area carbon emission will reach 6.54×10^4 t/km^2 in 2020, which is 60% greater than that in 2009. Therefore, urban-scale and built-up areas should be restricted through scientific low-carbon urban planning, and repeated construction should be avoided. Further, the potential of constructive land should be tapped, and urban sprawl should be replaced by inner, intensive land use and urban renewal. The ′compact city′ pattern should be introduced in urban planning, which will not only avoid rapid urban expansion, but also reduce energy use through the shortening of distances between different urban functional districts.

(4) Carbon emission is one of the important environmental impacts of regional land use. Therefore, the carbon emission effect evaluation should be introduced into land use planning, urban planning, land use structure adjustment and optimization through establishing the carbon emission evaluation system between carbon fluxes and land use types. This helps not only to quantitatively evaluate the carbon emission effect of different land use types, but also to explore pertinent low-carbon land use strategies in regional land use activities.

(5) Afforestation would offset carbon emissions through carbon sequestration in natural processes. Therefore, strengthening ecological protection, increasing urban green space and enhancing carbon fixation efficiency of productive land, would not only create a green living environment, but also effectively reduce regional carbon emission of human energy consumptions and its intensity. Through the above measures, the carbon sink capacity will be raised, and carbon emissions could be compensated and the carbon cycle pressure will be decreased to some extent.

5 Conclusions

Through establishing matching relationship between different land use types and carbon emissions, the carbon emission intensity of regional land use in Nanjing City were analyzed, and the influencing factors of carbon emission from land use was decomposed through LMDI model. The main conclusions are as follows: 1) The total anthropogenic carbon emission of Nanjing increased from $1.229\,28 \times 10^7$ t in 2000 to $3.069\,39 \times 10^7$t in 2009, in which that of Inhabitation, mining & manufacturing land was the highest ($2.867\,62 \times 10^7$ t), which account for 93 % of the total. 2) The average land use carbon emission intensity of Nanjing in 2009 was 46.63 t/ha. The carbon emission intensity of different land use types was quite different from one another. That of Inhabitation, mining & manufacturing land (200.52 t/ha) and Transportation land (68.93 t/ha) was much higher than that of other land use types, which indicates that the construction land was the main carbon source for there was huge energy consumption and intensive industrial activities on construction land. 3) The average carbon source intensity of Nanjing increased drastically and reached 46.63 t/ha in 2009, which was 16 times of the average carbon sink intensity (2.83 t/ha). It indicated that Nanjing was confronted with serious carbon deficit and high carbon cycle pressure. 4) The contribution value and contribution rate of economic factor was obviously higher than that of other factors, suggesting that land use area per unit GDP was an inhibitory factor for the increase of carbon emissions in Nanjing, while the other factors were all contributing factors.

In order to decrease the carbon emission intensity of land use in Nanjing, the following two aspects should be considered: 1) Reasonable land use scale, intensity and structure should be considered in the future land use activities and urban development. Especially, the construction land should be controlled by rigidly management of urban expansion and cropland occupation. 2) The carbon emission effect evaluation should be introduced into land use planning, land use structure adjustment and optimization. This helps to quantitatively evaluate the carbon emission effect of different land use types and promote the formulating of low-carbon land use strategies.

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