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A New Carbon and Oxygen Balance Model Based on Ecological Service of Urban Vegetation

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Abstract: The application of human induced oxygen consumption and carbon emission theory in urban region was summed up and on this base a new model of urban carbon and oxygen balance (UCOB) was constructed by calculating the carbon and oxygen fluxes. The purpose was to highlight the role of vegetation in urban ecosystems and evaluate the effects of various human activities on urban annual oxygen consumption and carbon emission. Hopefully, the model would be helpful in theory to keep the regional balance of carbon and oxygen, and provide guidance and support for urban vegetation planning in the future. To test the UCOB model, the Jimei District of Xiamen City, Fujian Province, China, a very typical urban region, was selected as a case study. The results turn out that Jimei′s vegetation service in oxygen emission and carbon sequestration could not meet the demand of the urban population, and more than 31.49 times of vegetation area should be added to meet the whole oxygen consumption in Jimei while 9.60 times of vegetation area are needed to meet the carbon sequestration targets. The results show that the new UCOB model is of a great potential to be applied to quantitative planning of urban vegetation and regional eco-compensation mechanisms.

Keywords: ecological service; carbon cycle; oxygen cycle; urban carbon and oxygen balance; urban vegetation planning

1 Introduction

The massive fossil fuel utilization and deforestation based on human activities have significantly increased the average content of CO_2 from 280 ppm before Industrial Revolution to the current level of 380 ppm, moreover, the figure could be expected to reach 700 ppm by the end of this century (IPCC, 2007). Oxygen-tonitrogen ratios in firn (the transition state from snow to ice) and archived air samples indicated that the terrestrial biosphere was approximately carbon-neutral on average during the 1980s (Colin *et al*., 2000). A series of global warming problems triggered by the growth of CO_2 content have already attracted considerable attention. It was predicted that if the emission of human activity related CO_2 and other greenhouse gases continue climbing, the condition of global warming and climate change would soon be out of the self-adjustment capacity of biosphere, and consequently lead to its complete collapse (Lovelock, 1990). The IEA study found that globally, urban area accounts for 67% of energy consumption and 71% of CO_2 emission worldwide (IEA, 2008). Previous researches showed that the carbon flow balance condition of forest ecosystem had an important feedback on global warming (Cox *et al*., 2000), and the contribution of forest ecosystem in global carbon balance has gained a growing focus from the research world (Lloyd *et al*., 2002; Kolari *et al*., 2004). Thus, the importance of urban vegetation to human world was quite obvious. Therefore, how to maximize the carbon sequestration and oxygen emission capability of urban vegetation, and how to achieve the carbon and oxygen balance in urban ecosystem become an important role in urban vegetation planning and management.

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In recent decades, a large number of researches related to land carbon cycling process and carbon footprint have been made around the world. Among them, the carbon cycling models used were ecological type Net Primary Production (NPP) based Miami Model, Terrestrial Ecosystem Model (TEM), *etc*. (Leith, 1975; Raich *et al*., 1991), as well as the dynamic carbon cycling process forecast models in combination with remote sensing data, such as Carbon Exchange Between Vegetation, Soil and the Atmosphere Model (CEVSA), Simple Biosphere Model (SiB), Boreal Ecosystem Productivity Simulator (BEPS), Atmosphere Vegetation Integrated Model (AVIM), *etc*. (Sellers *et al*., 1986; Liu *et al*., 1997; Cao and Woodward, 1998; Ji *et al*., 2008), and the carbon footprint assessment models were mostly resorted to life-cycle assessment model (LCA) and its improved type input-output LCA (IO-LCA) (Lenzen *et al*., 2004; Kok *et al*., 2006). All these models are very important tools to investigate sophisticated land ecosystem carbon cycling, global climate change and their interactions.

However, most model studies were focused on the carbon cycle of land to estimate carbon fluxes through forests, grasses and croplands, but completely omited urban areas from their scope (Galina, 2008). In addition, the models mentioned above are difficult to be applied in practical urban vegetation planning. Chinese scholars paid more attention to the carbon and oxygen balance in large scaled areas. Fang leaded land ecosystem carbon cycling estimation of China based on the biomass and production of Chinese land ecosystem (Fang *et al*., 1996a; 1996b; 2007). Peng′s research was mainly on the effect of vegetation in regional carbon and oxygen balance the Zhujiang (Pearl) River Delta (Peng, 2003). However, researches on the application of carbon and oxygen balance theory to quantitatively studying urban vegetation planning in a small urban scale were very limited. In the context of the increasing urban population pressure, could the ecological service from urban vegetation satisfy the growing needs? How to keep the balance in between? These questions are required to be answered emergently.

In order to find the answers to these questions, in this study we introduced the concept of defined urban carbon and oxygen balance assessment, which was used to describe whether the annual supply of carbon sequestration and oxygen emission service from vegetation ecosystem could be compatible with the maximum capacity of local population and social-economic development (carbon emission, oxygen consumption) in a specific administrative region or natural area. In addition, human activity based oxygen consumption model, carbon emission model, and urban area carbon and oxygen balance evaluation index system were constructed. A case study of the Jimei District of Xiamen City, Fujian Province, China was carried out. The purpose was to construct the carbon and oxygen balance assessment model, quantitatively evaluate the balance status of carbon and oxygen cycling in urban area, and further provide scientific evidence and data support for macroscopically adjusting human activities, and sensibly planning urban vegetation.

2 Model Building

In order to judge whether the net oxygen emission of vegetation meets the total demand of urban population and the current carbon emission induced by human activities can be completely absorbed by vegetation system, it is necessary to establish an evaluation system of urban carbon and oxygen balance. In this paper, a carbon and oxygen balance model is built, which is based on biogeochemical cycle, postulating that the ecological services of terrestrial vegetation in urban region ecosystem (mainly carbon sequestration and oxygen emission) are fully played. All the main oxygen consumption and carbon emission factors caused by human activities in urban area are taken into account in the model which is able to cover the entire urban ecosystem.

2.1 Oxygen consumption model based on human activities

The main human induced oxygen consumption in urban region can be expressed as:

$$O_C = O_R + O_D + O_{COD} + O_T + O_I \qquad (1)$$

where O_C represents the annual urban oxygen consumption (t/yr); O_R, O_D, O_{COD}, O_T and O_I are the annual oxygen consumption (t/yr) induced by urban population respiratory, urban domestic energy use, urban domestic wastewater treatment, transport energy use and industrial energy use, respectively.

In the Equation (1), the five factors are described as the following:

$$O_R = O_P \times P \times 365 \times 10^{-3}$$

where O_P represents the average oxygen consumption per person per day (kg/(person·d)); P, the urban population.

$$O_D = O_{DC} + O_{DLPG} + O_{DE} + O_{DS}$$
$$O_{DC} = C_{TD} \times (C_C \times R_{2O/C} + H_C \times R_{O/2H})$$
$$O_{DLPG} = LPG_D \times (C_{LPG} \times R_{2O/C} + H_{LPG} \times R_{O/2H})$$
$$O_{DE} = E_D \times I_{EC} \times (C_C \times R_{2O/C} + H_C \times R_{O/2H})$$
$$O_{DS} = S_D \times R_{O/SO_2}$$

where O_{DC}, O_{DLPG}, O_{DE} and O_{DS} represent the annual oxygen consumption (t/yr) induced by the annual domestic coal use, the annual domestic liquefied petroleum gas use, the annual domestic electricity consumption, and the annual domestic energy induced SO_2 emission, respectively; C_{TD}, the annual domestic coal consumption (t/yr); C_C and H_C, the contents of carbon and hydrogen in standard coal, respectively; $R_{2O/C}$ and $R_{O/2H}$, the molecular weight ratios of oxygen/carbon and oxygen/hydrogen, respectively; LPG_D, the annual domestic liquefied petroleum gas consumption (t/yr); C_{LPG} and H_{LPG}, the contents of carbon and hydrogen in liquefied petroleum gas, respectively; E_D, the annual domestic electricity consumption (kW/yr); I_{EC}, the conversion coefficient from electricity into standard coal; S_D, the domestic energy induced SO_2 emission (t/yr); R_{O/SO_2}, the molecular weight ratio of O_2 and SO_2.

$$O_{COD} = I_{COD} \times 365 \times P \times 10^{-6}$$

where I_{COD} represents the urban domestic wastewater COD production index (g/(person·d)).

$$O_T = F_T \times I_{FC} \times (C_C \times R_{2O/C} + H_C \times R_{O/2H})$$

where F_T represents the annual transport fuel consumption (t/yr); I_{FC}, the conversion coefficient from fuel into standard coal.

$$O_I = O_{IC} + O_{IFO} + O_{ILPG} + O_{ILNG} + O_{IE} + O_{ICOD} + O_{IS}$$
$$O_{IC} = C_{TI} \times (C_C \times R_{2O/C} + H_C \times R_{O/2H})$$
$$O_{IFO} = F_I \times I_{FC} \times (C_C \times R_{2O/C} + H_C \times R_{O/2H})$$
$$O_{ILPG} = LPG_I \times (C_{LPG} \times R_{2O/C} + H_{LPG} \times R_{O/2H})$$
$$O_{ILNG} = LNG_I \times (C_{LNG} \times R_{2O/C} + H_{LNG} \times R_{O/2H})$$
$$O_{IE} = E_I \times I_{EC} \times (C_C \times R_{2O/C} + H_C \times R_{O/2H})$$
$$O_{IS} = S_I \times R_{O/SO_2}$$

where O_{IC} represents the annual oxygen consumption (t/yr) by industrial coal use; O_{IFO}, by the industrial fuel use (transportation consumption not included); O_{ILPG}, by the industrial liquefied petroleum gas use; O_{ILNG}, by the industrial liquefied natural gas use; O_{IE}, by the annual industrial electricity; O_{ICOD}, by the industrial wastewater COD; O_{IS}, the industrial SO_2 emission; C_{TI}, the annual industrial coal consumption (t/yr); F_I, the annual industrial fuel consumption (t/yr); I_{FC}, the conversion coefficient from fuel into standard coal; LPG_I, the annual industrial liquefied petroleum gas consumption (t/yr); LNG_I, the annual industrial liquefied natural gas use (t/yr); C_{LNG} and H_{LNG}, the contents of carbon and hydrogen in liquefied natural gas, respectively; E_I, the annual industrial electricity consumption (kW/yr); S_I, the annual industrial SO_2 emission (t/yr). O_{ICOD} is obtained from statistical yearbook.

2.2 Oxygen emission model based on different vegetation types

The annual net oxygen emission from urban vegetation can be expressed as:

$$O_E = \sum_{i=1}^{3}[(O_{Ei} - O_{Ci}) \times A_i] \tag{2}$$

where O_E represents the annual net oxygen emission from urban vegetation (t/yr); O_{Ei}, the annual oxygen emission per unit area from vegetation type i (t/(ha·yr)), and in this study vegetation types include arable land, grassland and woodland; O_{Ci}, the annual soil respiration oxygen consumption per unit area from vegetation type i (t/(ha·yr)); A_i, the total area of vegetation type i (ha).

2.3 Carbon emission model based on human activities

The annual urban carbon emission induced by human activities can be expressed as:

$$C_E = C_R + C_D + C_T + C_I \tag{3}$$

where C_E represents the annual urban carbon emission (t/yr); C_R, C_D, C_T and C_I are the annual carbon emission (t/yr) from urban population respiratory, urban domestic energy use, transport energy use and industrial energy use, respectively.

In Equation (3), the four factors are described as the following:

$$C_R = C_P \times P \times 365 \times 10^{-3}$$
$$C_D = C_{DC} + C_{DLPG} + C_{DE}$$
$$C_{DC} = C_{TD} \times C_C \times R_{CO_2/C}$$
$$C_{DLPG} = LPG_D \times C_{LPG} \times R_{CO_2/C}$$
$$C_{DE} = E_D \times I_{EC} \times C_C \times R_{CO_2/C}$$

$$C_T = F_T \times I_{FC} \times C_C \times R_{CO_2/C}$$
$$C_I = C_{IC} + C_{IF} + C_{ILPG} + C_{ILNG} + C_{IE}$$
$$C_{IC} = C_{TI} \times C_C \times R_{CO_2/C}$$
$$C_{IF} = F_I \times I_{FC} \times C_C \times R_{CO_2/C}$$
$$C_{ILPG} = LPG_I \times C_{LPG} \times R_{CO_2/C}$$
$$C_{ILNG} = LNG_I \times C_{LNG} \times R_{CO_2/C}$$
$$C_{IE} = E_I \times I_{EC} \times C_C \times R_{CO_2/C}$$

where C_P represents the average carbon emission per person per day (kg/(person·d)); C_{DC}, the annual carbon emission induced by domestic coal use (t/yr); C_{DLPG}, by the domestic liquefied petroleum gas use; C_{DE}, by domestic electricity use; C_{IC}, by the industrial coal use; C_{IF}, by the industrial fuel use (transportation consumption not included); C_{ILPG}, by the industrial liquefied petroleum gas use; C_{ILNG}, by the industrial liquefied natural gas use (t/yr); C_{IE}, by the annual industrial electricity (t/yr); $R_{CO_2/C}$, the molecular weight ratio of CO_2 and carbon.

2.4 Carbon sequestration model based on different vegetation types

The annual net carbon sequestration by vegetation can be expressed as:

$$C_S = \sum_{i=1}^{3}[(C_{Si} - C_{Ei}) \times A_i] \quad (4)$$

where C_S represents the annual net carbon sequestration from urban vegetation (t/yr); C_{Si}, the annual carbon sequestration per unit area from vegetation type i (t/(ha•yr)); C_{Ei}, the annual soil respiration carbon emission per unit area from vegetation type i (t/(ha•yr)).

2.5 Evaluation system of carbon and oxygen balance

We deduced the oxygen and carbon balance coefficients as assessment indicators to judge whether oxygen and carbon are balanced in urban areas.

$$B_O = \frac{\sum_{i=1}^{3}[(O_{Ei} - O_{Ci}) \times A_i] - (O_R + O_L + O_{COD} + O_T + O_I)}{\sum_{i=1}^{3}[(O_{Ei} - O_{Ci}) \times A_i]} \quad (5)$$

$$B_C = \frac{\sum_{i=1}^{3}[(C_{Si} - C_{Ei}) \times A_i] - (C_R + C_D + C_T + C_I)}{\sum_{i=1}^{3}[(C_{Si} - C_{Ei}) \times A_i]} \quad (6)$$

where B_O and B_C represent the balance coefficients of oxygen and carbon, respectively.

Then we established the evaluation system of carbon and oxygen balance based on the balance coefficients (Table 1).

Table 1 Evaluation system of carbon and oxygen balance in urban area

Balance coefficient	Balance status
(1, +∞)	Far greater than balance threshold, with excellent vegetation services
(0, 1]	Greater than balance threshold, with good vegetation services
[0]	Balance threshold
[–1, 0)	Lower than balance threshold, with poor vegetation services
(–∞, –1)	Far lower than balance threshold, with worst vegetation services

3 Model Application

3.1 Site description

Jimei District (117°57′–118°04′N, 24°25′–24°26′E) is one of the six districts of Xiamen City, Fujian Province, China, and also the gateway of Xiamen Island. Jimei District consists of Xinglin, Jimei and Qiaoying neighbourhoods, and Guankou and Houxi towns. Sub-tropical humid climate dominates the region, with an average annual precipitation of 1 143.5 mm and average annual temperature of 20.5℃. So the four seasons are all mild there. Hills are distributed there widely, with rivers and canals dotted.

3.2 Data source and parameter determination

Based on the human induced urban oxygen consumption and carbon emission model, this study collected data from *Yearbook of Xiamen Special Economic Zone* (XMSB, 2007), *Xiamen Urban Environmental Statistics and Data Compilation from 2006* (XMEPB, 2007) and national coal and oil composition analysis and measurement standards (NCQC, 2007), to calculate the annual oxygen consumption and carbon emission indexes.

The annual resident daily energy oxygen consumption included the resident annual oxygen consumption from coal, gas, energy related SO_2 oxygen consumption and electricity which was converted to standard coal oxygen consumption. In this study, it was assumed that all the electricity consumed in the area was generated from thermal power. The annual total COD from municipal wastewater treatment was the product of urban COD generation coefficient and population. The annual industrial energy included the annual oxygen consumption from the industrial use of coal, oil (except traffic uses), LPG, gas, and electricity which was converted to standard coal oxygen consumption, industrial wastewater treatment and coal-fired induced SO_2. The annual oxygen consumption by population respiration and urban traffic energy were calculated directly.

The annual carbon emission of resident daily energy included the resident annual carbon emission from coal, gas, and electricity which was converted to standard coal carbon emission. The annual carbon emission of industrial energy included the annual carbon emission from the industrial use of coal, oil (except traffic uses), LPG, gas, and electricity which was converted to standard coal carbon emission. The annual carbon emission of population respiration and urban traffic energy are calculated directly.

Net carbon sequestration of vegetation in urban area can be reflected by net ecosystem productivity (NEP), which is the margin of net primary productivity (NPP) of vegetation system and net carbon emission of soil respiration. Similarly, net oxygen emission of vegetation in urban region is the margin of oxygen emission of vegetation system and net oxygen consumption of soil respiration. This research is based on plant photosynthesis equation, and adopted some findings from the Pearl River Delta vegetation research (Peng, 2003). Combined with Jimei land use data of 2006 (XMEPB, 2006; XMSB, 2007), we calculated the annual carbon sequestration and oxygen emission abilities of vegetation in Jimei District. The main parameters for the model were presented in Table 2.

Table 2 Main parameters for UCOB model

Main parameter	Value
Respiration carbon emission per person per day C_P	0.90 kg/(person·d) (Yang, 1996)
Respiration oxygen consumption per person day O_P	0.75 kg/(person·d) (Yang, 1996)
COD index of wastewater per person day I_{COD}	90 g/(person·d) (XMEPB, 2006)
Carbon content of standard coal C_C	80.99% (NCQC, 2007)
Hydrogen content of standard coal H_C	2.82% (NCQC, 2007)
Index of electricity converted to standard coal I_{EC}	0.4040 (SAC, 2007)
Index of fuel oil converted to standard coal I_{FC}	1.4286 (SAC, 2007)
Total annual oxygen emission of arable land O_{Ei}	11.20 t/(ha·yr) (Peng, 2003)
Total annual oxygen emission of grassland O_{Ei}	11.84 t/(ha·yr) (Peng, 2003)
Total annual oxygen emission of woodland O_{Ei}	27.28 t/(ha·yr) (Fang *et al*., 1996a)
Soil respiration oxygen consumption of arable land O_{Ci}	3.96 t/(ha·yr) (Fang *et al*., 1996b)
Soil respiration oxygen consumption of grassland land O_{Ci}	4.12 t/(ha·yr) (Fang *et al*., 1996b)
Soil respiration oxygen consumption of woodland land O_{Ci}	4.71 t/(ha·yr) (Fang *et al*., 1996b)
Total annual carbon sequestration of arable land C_{Si}	17.97 t/(ha·yr) (Peng, 2003)
Total annual carbon sequestration of grassland C_{Si}	16.32 t/(ha·yr) (Peng, 2003)
Total annual carbon sequestration of woodland C_{Si}	37.05 t/(ha·yr) (Fang *et al*., 1996a)
Soil respiration carbon emission of arable land C_{Ei}	5.44 t/(ha·yr) (Fang *et al*., 1996b)
Soil respiration carbon emission of grassland C_{Ei}	5.67 t/(ha·yr) (Fang *et al*., 1996b)
Soil respiration carbon emission of woodland C_{Ei}	6.47 t/(ha·yr) (Fang *et al*., 1996b)

3.3 Evaluation results

Based on equations 1 to 4, the oxygen consumption, oxygen emission, carbon emission and carbon sequestration of Jimei were calculated. According to equations 5 and 6, the oxygen and carbon balance coefficients of the area were calculated, and the oxygen and carbon balance coefficients for the whole Jimei District and its sub-administrative parts were all in deficits. The results show that vegetation service of oxygen emission and carbon sequestration can not meet the demand of the urban population. All in all, more than 31.49 times of vegetation area should be added in order to meet the whole oxygen consumption and 9.60 times of vegetation area are needed to meet the carbon sequestration targets in Jimei District (Table 3).

As the oxygen and carbon balance coefficients for the whole Jimei District and its sub-administrative parts were all in deficits, also, the range of variation was rather small. In order to directly reflect a spatial distribution of Jimei′s oxygen and carbon balance condition, the results

Table 3 Evaluation of carbon and oxygen balance in Jimei

	Oxygen consumption (t/yr)	Oxygen emission (t/yr)	Carbon emission (t/yr)	Carbon sequestration (t/yr)	Oxygen balance coefficient	Carbon balance coefficient
Jimei	423340.81	102.20	567819.38	336.97	–4141.39	–1684.09
Qiaoying	490434.42	3534.18	657810.82	14517.42	–137.77	–44.31
Xinglin	1372137.99	4117.15	1840423.87	16921.27	–332.27	–107.76
Guankou	503998.96	27041.12	676004.69	111135.56	–17.64	–5.08
Houxi	387123.49	63093.53	519241.74	259321.47	–5.14	–1.00
Total	3177035.68	97785.98	4261300.49	401895.72	–31.49	–9.60

were further graded by the integer power of 10, following the evaluation criteria in Table 1. The interval shows as follows: (–∞, –100), (–100, –10), (–10, –1), (–1, –0) (Fig. 1 and Fig. 2). The oxygen and carbon balance coefficients of Houxi were –1.00 and –5.14 respectively, implying that the oxygen and carbon balance condition in Houxi was better than those in other areas. The oxygen and carbon balance coefficients of Jimei neighborhood were –1684.09 and –4141.39, respectively, indicating that the oxygen and carbon balance condition in Jimei neighbourhood was the worst.

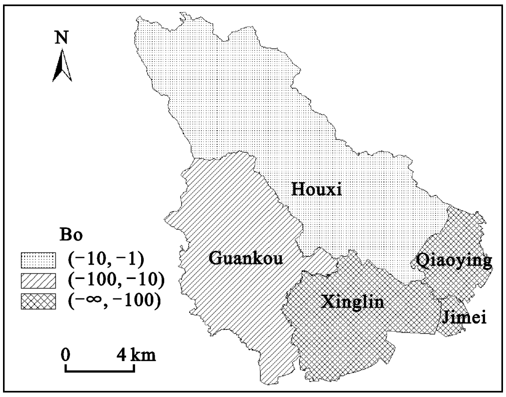

Fig. 1 Oxygen balance coefficient (B_O) distribution in different areas of Jimei District

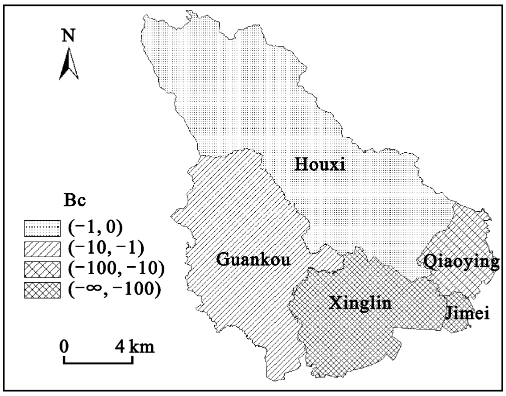

Fig. 2 Carbon balance coefficient (B_C) distribution in different areas of Jimei District

4 Discussion

As urban carbon source and carbon sequestration analysis inevitably involve the urban complex ecosystem which covers both natural and social-economic systems, many related variables are difficult to be handled and the data are hard to be collected. Therefore, relevant case studies concerning carbon source, carbon sequestration, and carbon and oxygen balance were very limited in China. There are, however, still a very few interdisciplinary studies on socioeconomic and biophysical factors that influence urban carbon cycle (Galina, 2008).

One advantage of land carbon cycling model at regional scale is that its requirement for initial data is quite low, allowing that remote sensed vegetation and environment data can be directly used, and then the regional or even the global carbon balance condition of forest ecosystem can be retrieved. The disadvantage, however, is that the parameters have dramatic influence on the forecast result, and the model forecast results can not be directly or broadly tested (Wang *et al*., 2008). Most of the urban ecosystem carbon cycling researches used urban metabolism methods, while these methods were often applied in the material flow and energy flow studies of urban ecosystem (Hendrics *et al*., 2000). However, so far further discussion in relation with the practical quantitative urban planning are not available. The carbon and oxygen balance model proposed in this paper has the similar thinking as carbon footprint does in essence. The difference is that our study tries to solve the problem that is hard to quantify during urban planning.

Guan *et al*. (1998) studied the carbon storage and distribution in urban green land, as well as its effect in carbon and oxygen balance in Guangzhou. Their results indicated that urban area consumed 2.5% of the total oxygen in the air, but, averagely the air exchanged 3 995 times each year, and hence, carbon and oxygen would not be seriously out of balance under normal conditions. However, we think that although urban ecosystem is an open system and its carbon and oxygen balance greatly relies on the exchangeability with the surrounding air, from the urban planning and management perspective, each urban area should be considered as a complete ecological zone. Our viewpoint is consistent with that of Zhang *et al*. (2007), but they just considered the oxygen consumption process of coal and natural gas combustion, respiration and excretion decomposition of population, and did not take oxygen consumption of traffic or industrial oil into account in their small town research.

Xie *et al*. (2008) calculated the carbon emission amount by combining the fossil energy heat transfer rate and carbon emission index, and further computed the ecological footprint of various fossil energy and electricity. One problem about their results was that they were in forms of the amount of forest or grassland occupied by per unit energy, and it could not be a direct, effective reference for the urban planning departments. The extent of vegetation types involved in the carbon and oxygen balance model established in this research was not just about the forests, but comprised the entire land vegetation ecosystem including farmland, grassland, woodland which provides carbon fixation and oxygen release ecological service in correspondence with the physical form of human inhabitant and urban system. Compared with the two major carbon sources (the fossil energy and rain forest loss), which were concerned in the global carbon source analysis by IPCC (Schimel *et al*., 1996), the urban carbon balance assessment model proposed in this study involved various human carbon emitting activities and oxygen consumption factors in urban area, which effectively quantified the relationship between vegetation ecological service (mainly carbon seqestration and oxygen emission) within an urban area and the urban population requirement, thus providing practical guides for the quantitative planning of urban vegetation.

In this study, the oxygen consumption model comprised five kinds of oxygen consumption. However, due to the limited data resources, oxygen consumption by livestock respiration and solid waste decomposition was not involved in the model. Similarly, in the carbon emission model, the annual domestic electricity consumption was converted into standard coal use, but the specific components of the electricity sources were not elucidated. In addition, some data used in this study were derived from the previous researches. Thereby, more work is needed to do to improve the model.

In the coming researches on the new UCOB model, more importance should be attached to obtaining more reliable and practical model parameters through field observation, for example, measuring carbon and oxygen flux with scientific instruments, recording the capability of urban vegetation to fix carbon and release oxygen at different seasons and under different environmental conditions.

5 Conclusions

On the basis of urban vegetation ecological service, the application of human induced oxygen consumption and carbon emission in urban area was summed up in this paper, and a new urban carbon and oxygen balance (UCOB) model based on a combination of natural systems and social systems and its evaluation system were constructed. The Jimei District of Xiamen City was used as a case study to test the UCOB model, and the results showed that vegetation service of oxygen emission and carbon sequestration could not meet the demand of the urban population. More than 31.49 times of vegetation area are needed to meet the whole oxygen consumption in Jimei and 9.60 times of vegetation area are needed to meet the carbon sequestration targets. Our result proved that the UCOB model can effectively quantify ecological service of vegetation (mainly carbon sequestration and oxygen emission) and population requirement in urban area, consequently providing important referential support for quantitative planning of urban vegetation and regional eco-compensation mechanisms.

References

Cao M, Woodward F I, 1998. Net primary and ecosystem production and carbon stocks of terrestrial ecosystem and their response to climate change. *Global Change Biology*, 4: 185–198.

Colin P, Martin H, Stephen S, 2000. The carbon balance of the terrestrial biosphere: Ecosystem models and atmospheric observations. *Ecological Applications*, 10(6): 1553–1573. DOI: 10.1890/1051-0761(2000)010[1553:TCBOTT]2.0.CO;2

Cox P M, Betts R A, Jones C D *et al*., 2000. Acceleration of global warming due to carbon cycle feedbacks in a coupled climate model. *Nature*, 408: 184–187. DOI: 10.1038/35041539

Fang Jingyun, Guo Zhaodi, Piao Shilong *et al*., 2007. 1981–2000 Chinese terrestrial vegetation carbon sink estimates. *Science in China* (*Series D*), 37(6): 804–812. (in Chinese)

Fang Jingyun, Liu Guohua, Xu Songling, 1996a. Biomass and net production of forest vegetation in China. *Acta Ecologica Sinica*, 16(5): 497–508 (in Chinese)

Fang Jingyun, Liu Guohua, Xu Songling, 1996b. Chinese terrestrial ecosystem carbon cycle and its global significance. In: Wang Gengchen, Wen Yupu, (eds.). *Greenhouse Gas Concentrations Emissions Monitoring and Related Processes*. Beijing: China Environmental Science Press, 81–149. (in Chinese)

Galina C, 2008. Modeling the carbon cycle of urban systems. *Ecological Modelling*, 216(2): 107–113. DOI: 10.1016/j.ecomolmodel.2008.03.006

Guan Dongsheng, Chen Yujuan, Huang Fenfang, 1998. The storage and distribution of carbon in urban vegetation and its roles in balance of carbon and oxygen in Guangzhou. *China Environmental Science*, 18(5): 437–441. (in Chinese)

Hendrics C R, Obernosterer R, Muller D *et al.*, 2000. Material flow analysis: A tool to support environmental policy decision making. Case studies on the city of Vienna and the Swiss lowlands. *Local Environment*, 5: 311–328. DOI: 10.1080/13549830050134257

IEA (International Energy Agency), 2008. World Energy Outlook 2008. Available from: http:// www.worldenergyutlook.org/docs/weo2008/WEO_2008_Energy_Use_in_Cities_Modelling.pdf. 2009-01-20.

IPCC (Intergovernmental Panel on Climate Change), 2007. Working group 1: The physical science basis. Summary for policymakers. Available from: http://ipcc-wg1.ucaredu/wg1/wg1-report.html. 2008-05-20.

Ji Jinjun, Huang Mei, Li Kerang, 2008. Analysis on carbon exchange prediction of Chinese terrestrial ecosystem and atmospheric in 21 Century. *Science in China* (*Series D*), 38(2): 211–223. (in Chinese)

Kok R, Benders R M J, Moll H C, 2006. Measuring the environmental load of household consumption using some methods based on input-output energy analysis: A comparison of methods and a discussion of results. *Energy Policy*, 34: 2744–2761. DOI: 10.1016/j.enpol.2005.04.006

Kolari P, Pumpanen J, Rannik U *et al*., 2004. Carbon balance of different aged Scots pine forests in Southern Finland. *Global Change Biology*, 10(7): 1106–1119.

Leith H, 1975. Modeling the primary of the world. In: Leith H, Whirtaker R H. (eds.). *Primary Productivity of the Biosphere*. Berlin: Springer Springerverlag. 237–263.

Lenzen M, Lise-Lotte P, Munksgaard J, 2004. CO_2 multipliers in multi-region input-output models. *Economic Systems Research*, 16: 391–412. DOI: 10.1080/0953531042000304272

Liu J, Chen J M, Cihlar J *et al*., 1997. A process-based boreal ecosystem productivity simulator using remote sensing inputs. *Remote Sensing of Environment*, 62: 158–175.

Lloyd J, Shibistova O, Zolotoukhine D *et al*., 2002. Seasonal and annual variations in the photosynthetic productivity and carbon balance of a central Siberian pine forest. *Tellus Series B-Chemical And Physical Meteorology*, 54(5): 590–610.

Lovelock J E, 1990. Hand up for Gaia hypothesis. *Nature*, 344: 100–102. DOI:10.1038/344100a0

NCQC (National Coal Quality Supervision and Inspection Center of the People's Republic of China), 2007. National coal and oil composition analysis and measurement standards. Available from: http://www.ccqtc.com. 2008-05-20.

Peng Jiangying, 2003. Roles of vegetation on balance of carbon and oxygen in the Pearl River Delta. *Acta Scientiarum Naturalium Universitatis Sunyatseni*, 42(5): 105–108. (in Chinese)

Raich J W, Rastetter E B, Melillo J M *et al*., 1991. Potential net primary productivity in South America: Application of a global model. *Ecological Applications*, 1(4): 399–429. DOI: 10.2307/1941899

SAC (Standardization Administration of the People's Republic of China), 2007. Different energy conversion coefficient to standard coal. Available from: http://www.stats.gov.cn/. 2008-05-20.

Schimel D, Alves D, Enting I *et al*., 1996. Radiative forcing of climate change. In: Houghton J T *et al*. (eds.). *Climate Change 1995. The Science of Climate Change*. Cambridge: Cambridge University Press, 69–131.

Sellers P J, Mintz Z, Sud Y C *et al*., 1986. A simple biosphere model (SIB) for use within general circulation models. *Journal of the Atmospheric Sciences*, 43(6): 505–531. DOI: 10.1175/1520-0469(1986)043<0505:ASBMFU>2.0.CO;2

Singh J S, Gupta S R, 1997. Plant decomposition and soil respiration in terrestrial ecosystems. *Botanical Review*, 43(4): 449–528. DOI: 10.1007/BF02860844

Wackemagel M, Onisto L, Bello P *et al*., 1999. National natural capital accounting with the ecological footprint concept. *Ecological Economics*, 29(3): 375–390. DOI: 10.1016/S0921-8009(98)90063-5

Wang Shaogang, He Guojin, Liu Dingsheng *et al*., 2008. Advances in carbon cycle model of forest ecosystem. *Science & Technology Review*, 26(9): 72–77. (in Chinese)

Xie Hongyu, Chen Xiansheng, Lin Kairong *et al*., 2008. The ecological footprint analysis of fossil energy and electricity. *Acta Ecologica Sinica*, 28(4): 1729–1735. (in Chinese).

XMEPB (Xiamen Municipal Environmental Protection Bureau), 2006. *Xiamen Urban Environmental Statistics and Data Compilation in 2006*. Xiamen: Xiamen Press. (in Chinese)

XMSB (Xiamen Municipal Statistical Bureau), 2007. *Yearbook of Xiamen Special Economic Zone in 2007*. Beijing: Chinese Statistics Press. (in Chinese)

Yang Shihong, 1996. Effect research on carbon and oxygen balance of urban greening trees. *Urban Ecology and Urban Environment*, 9(1): 37–39. (in Chinese)

Zhang L X, Liu Q, Hall N W *et al*., 2007. An environmental accounting framework applied to green space ecosystem planning for small towns in China as a case study. *Ecological Economics*, 60(3): 533–542. DOI: 10.1016/j.ecolecon.2006.07.022