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Carbon Sequestration in Forest Vegetation of Beijing at Sublot Level

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Abstract: Based on forest inventory data (FID) at sublot level, we estimated the carbon sequestration in forest vegetation of Beijing, China in 2009. In this study, the carbon sequestration in forest vegetation at sublot level was calculated based on net biomass production (ΔB) which was estimated with biomass of each sublot and function relationships between ΔB and biomass. The biomass of forested land was calculated with biomass expansion factors (BEFs) method, while those of shrub land and other forest land types were estimated with biomass, coverage and height of referred shrubs and shrub coverage and height of each sublot. As one of special forested land types, the biomass of economic tree land was calculated with biomass per tree and tree number. The variation of carbon sequestration in forest vegetation with altitude, species and stand age was also investigated in this study. The results indicate that the carbon sequestration in forest vegetation in Beijing is 4.12×10^6 tC/yr, with the average rate of 3.94 tC/(ha·yr). About 56.91% of the total carbon sequestration in forest vegetation is supported by the forest in the plain with an altitude of < 60 m and the low mountainous areas with an altitude from 400 m to 800 m. The carbon sequestration rate in forest vegetation is the highest in the plain area with an altitude of < 60 m and decreased significantly in the transitional area from the low plain to the low mountainous area with an altitude ranging from 200 m to 400 m due to intensive human disturbance. The carbon sequestration of *Populus* spp. forest and *Quercus* spp. forest are relatively higher than those of other plant species, accounting for 25.33% of the total. The carbon sequestration in vegetation by the forest of < 40 years amounts to 45.38% of the total. The carbon sequestration rate in forest vegetation peaks at the stand age of 30–40 years. Therefore, it would be crucial for enhancing the capability of carbon sequestration in forest vegetation to protect the forest in Beijing, to limit human disturbance in the transitional area from the plain to the low mountain area, and to foster the newly established open forest.
Keywords: forest; sublot; carbon sequestration in vegetation; biomass expansion factors (BEFs) method; Beijing

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1 Introduction

Forests play an important role in the global carbon cycle. Carbon stock in global forest vegetation was estimated to be 359–536 PgC, accounting for 77%–82% of the total carbon maintained by the terrestrial vegetation (Dixon *et al*., 1994; Mooney *et al*., 1999; Prentice *et al*., 2001). Photosynthetic carbon fixation in forest comprises a major component of the global carbon cycle. The forest net primary production (NPP) was calculated at 26.9–32.6 PgC/yr, supporting nearly half of the terrestrial NPP (Mooney *et al*., 1999; Geider *et al*., 2001). Thus, forest vegetation is an important carbon sequestration in terrestrial ecosystems. The forest of the Northern Hemisphere is a critical carbon sequestration in maintaining global carbon balance (Goodale *et al*., 2002). With compilations of the direct measurements of forest NPP, Huston and Wolverton (2009) found that the annual NPP in tropical forests was no different than that in temperate forests, which was contrary to the output of global vegetation models, and the terrestrial productivity reached a maximum between 30° and 50° before declining toward the poles. Thus, it is important to investigate the carbon sequestration in the mid-latitude tem-

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perate forest in the Northern Hemisphere.

Nowadays, there are a lot of methods to examine the forest carbon sequestration. With automated chamber system and eddy covariance technique, Sano *et al*. (2010) reported that the seasonal sum of net ecosystem production (NEP) of a Japanese larch plantation in northern Japan decreased from 159 ± 57 gC/m^2 to −80 ± 30 gC/m^2 because of a typhoon disturbance, which shows that the ecosystem shifted from a carbon sink to a source. The process-oriented biosphere models have been widely used to simulate regional and global carbon cycle and to investigate forest carbon sequestration, such as CENTURY, Carnegie-Ames-Stanford Approach (CASA), Biome-BioGeochemical Cycles (Biome-BGC) and Carbon-Fixation (C-Fix) (Veroustraete *et al*., 2002; Potter *et al*., 2005; de Vries and Posch, 2010). Wang *et al*. (2007) reported that the forest in China was a small carbon source to be 3.32 PgC, about 32.9 ± 22.3 TgC/yr from 1901 to 2001 using Integrated Terrestrial Ecosystem C-budget model (InTEC). Maselli *et al*. (2009) simulated the NPP in the Mediterranean region to be between 300 gC/(m^2·yr) and 400 gC/(m^2·yr) with C-Fix and Biome-BGC models.

However, as the results of process-oriented models were based on a series of embedded scientific hypotheses (Ťupek *et al*., 2010), it was crucial to adopt data from multiple sources to revise the results. Beer *et al*. (2010) estimated the terrestrial GPP flux at 123 ± 8 PgC/yr using eddy covariance flux data and various diagnostic models, such as the model tree ensemble and the artificial neural network. Xiao *et al*. (2011) reported a terrestrial carbon sink in the U.S. at 0.63 PgC/yr with the majority of the sink in regions dominated by evergreen and deciduous forests and savannas by integrating eddy covariance flux measurements and satellite observations.

Besides data from field survey, eddy covariance technique and remote sensing images, forest inventory data (FID) are also useful for estimating carbon stocks and net fluxes in areas or countries with systematic forest inventories. Woodbury *et al*. (2007) estimated the average carbon sequestration in U.S. forests to be 162 TgC/yr from 1990 to 2010 with FID supplemented with data from intensive research sites and models. Ťupek *et al*. (2010) reported that European NPP average (508 ± 183 gC/(m^2·yr)) estimated with forest inventory-based model European Forest Information SCENario (EFISCEN) was close to 487 ± 126 gC/(m^2·yr) estimated with climate-based Terrestrial Ecosystem Models (TEMs), including Biome-BGC, ORganizing Carbon and Hydrology In Dynamic EcosystEms (ORCHIDEE), and Joint UK Land Environment Simulator (JULES).

Compared to estimates from eddy-covariance sites or networks, inventory-based C budgets represent the full range of forest types, climate zones, and disturbance and management regimes across the forest areas. In contrast to process-based models, inventories incorporate the full range of impacts of human actions and natural disturbance, including forest harvest, fire, insect outbreaks, and land-use change (Goodale *et al*., 2002).

Actually, FID has been used to estimate forest biomass, NPP, carbon stock and carbon sequestration for a long time. Based on the first to the forth FID of China and biomass expansion factors (BEFs) method, Liu *et al*. (2000) showed that the carbon storage of forest in China increased from 3.75 PgC to 4.20 PgC, with the annual increment of 26.5 TgC. Fang *et al*. (2001) reported that the forest in China was a carbon source between 1949 and 1980, with the annual emission rate of 0.022 PgC, and that it was a carbon sink from the end of the 1970s to 1998, with the annual assimilation rate of 0.021 PgC, based on field experiment data, FID of China and BEFs method. Goodale *et al*. (2002) calculated the carbon sink of forests and woodlands in the Northern Hemisphere to be 0.6−0.7 PgC/yr during the early 1990s with FID and allometric relationships. de Wit *et al*. (2006) reported the C sink strength in forest biomass in southeast Norway to be 0.38 MgC/(ha·yr) from 1971 to 2000 based on FID and the BEFs method. Guo *et al*. (2010) estimated the carbon stocks in China and their changes from 1984 to 2003 using three methods based on the FID, and found that the forest carbon stock varied among different methods, and forest age class was a major factor responsible for the variation.

It could be concluded that the FID-based method was one of the important ways to investigate carbon sequestration in forest vegetation and a crucially complementary approach for other carbon budget methods. However, most studies on carbon sequestration in forest vegetation were conducted based on summarized FID data. Only few of researches deal with the spatial heterogeneity of FID at sublot level (Xie *et al*., 2010). Thus, the information at sublot level about vegetation, standing age, soil, site, community structure, coverage, *etc*., would not be involved in the process of carbon sequestration in forest vegetation estimation.

In this study, we would incorporate the forest attributes, such as forest land type, plant species, shrub coverage, shrub height, tree number, from FID on sublot level in Beijing into the investigation of carbon sequestration in forest vegetation and their spatial distribution, and analyze their variations with plant species, altitude and stand age.

2 Methodology

2.1 Study area

Beijing lies in 39º28′–41º05′N and 115º25′–117º30′E, on the northern edge of the North China Plain. The total area of Beijing is 16 807 km^2, about 62% of which is low mountain area, mostly distributed in the northern and western parts, including the counties or districts of Yanqing, Huairou, Miyun, Mentougou, the northwestern part of Changping, the northern part of Pinggu and western part of Fangshan. The mountain descends into a foothill area and then to the small Beijing plain in the southeastern part. The plain area is less than 100 m a. s. l., mostly 30–50 m, including the districts of Dongcheng, Xicheng, Chongwen, Xuanwu, Chaoyang, Haidian, Shijingshan, Fengtai, Daxing, Shunyi, Tongzhou, the southeastern part of Changping, the southern part of Pinggu and eastern part of Fangshan. It has a warm and semi-humid continental monsoon climate, with cold and dry winter and hot summer. Annual precipitation averages nearly 700 mm, most of which comes in July and August. The average annual temperature is 11.7℃.

According to the Seventh Forest Resource Inventory of Beijing in 2009, the total forest area was 1.05×10^6 ha, with a forest coverage rate of 36.75%. There are eight types of forest lands in Beijing, which are forested land, open forest land, shrub land, newly established open forest land, nursery, unstocked forest land, land suitable for forest and assistant production forest land. The area of forested land accounted for 62.99% of the total area of forest lands of Beijing, the shrub land 29.23%, and other six types 7.78%. The dominant plant species include *Populus* spp., *Quercus* spp., *Pinus tabulaeformis*, *Larix principisrupprechtii*, *Platycladus orientalis*, *Betula* spp., *Robinia pseudoacacia*, *Vitex negundo* var. *heterophylla*, *Spiraea velutina*, *Ziziphus jujube* and *Zizyphus jujuba* var. *spinosa*, which host a rich variety of other species of fauna and flora.

2.2 Data sources

Totally 109 736 forest data on sublot level from the Seventh Forest Resource Inventory of Beijing in 2009 were provided by Beijing Forestry Survey and Design Institute. The data described the spatial distribution of forest on the scale of 1∶10000 and a series of attributes of all the forest sublots, including forest type, area, altitude, stand age, volume, tree species, tree coverage, tree height, shrub species, shrub height, shrub coverage, economic tree species, economic tree number, *etc*.

2.3 Estimation methods

2.3.1 Method to estimate forest biomass

(1) Biomass of forested land

The biomass of forested land was calculated with biomass expansion factors (*BEFs*) method (not including the economic tree land) with the equation as follows (Fang *et al*., 1996; 2001):

$$W_{\mathrm{f}} = (V \times BEFs) / A = (V \times (a + b / V)) / A = (aV + b) / A \tag{1}$$

where W_{f} is the biomass of forested land per unit area of a sublot (t/ha), including the above- and below-ground biomass of all living trees, shrubs and herbs; V is forest volume (m^3); A is sublot area (ha); and a (t/m^3) and b (t) are constants for different tree species (Table 1).

Table 1 Parameters to calculate forested land biomass of Beijing

Tree species	*a* (t/m^3)	*b* (t)
Pinus tabulaeformis	0.7554	5.0928
Larix principisrupprechtii	0.6096	33.8060
Platycladus orientalis	0.6129	46.1451
Quercus spp.	1.1453	8.5473
Betula spp.	1.0687	10.2370
Populus spp.	0.4754	30.6034
Other broad-leaved forests	0.7564	8.3103

Sources: Fang *et al*., 1996; 2001

(2) Biomass of economic tree land

The economic tree land was one special type of forested land, but there was no volume for the sublots of the economic tree land. In this study, we estimated the biomass of economic tree land with tree number and biomass per tree by the following equation (Fang *et al*., 1996):

$$W_e = (B_e \times N_e / A)/1000 \quad (2)$$

where W_e is the biomass of economic tree land per unit area of a sublot (t/ha); B_e is the referred biomass per economic tree (kg/tree) (Table 2); and N_e is the economic tree number of a sublot.

(3) Biomass of shrub and other forest land types

As the dominant species of shrub land and other forest land types were shrubs and young trees, there was no volume for these sublots in the Seventh Forest Resource Inventory of Beijing. The biomass of shrub land and other forest land types was closely related with the height and coverage of plant. In this study, we assumed that the biomass of shrub and other forest land types was linearly related with the height and coverage of plant, which was calculated by the following equation:

$$W_s = (C_s / C_0) \times (H_s / H_0) \times w_{s0} \quad (3)$$

where W_s is the biomass of shrub per unit area of a sublot (t/ha); C_s is the coverage of shrub (%); C_0 is the coverage of the referred shrub (%); H_s is the height of shrub (cm); H_0 is the height of the referred shrub (cm); and w_{s0} is the biomass of the referred shrub per unit area (t/ha).

The biomass, coverage and average height of different referred shrubs are listed in Table 3. As the assistant production forest land was mostly construction land, its biomass was not estimated in this study.

2.3.2 *Method to estimate net biomass production*

The net biomass production was calculated by Equation (4) (Fang *et al*., 1996):

$$\Delta B = f(W) \quad (4)$$

where ΔB is the net biomass production of forest land per unit area of a sublot (t/(ha·yr)); W is the biomass of different types of forest land per unit area of a sublot (t/ha). Function relationships between net biomass production (ΔB) and biomass (W) of forest land were listed in Table 4.

Table 2 Biomass per tree of referred economic trees

Economic tree type	Biomass per tree (kg/tree)	Site	Reference
Malus pumila	29.57	Fengqiu of Henan	Feng *et al*., 1999
Armeniaca vulgaris	30.55	Lingyuan of Liaoning	Lu *et al*., 2004
Castanea mollissima	19.47	Xinyi of Jiangsu	Peng and Wang, 1998
Crataegus pinnatifida	33.27	Pingdingshan of Henan	Li *et al*., 1998
Other fruit trees	28.22	Average of four fruit trees	
Other economic trees	13.84	Zoucheng of Shandong	Yang *et al*., 1996

Table 3 Biomass, coverage and average height of referred shrubs

Shrub type	Biomass per unit area (t/ha)	Average height (cm)	Coverage (%)	Site	Reference
Spiraea velutina	23.84	65	90	Xishan Mountain of Beijing	Dai, 1989
Zizyphus jujuba var. *spinosa*	6.55	95	65	Tianshui of Gansu	Cai, 2003
Corylus heterophylla Fisch	6.25	75	80	Yudingshan Mountain of Shanxi	Shangguan and Zhang, 1989
Vitex negundo var. *heterophylla*	14.21	100	60	Huairou of Beijing	Dai, 1989
Other shrubs	12.71	84	74	Average of four shrubs	

Table 4 Function relationships between net biomass production (ΔB) and biomass (W) of forest land (Fang *et al*., 1996)

Forest type	Species	Function relationship
Forested land	*Pinus tabulaeformis*	$1/\Delta B = 5.71/W + 0.0471$
	Larix principisrupprechtii	$\Delta B = -0.018W + 14.294$
	Platycladus orientalis	$1/\Delta B = 12.092/W + 0.048$
	Broad-leaved trees	$\Delta B = 0.208W + 1.836$
Other forest land types[1)]		$1/\Delta B = 1.27/W^{1.196} + 0.056$

Notes: 1) Other forest land types include open forest land, shrub land, newly established open forest land, nursery, unstocked forest land, and land suitable for forest. As the assistant production forest land was mostly construction land, its net biomass production was not calculated in this study

2.3.3 Method to estimate carbon sequestration in forest vegetation

The carbon sequestration in forest vegetation was calculated with net biomass production (ΔB) and average carbon content of vegetation (Fang *et al*., 2006):

$$C = \Delta B \times 50\% \quad (5)$$

where C is the carbon sequestration rate of forest land of a sublot (tC/(ha·yr)); and 50% is the average carbon content of vegetation (Fang *et al*., 2006).

3 Results

3.1 Carbon sequestration in forest vegetation

The forest area in Beijing in 2009 was 1.05×10^6 ha, with the biomass of 2.799×10^7 t, net biomass production 8.24×10^6 t/yr and carbon sequestration in vegetation 4.12×10^6 tC/yr (Table 5). The results did not cover the forests in Dongcheng, Xicheng, Chongwen and Xuanwu districts, as they were totally classified into urban green area, and were not involved in this forest survey. Forested land was the main carbon sequestration in forest vegetation of Beijing, as it supported 73% of the total forest biomass, 55% of the total net biomass production and 55% the total carbon sequestration in forest vegetation. In forested land, carbon sequestration by the broad-leaved forest was more than that by coniferous forest and mixed forest, which supplied more than 40% of the total carbon sequestration in forest vegetation of Beijing.

The forest biomass per unit area was estimated to be 26.66 t/ha, ranging from 1.90 t/ha to 54.74 t/ha; net biomass production per unit area 7.85 t/(ha·yr), ranging from 1.23 t/(ha·yr) to 13.42 t/(ha·yr); and carbon sequestration rate in forest vegetation 3.94 tC/(ha·yr), ranging from 0.61 tC/(ha·yr) to 6.71 tC/(ha·yr). The carbon sequestration rate in forest vegetation by nursery, newly established open forest land and forested land was much higher than that by other types (Table 5). However, the proportion of the area of nursery and newly established open forest land to the total forest area was only 3.63%, thus their carbon sequestration contributed little to the total of Beijing.

In the ridge areas of districts and counties with high altitude, such as Fangshan, Huairou, Yanqing and Miyun, the carbon sequestration rate in forest vegetation was much higher than other areas. It was relatively lower in the transitional area between the plain and mountain areas in western and northern parts of Beijing and the foothill areas in Pinggu, the southern Miyun, the northern Changping, and the southern Huairou. As most of the shelter forest for cropland, road and river was located in the plain area of southeastern part of Beijing, the carbon sequestration rate of this area was also higher with better soil nutrient and water condition (Fig. 1). Nevertheless, the carbon sequestration in vegetation of shelter forest for cropland, road and river contributed a

Table 5 Biomass, net biomass production and carbon sequestration of forest in Beijing

Forest type	Area ($\times 10^3$ ha)	Biomass per unit area (t/ha)	Net biomass production per unit area (t/(ha·yr))	Carbon sequestration rate (tC/(ha·yr))	Biomass ($\times 10^6$ t)	Net biomass production ($\times 10^6$ t/yr)	Carbon sequestration ($\times 10^6$ tC/yr)
FL	658.91	39.16	7.80	3.90	20.47	4.53	2.26
CF	150.53	31.05	3.37	1.68	4.56	0.49	0.25
BF	404.06	54.74	13.42	6.71	12.90	3.48	1.74
CBMF	104.32	31.69	6.60	3.30	3.01	0.55	0.28
OFL	5.58	21.70	4.39	2.20	0.12	0.02	0.01
SL	305.81	10.60	5.28	2.64	6.60	3.16	1.58
NEFL	21.10	13.03	7.82	3.91	0.28	0.17	0.08
NS	16.90	11.43	8.01	4.00	0.19	0.14	0.07
UFL	4.84	1.90	1.23	0.61	0.04	0.02	0.01
SFL	32.76	4.73	3.18	1.59	0.30	0.20	0.10
APFL	0.20	–	–	–	–	–	–
Sum/Average	1 046.10	26.66	7.85	3.94	27.99	8.24	4.12

Notes: FL: forested land; OFL: open forest land; CF: coniferous forest; BF: broad-leaved forest; CBMF: coniferous and broad-leaved mixed forest; SL: shrub land; NEFL: newly established open forest land; NS: nursery; UFL: unstocked forest land; LSF: land suitable for forest; APFL: assistant production forest land '–': As the assistant production forest land was mostly construction land, its biomass, net biomass production and carbon sequestration in vegetation per unit area and their sums were not calculated in this study

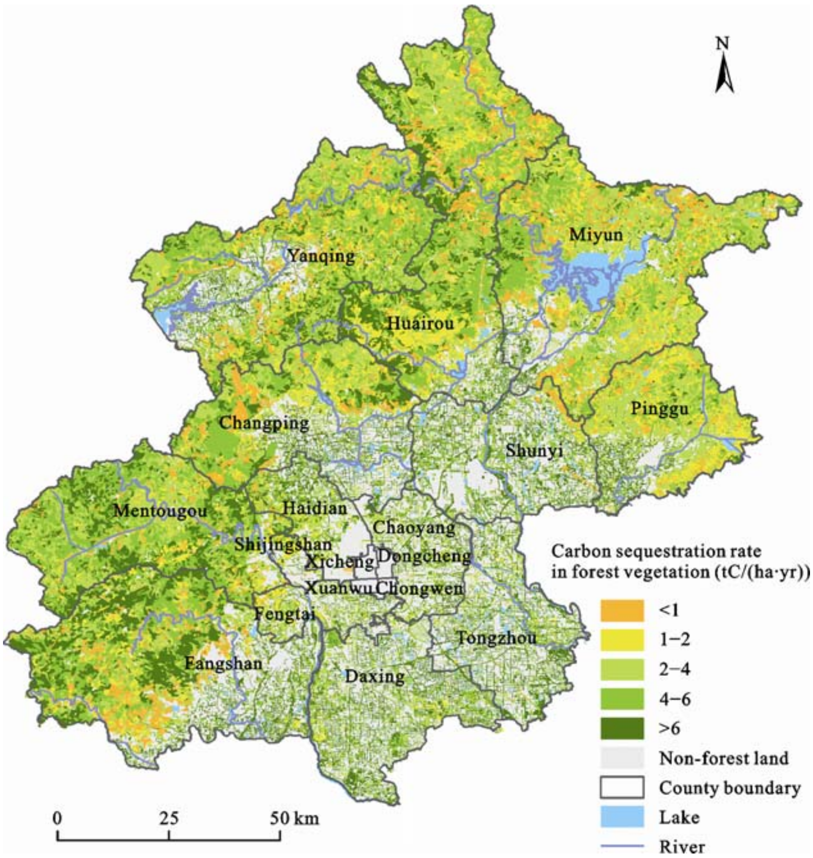


Fig. 1 Spatial distribution of carbon sequestration in forest vegetation in Beijing

little to the total carbon sequestration of Beijing because its area accounted for only 5% of the total forest area.

3.2 Change of carbon sequestration in forest vegetation with altitude

Most of the carbon sequestration in forest vegetation of Beijing was distributed in the plain area with an altitude of < 60 m and the low mountainous area with an altitude of 400–800 m, which accounted for 56.91% of the total. The carbon sequestration rate in forest vegetation was highest in the plain area with an altitude of < 60 m, and decreased significantly in the area with an altitude ranging from 200 m to 400 m, and increased again with altitude (Fig. 2). However, as the area of forest in plain area with an altitude of < 60 m was only 12.85% of the total forest area, the carbon sequestration in forest vegetation of this area only contributed to 17.87% of the total.

3.3 Carbon sequestration in forest vegetation among tree species

The area of forest land with dominant species amounted for 48.75% of the total forest land area in Beijing, supplying 45.05% of the total carbon sequestration in forest vegetation. Among all dominant plant species, the forests of *Populus* spp. and *Quercus* spp. were the main carbon sinks in forest vegetation, accounting for 25.33% to the total (Fig. 3). The carbon sequestration rate in vegetation of *Populus* spp. forest was estimated to be 9.50 tC/(ha·yr), which was higher than those of other tree species. The carbon sequestrations rate in vegetation of *Pinus tabulaeformis* forest, *Platycladus oriental* forest, *Quercus* spp. forest, other broad-leaved forest and other

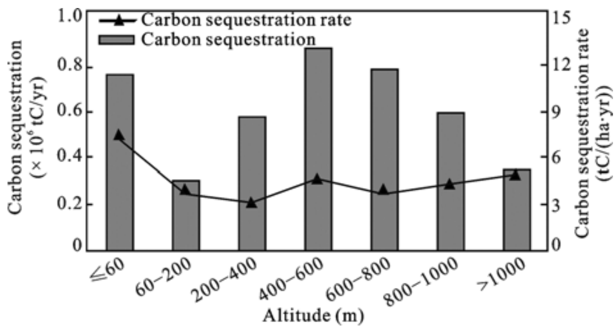
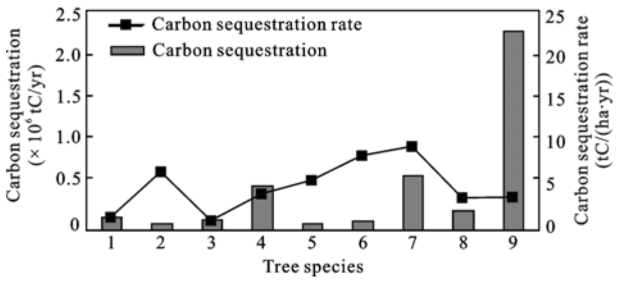


Fig. 2 Variation of carbon sequestration in forest vegetation with altitude in Beijing

forest lands without tree species records were not surpass 5 tC/(ha·yr) (Fig. 3).

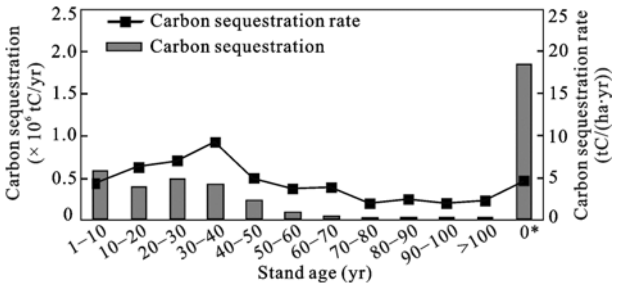
3.4 Age-related change of carbon sequestration in forest vegetation

The forest land in Beijing with stand age record were forested land and open forest land, which accounted for 63.52% of the total forest area. Their carbon sequestration in vegetation was calculated to be 2.28 × 10^6 tC/yr, accounting for 55.23% of the total (Fig. 4). The carbon sequestration in forest vegetation decreased with stand age. The carbon sequestration in vegetation of forested land and open forest land with the stand age of < 40 years was higher than that with other stand ages, amounting to 45.38% of the total (Fig. 4). The carbon sequestration rate in forest vegetation peaked at the stand age of 30–40 years (9.11 tC/(ha·yr)).



1. *Pinus tabulaeformis*; 2. *Larix principisrupprechtii*; 3. *Platycladus orientali*; 4. *Quercus* spp.; 5. *Betula* spp.; 6. *Robinia pseudoacacia*; 7. *Populus* spp.; 8. Other broad leaved trees; 9. other forest lands without tree species records

Fig. 3 Carbon sequestration in forest vegetation in Beijing by different tree species



* refers to those forest lands without stand age record

Fig. 4 Variation of carbon sequestration in forest vegetation in Beijing with stand age

4 Discussion

4.1 Carbon sequestration in forest vegetation

Fang *et al*. (1996) estimated the biomass and net biomass production of forest of Beijing in 1989 to be 10.93 × 10^6 t and 2.04 × 10^6 t/yr, respectively. Although the forest area of Beijing in 2009 was five times as that in 1989, the biomass in 2009 was just twice as that in 1989, and the net biomass production was 4 times. The possible reasons could be the difference of data format (FID used in Fang *et al*. was compiled data, while those used in this study were FID on sublot level) and parameters adopted in estimation. Besides, the increased forest area since 1989 mostly consisted of newly established forest, which contributed little to the forest biomass but much to the net biomass production.

There were lots of studies on carbon sequestration rate in forest vegetation based on field measurement or model simulation. Dai (1989) reported that the carbon sequestration rate in vegetation of *Vitex negundo* var. *heterophylla* shrub in the mountainous area of Huairou of Beijng was 2.33 tC/(ha·yr). The results of Sang *et al*. (2002) showed that the carbon sequestration rate in vegetation of *Quercus liaotungensis* forest in Donglingshan Mountain of Beijing was 4.78 tC/(ha·yr). With compilation data, Pregitzer and Euskirchen (2004) found that the carbon sequestration rate in vegetation of temperate forest was 7.1 tC/(ha·yr). With CASA model based on satellite observations, the carbon sequestrations rates in vegetation of the deciduous broad-leaved forest, evergreen coniferous forest, deciduous forest, and mixed broad-leaved and coniferous forest of China were estimated to be between 2.10 tC/(ha·yr) and 5.68 tC/(ha·yr) (Piao *et al*., 2001; Sun and Zhu, 2001; Yu *et al*., 2005). Liu *et al*. (2009) simulated the carbon sequestration rate in vegetation in Beijing with Lund-Potsdam-Jena dynamic global vegetation model and General Ecosystem Simulator (LPJ-GUESS), which was estimated to be 7.00 ± 1.1 tC/(ha·yr) for *Quercus liaotungensis* forest, 6.64 ± 1.06 tC/(ha·yr) for *Betula platyphylla* forest, and 7.59 ± 1.32 tC/(ha·yr) for *Pinus tabulaeformis* forest.

Compared to other studies, the carbon sequestration rate in forest vegetation in this study was relatively low. The main reason was that the forest in Beijing was seriously disturbed by human activities, the original forest disappeared totally, and the existing forest was the secondary forest evolved from forest reservation practices during the 1950s and the 1960s. Besides, the carbon sequestration rates in forest vegetation of other studies were mostly based on field measurements, while it was the average of all forest sublots in Beijing in our study. Many sublots with human disturbance, adverse soil and water conditions, and unfavorable slope direction were also involved in our study, which resulted in low vegetation growth. Therefore, the average carbon sequestration rate in forest vegetation in this study was lower than those based on field measurements of other studies.

4.2 Change of carbon sequestration in forest vegetation with altitude

Generally, altitude affects vegetation growth significantly with vertical zonation of temperature, humidity, sunshine time, soil, *etc*. Temperature, atmospheric pressure, CO_2 partial pressure decrease with altitude, which limits vegetation growth, while rainfall, atmospheric humidity, soil humidity and sunshine intensity increase with altitude, which accelerates vegetation photosynthesis (Pan *et al*., 2009). Zhang *et al*. (2010) reported that the soil total organic carbon and soil labile organic carbon in soil upper layers in the Changbai Mountains increased with altitude. Alvesa *et al*. (2010) found that the live above ground biomass of the coastal Atlantic Forest in the southeastern Brazil ranged from 166.3 Mg/ha to 283.2 Mg/ha, and increased with the elevational gradient (0−1100 m a. s. l.). Zeng *et al*. (2008) found that the forest NPP in the Three Gorge Reservoir Region of China decreased with altitude ranging from 300 m to 600 m, peaked at an altitude range of 900 m to 1200 m and then decreased again.

For this study, except biological factors, such as heat, precipitation, soil, *etc*., human disturbance was the major reason resulting in the variation of carbon sequestration rate in forest vegetation with altitude. At lower altitudes, with good management practices, such as fertilization, irrigation, pest killing, *etc*., average carbon sequestration rate in forest vegetation was relatively higher than other areas. However, in the transitional area with an altitude of 200 m to 400 m, frequent human disturbance, such as orchard cultivation, farmland cultivation, shrub harvest, *etc*., resulted in the reduction of carbon sequestration rate in forest vegetation. In the mountain ridge areas, with little human disturbance, the carbon sequestration rate in forest vegetation increased again.

4.3 Carbon sequestration in forest vegetation among tree species

Fang *et al*. (1996) estimated the net biomass production per unit area by forest in China to be 6.24 tC/(ha·yr) for *Larix principisrupprechtii*, 1.80 tC/(ha·yr) for *Pinus tabulaeformis*, 4.43 tC/(ha·yr) for *Betula* spp. and *Quercus* spp., and 5.22 tC/(ha·yr) for *Populus* spp. Liang *et al*. (2006) reported that the carbon sequestration rate in vegetation of *Populus* spp. forest in warm temperate zone ranged from 4.12 tC/(ha·yr) to 10.17 tC/(ha·yr) with compilation of other studies. The results of Vedrova *et al*. (2006) showed that the NPP of mature and overmature larch stands in the Turukhansk Research Station of Yenisei Transect was between 1.76 tC/(ha·yr) and 3.00 tC/(ha·yr). With Biome-BGC models, Fan *et al*. (2010) estimated the carbon sequestration rate in vegetation of *Pinus tabulaeformis* forest to be 3.87 tC/(ha·yr) from 1970 to 1988. The carbon sequestration rate in forest vegetation in our study was close to other results.

4.4 Age-related carbon sequestration in forest vegetation

The carbon sequestration rate in forest vegetation at the stand age of 30–40 years was much higher than that at other ages. According to FID of Beijing, the area of forested land and open forest with the stand age of less than 30 years and the newly established open forest land accounted for 43.73% of the total. With development of these forest lands, they would play an important role in carbon sequestration in vegetation of Beijing. It could be concluded that there was a high potential for the carbon sequestration in forest vegetation in Beijing in future.

Generally, the tree growth rate is slow at early stage, peaks at the maximum leaf area and closure of canopy, and decreases again with development of stand age (Ryan *et al*., 2004). Sun *et al*. (2001) found that the net biomass production per unit area of planted *Larix principisrupprechtii* forest was the lowest at the young stage (< 20 years), peaked at the nearly mature stage (31–40 years), and then decreased again. Ryan *et al*. (2004) reported that the aboveground wood production of *Eucalyptus saligna* forest peaked in 1–2 years after seedling, then it declined proportionally larger than the decline in canopy photosynthesis because the fraction of GPP partitioned to belowground allocation and foliar respiration increased with stand age. With compilation of 1200 records from 120 references, Pregitzer and Euskirchen (2004) found that the NPP of temperate forest peaked at the stand age ranging from 11 years to 30 years, and then decreased with stand age. Peichl *et al*. (2010) also reported that the annual NPP, GPP, Ecosystem Respiration (RE), and NEP were the greatest at the 19-year-old site with biometric and eddy covariance methods.

The explanations about the reasons for the decline of NPP with stand age were controversy. Whittaker and Woodwell (1967) proposed that photosynthesis remained constant when the leaf area reached a plateau, but respiration continued to increase with biomass, which resulted in the decline of tree growth. Ryan *et al*. (1997) figured out that the reason why the tree growth decreased with stand age was not respiration increasing, but: 1) reduction of photosynthesis because of the increasing hydraulic resistance of taller trees; 2) decreasing nutrient supply resulting from nutrient immobilization by trees, leading to the decrease of leaf area, more carbon allocating to root production; 3) decline of leaf area from abrasion in the crowns with longer branches; 4) increasing of mortality of older trees; 5) physiological changes associated with changes in genetic expression (i.e., maturation of tissues); and 6) enhancement of reproductive effort. The latter explanation for the decline of NPP with stand age was supported by more and more researches (Henderson and Jose, 2005; Binkley *et al*., 2010).

5 Conclusions

Considering the spatial heterogeneity of sublots in different types of forest lands, this study investigated the carbon sequestration in forest vegetation based on the FID at sublot level from the Seventh Forest Resource Inventory of Beijing in 2009. The following conclusions are drawn.

(1) Carbon sequestration in forest vegetation in Beijing was 4.12×10^6 tC/yr, and the forested land was the main carbon sequestration in forest vegetation of Beijing, as it supported 55% of the total. The carbon sequestration rate in forest vegetation was 3.94 tC/(ha·yr).

(2) The carbon sequestration in forest vegetation in Beijing were related to altitude, plant species and stand age. About 56.91% of the carbon sequestration in forest vegetation was supported by the forest in the plain area with an altitude of < 60 m and the low mountainous area with an altitude of 400–800 m. The carbon sequestration rate in vegetation of forest land with an altitude of < 60 m was higher than other areas. The *Populus* spp. and *Quercus* spp. forests were the main carbon sinks in forest vegetation, accounting for 25.33% to the total. The carbon sequestration rate of *Populus* spp. forest was 9.50 tC/(ha·yr), which was higher than that of other tree species. The carbon sequestration in vegetation of forested land and open forest land with the stand age of < 40 years was higher than that with other stand ages, amounting to 45.38% of the total. The carbon sequestration rate in forest vegetation peaked at the stand age of 30–40 years (9.11 tC/(ha·yr)).

(3) The potential of carbon sequestration in forest vegetation in Beijing is still huge as the area of forested land and open forest land with the stand age of < 30 years and the newly established open forest land accounted for 43.73% of the total according to FID. In consideration of factors influencing forest carbon sequestration, we should protect the forest in Beijing, reduce the human disturbance in the transitional area from the plain to the low mountain area, and foster the newly established open forest for further enhancing the capability of forest carbon sequestration in Beijing.

(4) FID supports an important data source to investigate the carbon stock and sink of forest, which involves the actual status of forest and human practices. In future, with long series of FID, remote sensing data and eddy covariance measurements, more and more information on forest carbon cycle could be explored combined with the process-based models, such as CENTURY, Biome-BGC, and C-Fix.

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References

Alvesa L F, Vieira S A, Scaranello M A *et al*., 2010. Forest structure and live aboveground biomass variation along an elevational gradient of tropical Atlantic moist forest (Brazil). *Forest Ecology and Management*, 260(5): 679–691. doi: 10.1016/j.foreco.2010.05.023

Beer C, Reichstein M, Tomelleri E *et al*., 2010. Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate. *Science*, 329(5993): 834–838. doi: 10.1126/science.1184984

Binkley D, Stape J L, Bauerle W L *et al*., 2010. Explaining growth of individual trees: Light interception and efficiency of light use by *Eucalyptus* at four sites in Brazil. *Forest Ecology and Management*, 259(9): 1704–1713. doi: 10.1016/j.foreco.2009.05.037

Cai Jizeng, 2003. Investigation of the biomass of *Zizyphus jujuba* var. *spinosa* shrubland in hilly loess area of the Loess Plateau of the northern area of Weihe River. *Gansu Science and Technology*, 19(10): 163–164. (in Chinese)

Dai Xiaobing, 1989. The seasonal dynamics of the biomass of *vitex* shrubland in mountainous area of Huairou County in Beijing. *Acta Botanica Sinica*, 31(4): 307–315. (in Chinese)

de Vries W, Posch M, 2010. Modelling the impact of nitrogen deposition, climate change and nutrient limitations on tree carbon sequestration in Europe for the period 1900–2050. *Environmental Pollution*, online first. doi: 10.1016/j.envpol.2010.11.023

de Wit H A, Palosuo T, Hylen G *et al.*, 2006. A carbon budget of forest biomass and soils in southeast Norway calculated using a widely applicable method. *Forest Ecology and Management*, 225(1–3): 15–26. doi: 10.1016/j.foreco.2005.12.023

Dixon R K, Brown S, Houghton R A *et al.*, 1994. Carbon pools and flux of global forest ecosystems. *Science*, 263(5144): 185–190. doi: 10.1126/science.263.5144.185

Fan Minrui，Yu Xinxiao，Zhang Zhenming *et al.*, 2010. Net primary productivity of a *Pinus tabulaeformis* Forest in Beijing mountainous area in response to different climate change scenarios. *Journal of Northeast Forestry University*, 38(11): 46–48. (in Chinese)

Fang J Y, Chen A P, Peng C H *et al.*, 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. *Science*, 292(5525): 2320–2323. doi: 10.1126/science.1058629

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

Fang Jingyun, Liu Guohua, Zhu Biao *et al.*, 2006. Carbon cycle of three temperate forest ecosystems of Donglingshan Mountain in Beijing. *Science in China* (*Series D*), 36(6): 533–543. (in Chinese)

Feng Zongwei, Wang Xiaoke, Wu Gang, 1999. *Biomass and Productivity of Forest Ecosystems in China*. Beijing: Science Press. (in Chinese)

Geider R J, Delucia E H, Falkowski P G *et al.*, 2001. Primary productivity of planet earth: Biological determinants and physical constraints in terrestrial and aquatic habitats. *Global Change Biology*, 7(8): 849–882. doi: 10.1046/j.1365-2486.2001.00448.x

Goodale C L, Apps M J, Birdsey R A *et al.*, 2002. Forest carbon sinks in the Northern Hemisphere. *Ecological Applications*, 12(3): 891–899.

Guo Zhaodi, Fang Jingyun, Pan Yude *et al.*, 2010. Inventory-based estimates of forest biomass carbon stocks in China: A comparison of three methods. *Forest Ecology and Management*, 259(7): 1225–1231. doi: 10.1016/j.foreco.2009.09.047

Henderson D E, Jose S, 2005. Production physiology of three fast-growing hardwood species along a soil resource gradient. *Tree Physiology*, 25(12): 1487–1494.

Huston M A, Wolverton S, 2009. The global distribution of net primary production: Resolving the paradox. *Ecological Monographs*, 79(3): 343–377.

Li Zhihua, Jing Fengrui, Hu Gaochun, 1998. Study on vegetative measure disposition for gully head protection in hilly region of Pingdingshan City. *Bulletin of Soil and Water Conservation*, 8(l): 18–12. (in Chinese)

Liang Wanjun, Hu Haiqing, Liu Fujin, 2006. Research advance of biomass and carbon storage of poplar in China. *Journal of Forestry Research*, 17(1): 75–79. doi: 10.1007/s11676-006-0018-0

Liu Guohua, Fu Bojie, Fang Jingyun, 2000. Carbon dynamics of Chinese forests and its contribution to global balance. *Acta Ecologica Sinica*, 20(5): 733–740. (in Chinese)

Liu Ruigang, Li Na, Su Hongxin *et al.*, 2009. Simulation and analysis on future carbon balance of three deciduous forests in Beijing mountain area, warm temperate zone of China. *Chinese Journal of Plant Ecology*, 33(3): 516–534. (in Chinese)

Lu Guozhen, Li Hongbo, Bu Zhaodong *et al.*, 2004. Research on agroforestry in semi-arid region of west Liaoning Province. *Liaoning Forestry Science and Technology*, (5): 16–19. (in Chinese)

Maselli F, Chiesi M, Moriondo M *et al.*, 2009. Modelling the forest carbon budget of a Mediterranean region through the integration of ground and satellite data. *Ecological Modelling*, 220(3): 330–342. doi: 10.1016/j.ecolmodel.2008.10.002

Mooney H A, Canadell J, Chapin III F S *et al.*, 1999. Ecosystem physiology responses to global change. In: Walker B H *et al.* (eds.). *Implications of Global Change for Natural and Managed Ecosystems*. *A Synthesis of GCTE and Related Research. IGBP Book Series No. 4.* Cambridge: Cambridge University Press, 141–189.

Pan Honglin, Li Maihe, Cai Xiaohu *et al.*, 2009. Responses of growth and ecophsiology of plants to altitude. *Ecology and Environmental Sciences*, 18(2): 722–730. (in Chinese)

Peichl M, Brodeur J J , Khomik M *et al.*, 2010. Biometric and eddy-covariance based estimates of carbon fluxes in an age-sequence of temperate pine forests. *Agricultural and Forest Meteorology*, 150(7–8): 952–965. doi: 10.1016/j.agrformet.2010.03.002

Peng Fangren, Wang Lianggui, 1998. Study on the growth and biomass production of *Castanea mollissima* planted in different density. *Economic Forest Research*, 16(3): 12–16. (in Chinese)

Piao Shilong, Fang Jingyun, Guo Qinghua, 2001. Terrestrial net primary production and its spatio-temporal patterns in China during 1982–1999. *Acta Scientiarum Naturalium Universitatis Pekinensis*, 37(4): 563–569. (in Chinese)

Potter C, Klooster S, Tan P *et al.*, 2005. Variability in terrestrial carbon sinks over two decades: Part 2—Eurasia. *Global and Planetary Change*, 49(3–4): 177–186. doi: 10.1016/j.gloplacha.2005.07.002

Pregitzer K S, Euskirchen E, 2004. Carbon cycling and storage in world forests: Biome patterns related to forest age. *Global Change Biology*, 10(12): 2052–2077. doi: 10.1111/j.1365-2486.2004.00866.x

Prentice I C, Farquhar G D, Fasham M J R *et al*., 2001. The Intergovernmental Panel on Climate Change (IPCC) third assessment report. In: Houghton J H *et al*. (eds.). *Climate Change 2001*: *The Scientific Basis*. Cambridge: Cambridge University Press, 183–237. Available at: http://www.ipcc.ch/ipccreports/tar/wg1/index.htm

Ryan M G, Binkley D, Fownes J H, 1997. Age-related decline in forest productivity: Pattern and process. *Advances in Ecological Research*, 27: 213–262. doi: 10.1016/S0065-2504(08)60009-4

Ryan M G, Binkley D, Fownes J H *et al*., 2004. An experimental test of the causes of forest growth decline with stand age. *Ecological Monographs*, 74(3): 393–414. doi: 10.1890/03-4037

Sang Weiguo, Su Hongxin, Chen Lingzhi, 2002. Coupling biomass and energy in warm temperate deciduous broad-leaved oak (*Quercus Liaotungensis*) forest ecosystem. *Acta Phytoecologica Sinica*, 26(supp.): 88–92. (in Chinese)

Sano T, Hiranoa T, Liang N *et al*., 2010. Carbon dioxide exchange of a larch forest after a typhoon disturbance. *Forest Ecology and Management*, 260(12): 2214–2223. doi: 10.1016/j.foreco.2010.09.026

Shangguan Tieliang, Zhang Feng, 1989. On synecological features and biomass of *Ostryopsis davidiana* bush-wood in Yunding Mountain, Shanxi Province. *Journal of Shanxi University* (*Natural Sciences Edition*), 12(3): 347–352. (in Chinese)

Sun Changzhong, Shen Guofang, Li Jiyue *et al*., 2001. Study on the present condition and the potentialities of the productivity of main tree species plantation of China. II. Study on the plantation productivities of *Eucalyptus*, *Larix* and *Pinus sylvestris* var. *mongolica*. *Forest Research*, 14(6): 657–667. (in Chinese)

Sun Rui, Zhu Qijiang, 2001. Effect of climate change of terrestrial net primary productivity in China. *Journal of Remote Sensing*, 5(1): 58–61. (in Chinese)

Ťupek B, Zanchi G, Verkerk P J *et al*., 2010. A comparison of alternative modelling approaches to evaluate the European forest carbon fluxes. *Forest Ecology and Management*, 260(1): 241–251. doi: 10.1016/j.foreco.2010.01.045

Vedrova E F, Pleshikov F I, Kaplunov V Y, 2006. Net ecosystem production of boreal larch ecosystems on the Yenisei transect. *Mitigation and Adaptation Strategies for Global Change*, 11(1): 173–190.

Veroustraete F, Sabbe H, Eerens H, 2002. Estimation of carbon mass fluxes over Europe using the C-FIX model and Euroflux data. *Remote Sensing of Environment*, 83(1–2): 376–399. doi: 10.1016/S0034-4257(02)00043-3

Wang S, Chen J M, Ju W M *et al*., 2007. Carbon sinks and sources in China′s forests during 1901–2001. *Journal of Environmental Management*, 85(3): 524–537. doi: 10.1016/j.jenvman.2006.09.019

Whittaker R H, Woodwell G M, 1967. Surface area relations of woody plants and forest communities. *American Journal of Botany*, 54(8): 931−939.

Woodbury P B, Smith J E , Heath L S, 2007. Carbon sequestration in the U.S. forest sector from 1990 to 2010. *Forest Ecology and Management*, 241(1–3): 14–27. doi: 10.1016/j.foreco.2006.12.008

Xiao Jingfeng, Zhuang Qianlai, Law B *et al*., 2011. Assessing net ecosystem carbon exchange of U.S. terrestrial ecosystems by integrating eddy covariance flux measurements and satellite observations. *Agricultural and Forest Meteorology*, 151(1): 60–69. doi: 10.1016/j.agrformet.2010.09.002

Xie Gaodi, Li Wenhua, Xiao Yu *et al*., 2010. Forest ecosystem services and their values in Beijing. *Chinese Geographical Science*, 20(1): 51–58. doi: 10.1007/s11769-010-0051-y

Yang Jihua, Wang Huatian, Zhang Guangcan *et al*., 1996. Study on the photosynthetic characteristics and biomass distribution of *Zanthoxylum bungeanum*. *Forest Science and Technology*, (12): 26–27. (in Chinese)

Yu Deyong, Pan Yaozhong, Jiang Ping *et al*., 2005. Spatial and temporal response of NPP of east Asian vegetations to climate changes. *Journal of Beijing Forestry University*, 27(supp. 2): 96–101. (in Chinese)

Zeng Lixiong, Wang Pengcheng, Xiao Wenfa *et al*., 2008. Estimating vegetation biomass and productivity and their distribution patterns in the Three Gorges Reservoir region. *Acta Ecologica Sinica*, 28(8): 3808–3816. (in Chinese)

Zhang Xinyu, Meng Xianjing, Gao Lupeng *et al*., 2010. Potential impacts of climate warming on active soil organic carbon contents along natural altitudinal forest transect of Changbai Mountain. *Acta Ecologica Sinica*, 30(2): 113–117. doi: 10.1016/j.chnaes.2010.03.011