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Characteristics of Carbon Storage and Density in Different Layers of Forest Ecosystems[1]

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Abstract—Characteristics of carbon storage and density in different layers of forest ecosystems should be studied comprehensively and in more detail. Using forest inventory data in combination with field survey data, we explored the characteristics of carbon storage and density in different layers of forest ecosystems in Liaoning Province of China. Results showed that total carbon storage was 813.034 Tg C. The carbon storage of soil layer accounted for 81.0% of the total storage with 658.783 Tg C, followed by those of arbor, litter and shrub layers with 128.403 Tg C (15.8%), 22.723 Tg C (2.8%) and 3.125 Tg C (0.4%), respectively. The average carbon density for the forest ecosystems were 183.571 Mg C ha^{-1}, with soil layer (148.744 Mg C ha^{-1}) being the highest one, followed by arbor layer (28.992 Mg C ha^{-1}), litter layer (5.131 Mg C ha^{-1}) and shrub-grass layer (0.706 Mg C ha^{-1}). Carbon storage in different forest ecosystems varied from 1.595 to 319.161 Tg C, while C density ranged from 165.067 to 235.947Mg C ha^{-1}, with the highest and lowest values being observed in soil layer and shrub-grass layers, respectively, implying that soil is the main body of forest carbon storage. Young-aged forests accounted for a greater proportion of forests in the Province than forests in other age classes; and proper management of forests could increase the carbon sequestration in the forest ecosystems. The comparison with previous estimations of carbon storage for forest ecosystem implied that methods and data used for forest carbon storage estimation affected the results of estimates obviously.

Keywords: forest ecosystem, carbon storage, carbon density, estimation method

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Global warming is mainly caused by the increasing greenhouse gases emanating from the burning of fossil fuels, forest degradation and conversion, forest fires and the accelerated decay of organic matter in the soil [1]. It has become the most important global ecological and environmental problem that mankind is facing today [2, 3]. Forests, which account for 2/3 of total terrestrial carbon sequestration annually [4], can reduce the rate of build-up of greenhouse gases in the atmosphere and thus play an important and irreplaceable role in mitigating global warming [5]. Accurately estimating carbon budgets of the forest ecosystem is important for understanding the role of forests not only in global warming but also in supporting decision-making processes in forest management [6].

At present, a number of studies have been done in carbon storage and density of forest vegetation and soil [7, 8]. However, most of these studies mainly focused on the overall forest carbon storage on the global scale or a national scale. The estimated results of forests even in the same area were quite different because different areas possessed different bio-climatic types and diverse vegetation types. While more attention has been paid to estimating the carbon storage for arbor layer of forests, little attention has been given to understory plants, litter and soil carbon. The carbon storage capacity for forest ecosystem should be studied comprehensively and in more details.

In this study, carbon storage of arbor, shrub-grass, litter and soil layers for forest ecosystems in Liaoning Province in Northeast of China were estimated, aiming to explore the characteristics and contributions of carbon storage and density in different layers for forest ecosystems.

MATERIAL AND METHODS

Study Area Overview and Forest Inventory Data

Liaoning Province (118°50′–125°46′ E in longitude, 38°43′–43°29′ N in latitude) is located in south part of Northeast China. The total area of Liaoning

[1] The article is published in the original.

Province encompasses 1.46 × 10^5 km^2. Liaoning province stretches across both the warm temperate zone and temperate zone and this area has a warm temperate continental monsoon climate. The annual mean temperature in the area ranges 4–10°C, and annual average precipitation is 714.9 mm. The main forest type is *Quercus* forests.

During period from 1950s to 1990s, with the rapid increase in the regional populations and the economic development, the regional forests had suffered from being seriously damaged. After 1990s, with the implement of China's Natural Forest Conservation Program [9] and Grain-for-Green Program [10], the damaged regional forests have been partially restored. However, currently, the qualities of regional forests are generally still lower. With the aggravation of green-house effects, people began to pay more attention to enhance the carbon accumulation capacity of forests through forest management. Liaoning Province is the representative region with a serious confliction between the rapid social economic development and the forest protection. To gain a clear understanding of the forest carbon storage capacity in this region can provide the basic data and scientific rationale for the forest management and for enhancing the forest carbon storage capacity. Thus, conducting study on forest carbon storage capacity in Liaoning Province is of representativeness in certain extend and scientific significance.

In this study, forest resource inventory data for management in 2006 were utilized to estimate carbon storage of forest ecosystem in Liaoning Province. Both forest area and timber volume by age class as well as by forest type were documented at county levels in the database.

Plots Setting and Investigation

According to typical sampling method, a total of 163 sample plots being distributed in 11 forest types, i.e. *Abies* and *Picea, Pinus koraiensis, Larix, Malva sylvestris var. Mongolica, Pinus tabulaeformis. Orientalis, Robinia, Betula, Populus and Salix,* Hardwood, *Quercus* and mixed broad-leaved forests, with the size of 20 × 20 m, were set in the study area in 2009. The heights and diameter measured at 2 cm above the ground (dbh) of trees (dbh > 2 cm) in each plot were then measured. Three 5 × 5 m subplots were set up within each tree plot, from which live shrubs were harvested and weighed. Three 1 × 1 m subplots within each shrub plot were established to harvest live grass. Then the grass was mixed and weighed. Three 20 × 20 cm subplot within each tree plot was established to collect all litters.

We dug two 100 cm deep soil profiles in each plot. Each soil profile was divided into 5 layers (i.e. 0–10, 10–20, 20–40, 40–60, and 60–100 cm in depth). One 100 cm^3 soil sample was collected from each layer. Carbon bulk density was then measured.

The authority who issued the permission for data collection from sample plots in the study area is the Forest Research Institute of Liaoning Province.

Vegetation Biomass Estimation

(1) Arbor

Forest biomass density was calculated by applying formula (1) to each forest type.

$$W = aV + b. \quad (1)$$

Where W (Mg ha^{-1}) is forest biomass density, V (m^3 ha^{-1}) is stocking per hectare contained in the forest inventory data; a and b are parameters established by Pan et al. (2004) [11] based on the sampling sites located in a total of 5045 plots throughout whole China. The parameters which were used in this study were presented in Table 1. Whether these models are applicable in the Liaoning province still needed to be further tested and validated.

We conducted a survey on the diameter at breast height (DBH) and plant height for those arbors with DBH > 2 cm. The measured values of both DBH and plant height were substituted into the growth equation (Eq. (2)) of the corresponding types of trees to calculate the arbors biomass of the sampling sites, and the biomass per unit area of the sampling plot site was then calculated according to equation 3.

$$TB = a \times D^b \times H^c. \quad (2)$$

Where *TB* (kg) refers to the biomass of single arbor plant; *D* (cm) refers to the DBH of arbor; *H* (m) refers to plant height; *a*, *d*, and *c* are the parameters of allometric equations based on Chen and Guo [12].

$$W = \frac{\sum_{i=1}^{N} TB_i}{A}. \quad (3)$$

Where W (Mg ha^{-1}) represents the biomass per unit area of the sampling site; TB_i (Mg) represents the biomass of a single plant in the sampling site; N refers to the number of arbor plants in sampling site; A (ha^{-1}) is the area of sampling site. These were the original data of the arbor biomass used in this study.

Based on the obtained arbor biomass data of forest, the measured values of DBH and plant height were substituted into the accumulation volume equation (Eq. (4)) for the corresponding trees to calculate the accumulation volume of arbor in the sampling site. The accumulation volume of arbor per unit area can be calculated by using the same method as well:

$$TV = a \times D^b \times H^c. \quad (4)$$

Where TV (m^3) refers to the volume of a single arbor plant; D (cm) refers to DBH of arbor; H (m) represents plant height; a, b and c are the parameter of the equation. By using the biomass density data and the

Table 1. Parameters (*a* and *b*) suitable for Liaoning Province to calculate forest live-biomass density (Pan et al., 2004)

Forest type	Age group		*a*	*b*	Plot number	R^2
Larix forests	Young forest	≤40a	0.6598	15.620	94	0.8211
	Middle-aged forest	41~80a	0.6367	31.878	91	0.7924
	Near-mature forest	81~100a	0.6703	15.857	14	0.9003
	Mature forest	101~140a	0.7406	12.576	37	0.9420
	Over-mature forest	≥141a	0.7757	–7.9247	70	0.9403
Abies and *Picea* forests	Young forest	≤40a	0.7376	13.210	69	0.8605
	Middle-aged forest	41~80a	0.6317	12.042	227	0.8662
	Near-mature forest	81~100a	0.4982	41.312	109	0.8238
	Mature forest	101~140a	0.4306	48.690	239	0.7913
	Over-mature forest	≥141a	0.4313	39.201	358	0.8557
Pinus sylvestris var. *mongolica* forests	Young forest	≤40a	0.6490	18.967	26	0.8078
	Middle-aged and near-mature forest	41~100a	0.3927	34.902	19	0.5867
	Mature and over-mature forest	≥101a	0.3742	22.470	23	0.8375
Pinus koraiensis and its mixed forests	Young forest	≤60a	0.5383	24.946	106	0.6013
	Middle-aged, near-mature, mature, and over-mature forest	≥61a	0.2974	115.6	51	0.4395
Oaks and other deciduous forests	Young forest	≤40a	0.9957	5.7107	162	0.8578
	Middle-aged forest	41~60a	1.0564	13.394	123	0.8278
	Near-mature forest	61~80a	0.8515	24.774	66	0.7246
	mature and over-mature forest	≥81a	0.4829	50.649	42	0.6206
Betula and *Populus* forests	Young forest	≤10a	0.8682	4.1318	71	0.9060
	Middle-aged forest	11~15a	0.8491	8.5271	77	0.9056
	Near-mature forest	16~20a	0.7594	21.235	61	0.8412
	Mature forest	21~30a	0.6455	36.308	145	0.8434
	Over-mature forest	≥31a	0.6642	33.54	314	0.8129

accumulation volume density data obtained through the procedures described above, the applicability of the model proposed by Pan et al. [11] for estimation of the arbor biomass in the forest was tested in this study. The results of the validation have indicated that this model is applicable in this region.

Forest biomass for each forest type was calculated by multiplying the forest biomass density by the area of the forest type.

Some forest types used in this study differed from those listed in Table 1. The parameters used for biomass estimation of some forest types were the same. The parameters for *Pinus tabulaeformis* and *Platycladus orientalis* (L.) Franco forests were the same as those for *Larix* forests in Table 1. The parameters for mixed broadleaf-conifer forests were same as those for *Pinus koraiensis* and its mixed forests (Table 1). The parameters for *Betula* forests, *Populus* and *Salix* forests were the same as those for *Betula* and *Populus* forests shown in Table 1. The parameters for hardwood forests, *Robinia* forests, *Quercus* forests and mixed broadleaved forests were the same as those for oaks and other deciduous forests shown in Table 1.

In this study, the forest resource inventory data obtained by estimation on forest biomass were the summarized inventory data. These data only provided age groups of various forest types (Young forest, Middle-aged forest, Near-mature forest, mature forest and over-mature forest) in the study region.

(2) Shrub

Biomass of shrubs in each subplot was calculated by multiplying the average dry matter ratio of shrubs [13] in study area to fresh weight of shrubs of each shrub plot, and biomass per hectare was calculated based on it.

(3) Grass

Biomass of grasses in each subplot was calculated by multiplying the dry matter ratio of grass to fresh weight of grasses of each grasses plot, and biomass per hectare was calculated based on it. The dry matter ratio of grass was measured by steps described in the follow paragraph.

A certain amount of samples were collected according to the weight proportion of grass category. The samples were mixed, weighted and then placed in an oven for drying to a constant weight, and their dry matter ratios were calculated. This enabled the subsequent calculation of the biomass density and menstruation of carbon ratio for grass.

(4) Litter

Biomass of litters in each plot was calculated by multiplying the dry matter ratio of litters which was measured by steps described in the follow paragraph to fresh weight of grasses of each grasses plot, and biomass per hectare was calculated based on it. The dry matter ratio of litters was measured by steps described in the follow paragraph.

All the litters in each plot were collected, placed in an oven and dried to a constant weight, and their dry matter ratios were calculated. This enabled the subsequent calculation of the biomass density and menstruation of carbon ratio for litter.

Menstruation of Carbon Ratio for Soil, Litter and Herbaceous Plants

Carbon ratio for soil (carbon content in 100 g dry soil) was measured by potassium dichromate and sulfuric acid oxidation method [14]. Carbon assessment in the litter and herbaceous plants was conducted with the method described in reference [15].

Calculation of Carbon Storage for Forest Ecosystems

Carbon storage for forest ecosystems is composed of the carbon storages for arbor, shrub-grass, litter and soil layers. Caron storages for arbor, shrub-grass and litter were calculated by multiplying biomass to carbon ratio. The carbon ratio for arbor and shrub were 0.5, which was used popularly in the world [7, 11]. The carbon ratios for grass and litter were measured by potassium dichromate and sulfuric acid oxidation method [14] too.

Carbon storage for shrub, grass, litter, and soil layer of each forest type in Liaoning Province was calculated by vegetation type method [16] by using the following formula:

$$SOC_i = C_i \times S_i, \tag{5}$$

where SOC_i (Mg) is carbon storage capacities for shrub, grass, litter, and soil layers of i forest type, C_i (Mg ha^{-1}) is average carbon density for shrub, grass, litter, and soil layers of i forest type, S_i (ha) is area for i forest type.

Finally, carbon storage for forest ecosystem of each forest type was calculated by summing the carbon storages for arbor, shrub, grass, litter, and soil layers of each forest type together.

RESULTS

Carbon Storage and its Components for Forest Ecosystems in Liaoning Province

Total carbon storage for forest ecosystems in Liaoning Province was 813.034 Tg C (Table 2). The carbon storages for arbor, shrub-grass, litter and soil layers accounted for 15.8, 0.4, 2.8, and 81.0% of the total carbon storage, respectively. The soil layer accounted for the most storage with 658.783 Tg C. This was followed by those of arbor, litter and shrub layers with 128.403, 22.723 and 3.125 (Tg C), respectively.

The carbon storage volumes of different types of forest varied greatly. The types of forest whose carbon storage volumes were the lowest one in arbor layer, undergrowth layer, litter layer, soil layer and ecosystem in various types of forest were *Abies* and *Picea* forests. The carbon storage volumes of these layers were 0.211, 0.002, 0.073, 1.309 and 1.595 (Tg C), respectively. The carbon storage volumes of *Quercus mongolica* forest was the highest one. The carbon storage volumes of various layers of *Quercus mongolica* forest were 57.477, 1.504, 8.021, 252.189 and 319.161Tg C, respectively. In term of carbon distribution pattern of *Quercus mongolica* forest, the carbon storage capacity of soil layer were the largest one whereas the carbon storage capacity of undergrowth layer was the smallest one. Among all types of forest, the carbon storage capacity of *Quercus mongolica* forest was the largest one, which was 319.161 Tg C, accounting for 39.26% of total carbon storage capacity, followed by those of *Pinus tabulaeformis* and *Platycladus orientalis* (L.) Franco forests, whose carbon storage capacity was 148.27 Tg C, accounting for 18.24% of the total carbon storage capacity; the third place was larch forest, whose carbon storage capacity was 123.84 Tg C, accounting for 15.23% of total carbon storage capacity. The carbon storage capacity of these three types of forest reached as high as 591.271 Tg C, accounting for 72.73% of total carbon storage. These were related to their areas. The areas of these three types of forest accounted for 72.13% of total areas of all types of forest. These results indicated that the dynamic changes in the carbon storage capacity of these types of forest greatly affected the carbon storage functions of forest ecosystems in the entire Liaoning province. Thus, to protecting these types of forest well is of great significance for stabilizing the carbon-storage functions of forest in Liaoning province.

Carbon Density and their Components of the Forest Ecosystems in Liaoning Province

The average carbon density for forest ecosystems in Liaoning Province were 183.571 Mg C ha^{-1}, with soil layer (148.744 Mg C ha^{-1}) being the most dense one, followed by those of arbor layer (28.992 Mg C ha^{-1}), litter layer (5.131 Mg C ha^{-1}) and shrub layer (0.706 Mg C ha^{-1}) (Table 2).

Table 2. Carbon storage (CS) and carbon density (CD) of arbor, shrub-grass, litter, soil and ecosystem in different forests in Liaoning Province of China

Forest type	Area, 10^4 ha	Arbor layer		Shrub-grass layer		Litter layer		Soil layer		Ecosystem	
		CS, Tg C	CD, Mg C ha^{-1}	CS, Tg C	CD, Mg C ha^{-1}	CS, Tg C	CD, Mg C ha^{-1}	CS, Tg C	CD, Mg C ha^{-1}	CS, Tg C	CD, Mg C ha^{-1}
1	0.676	0.211	31.213	0.002	0.296	0.073	10.799	1.309	193.639	1.595	235.947
2	5.567	2.172	39.016	0.038	0.683	0.381	6.844	10.387	186.582	12.978	233.124
3	56.099	22.876	40.778	0.203	0.362	4.189	7.467	96.572	172.146	123.84	220.753
4	3.533	0.864	24.455	0.016	0.453	0.253	7.161	6.086	172.262	7.219	204.331
5	73.252	16.504	22.530	0.33	0.450	5.248	7.164	126.188	172.266	148.27	202.411
6	31.946	5.021	15.717	0.303	0.948	1.124	3.518	42.882	134.233	49.33	154.417
7	3.534	1.61	45.557	0.035	0.990	0.169	4.782	5.469	154.754	7.283	206.084
8	50.141	13.221	26.368	0.476	0.949	1.764	3.518	67.305	134.231	82.766	165.067
9	18.368	7.119	38.758	0.155	0.844	1.008	5.488	33.894	184.527	42.176	229.617
10	190.126	57.447	30.215	1.504	0.791	8.021	4.219	252.189	132.643	319.161	167.868
11	9.656	1.357	14.053	0.063	0.652	0.493	5.106	16.502	170.899	18.415	190.710
Total	442.898	128.403	28.992	3.125	0.706	22.723	5.131	658.783	148.744	813.034	183.571

(1) *Abies* and *Picea* forests; (2) *Pinus koraiensis* forests; (3) *Larix* forests; (4) *Pinus sylvestris var. Mongolica* forests; (5) *Pinus tabulaeformis* and *Platycladus orientalis* (L.) *Franco* forests; (6) *Robinia* forests; (7) *Betula* forests; (8) *Populus* and *Salix* forests; (9) Hardwood forests; (10) *Quercus* forests; and (11) mixed broad-leaved forests.

The carbon densities of the ecosystems of different types of forest also varied largely and they were in the range between 165.067–235.947 Mg C ha^{-1}. Among all types of forest, the type of forest with the highest carbon density was *Abies* and *Picea* forests and the one with the lowest carbon density was *Robinia* forests. The forest types with the highest carbon density of arbor, shrub-grass, litter and soil for different forest types were *Betula* forests (45.557 Mg C ha^{-1}), *Betula* forests (0.990 Mg C ha^{-1}), *Abies* and *Picea* forests (10.779 Mg C ha^{-1}), *Abies* and *Picea* forests (193.639 Mg C ha^{-1}), respectively. The forest types with the lowest carbon density were the mixed broad-leaved forests (14.063 Mg C ha^{-1}), *Abies* and *Picea* forests (0.296 Mg C ha^{-1}), *Populus* and *Salix* forests (3.518 Mg C ha^{-1}), and *Quercus* forests (132.643 Mg C ha^{-1}), respectively. The distribution of carbon density displayed that the carbon density of the soil layer was the highest one whereas that of the undergrowth layer was the lowest one, indicating that soil is the most important organic storage pool within the forest ecosystem. This is consistent with the results obtained previously by other investigators [17]. The ratios of organic carbon density to the vegetation carbon density of various types of forest in Liaoning province were in the range between 4.51–10.86, with the mean value of 5.17. Studies have indicated that the ratios of organic carbon density of the soil layer of forest located in high latitude, middle latitude and low latitude were in the ranges of 3–17, 1.2–3 and 0.9–1.2, respectively. The forest ecosystems with the higher ratio of organic carbon density to the vegetation carbon density have higher carbon flux, which displayed the positive value, i.e. the carbon sink [17]. This implies that the forests in Liaoning province have obvious carbon sink function.

Carbon Sequestration Function of Arbor for Different Forest Types

It can be seen from Table 3 that the total carbon storage volume of arbor layer of the forest ecosystem in Liaoning province was 128.403 TgC. The sizes of the carbon storage volumes of various types of forest were related to their basal areas of stand. Among all types of forest types in Liaoning province, the carbon storage of arbor for *Quercus mongolica* forests, *Larix* forests, *Pinus tabulaeformis* and *Platycladus orientalis* (L.) Franco forests, and *Populus* and *Salix* forests were higher, accounting for 44.74, 17.82, 12.85 and 10.30% of total carbon storage volume of forests of the entire Liaoning province, respectively. The areas of these four types of forest accounted for 42.93, 16.54, 12.67 and 11.32% of total forest areas in Liaoning province, respectively. The larger the forest area was, the higher the carbon storage volume was. Young forest accounted for a greater proportion of forests in Liaoning Province than the forests in other age classes did. The area and arbor carbon accounted for 59.5 and 37.3% of the total area and total carbon, respectively (Table 3).

The carbon densities of the arbor layer of various types of forest differed largely and were in the range between 15.717 and 45.557 Mg C ha^{-1} with the mean value of 28.992 Mg C ha^{-1}. The carbon density of the arbor layer is related to the forest types and the compositions of age groups. The forest type with the highest carbon density among young forests, middle-aged forests, near-mature forests and mature forests among all the forest types was *Pinus koraiensis* forests. The forest types with the highest carbon density of over-mature forests among all forest types was *Larix* forests. The components of age group of a forest type affected its arbor carbon density. The forest type with the highest arbor carbon density among all forest types was *Betula* forests. Of which, the combined areas of near-mature forests, mature forests and over-matures forests accounted for 77.2% of the total. Of which, the lowest arbor carbon density among all the forest types was mixed broad-leaved forests, area of near-mature forests, mature forests and over-matures forests accounted for 9.3% of the total. The forest type with the lowest carbon density in young aged forests was *Populus and Salix* forests whose carbon density was 5.497 Mg C ha^{-1}. The one with the highest carbon density was *Pinus koraiensis* forests whose carbon density was 36.011 Mg C ha^{-1}. The forest type with the lowest carbon density among middle aged forests was *Robinia* forests whose carbon density was 21.944 Mg C ha^{-1}. The one with the highest carbon density was *Pinus koraiensis* forests whose carbon density was 81.844 Mg C ha^{-1}. The forest type with the lowest carbon density among near matured forests was *Robinia* forests,whose carbon density was 30.769 Mg C ha^{-1}, the one with the highest carbon density was *Pinus koraiensis* forests whose carbon density was 100.000 Mg C ha^{-1}. The forest type with the lowest carbon density among mature forest was *Pinus sylvestris var. Mongolica* forests whose carbon density was 25.000 Mg C ha^{-1}, and the one with the highest carbon density was *Pinus koraiensis* forests whose carbon density was 100.000 Mg C ha^{-1}. The forest type with the lowest cancer density among the over-matured forest was *Pinus sylvestris var. Mongolica* forests,whose carbon density was 40.000 Mg C ha^{-1}, the one with the highest carbon density was *Larix* forests which carbon density was 98.095 Mg C ha^{-1}, respectively (Table 3). It can be seen from the above analyses that the biomasses of *Pinus koraiensis* forests in various age groups in Liaoning province were relatively higher, indicating that its forest quality is better. The biomass of *Pinus sylvestris var. Mongolica* forests in both mature and over-matured forests were the lowest, indicating that after having become mature, its forest quality is lower. To view the situation as a whole, the carbon density of matured forest was 50.579 Mg C ha^{-1}, the carbon density of young forest was 18.221 Mg C ha^{-1} and the carbon density of arbor layer of the mature forest was 2.77 times that of the young forest. Proper management of the young forests could increase the carbon sequestration in the forest ecosystems.

DISCUSSION

Contributions of Soil, Shrub-Grass, and Litter to Carbon Sequestration of Forest

The results of this study showed that soil accounted for the highest proportion or 81.0% of all the components of forest ecosystems in Liaoning Province, implying that soil is the main body of forest carbon storage, which has been confirmed by another study [3].

It is estimated that about 50 Pg C a^{-1} organic carbon is returned to soil by the decomposition of litters [18]. The study by Sheng and Yang [19] showed that the contents of both organic and inorganic nutrients of soil increased when the understory vegetation cover was above 70% and biomass content was about 4 Mg C ha^{-1}) in the fir plantation, especially for surface soil.

Changes in the amount of living forest litters can affect obviously soil carbon storage capacity. This study showed that the higher of carbon density of litter for a forest type was, the higher of carbon density of its soil was. But litter and shrub-grass layers of forests can be damaged easily by human disturbance. Thus, reducing human disturbance to forest ecosystem and strengthening protection of shrub-grass and litter layers can maintain and increase carbon storage capacity in soil. It is also important to reduce the concentration of CO_2 in the atmosphere and to slow down the changes in global climate [20].

Comparison with Previous Estimations of Carbon Storage for Forest Ecosystem

Fang et al. [7] estimated forest biomass carbon storage in China according to biomass-volume linear models of different forest types, which were established based on biomass data of the simple plots in the literatures. Their study did not consider the influence of forest age on the relation between forest volume and biomass. Pan et al. [11] estimated forest biomass carbon storage in China based on the modified biomass-volume linear models. The results indicated that Fang et al. [7] might over-estimate forest biomass of China. Li and Lei [21] estimated forest biomass carbon storage in 27 provinces and 4 municipalities directly under the Central Government based on 2004–2008 forest inventory data and biomass empirical model. They reported that the forest biomass carbon storage in Liaoning Province was 125.76 Tg C, which was close to 128.403 Tg C estimated in the present study. The models used in the study were biomass empirical model, which can be used to calculate biomass of a forest type by multiplying total volume with the average ratio of biomass and volume of all sample plots used in the study for the forest type, which was different from our study. Forests in China were divided into 49 forest types and the carbon ratio of each forest type was calculated based on the components of woodiness of the forest type, which were different from our study. The forest biomass carbon storages in the study were com-

Table 3. Area, carbon storage (CS), and density (CD) for arbor layer of different age forests in Liaoning Province of China

Forest type	Young forest			Middle-aged forest			Near-mature forest			Mature forest			Over-mature forest		
	area, 10^4 ha	CS, Tg C	CD, Mg C ha^{-1}	area, 10^4 ha	CS, Tg C	CD, Mg C ha^{-1}	area, 10^4 ha	CS, Tg C	CD, Mg C ha^{-1}	area, 10^4 ha	CS, Tg C	CD, Mg C ha^{-1}	area, 10^4 ha	CS, Tg C	CD, Mg C ha^{-1}
1	0.451	0.085	18.847	0.174	0.094	54.023	0.030	0.020	66.667	0.019	0.010	52.632	0.002	0.001	50.000
2	5.204	1.874	36.011	0.358	0.293	81.844	0.003	0.003	100.000	0.002	0.002	100.000	0.0004	0.0003	75.000
3	28.638	7.375	25.752	16.816	8.672	51.570	6.907	3.985	57.695	3.528	2.639	74.802	0.210	0.206	98.095
4	2.713	0.601	22.153	0.817	0.263	32.191	0.002	0.001	50.000	0.0008	0.0002	25.000	0.0001	0.00004	40.000
5	31.689	5.057	15.958	32.162	7.737	24.056	6.748	2.582	38.263	2.477	1.049	42.350	0.176	0.078	44.318
6	17.065	0.938	5.497	8.909	1.955	21.944	2.522	0.776	30.769	2.598	0.994	38.260	0.852	0.358	42.019
7	0.815	0.139	17.055	1.476	0.723	48.984	0.591	0.352	59.560	0.588	0.360	61.224	0.064	0.036	56.250
8	26.482	2.262	8.542	5.163	2.206	42.727	3.932	1.982	50.407	7.349	3.769	51.286	7.215	3.002	41.608
9	9.089	1.899	20.893	7.191	3.986	55.430	1.213	0.749	61.748	0.815	0.452	55.460	0.060	0.034	56.667
10	133.280	23.391	17.550	49.587	29.788	60.072	5.137	3.100	60.347	2.070	1.139	55.024	0.052	0.029	55.769
11	8.115	0.815	10.043	1.415	0.475	33.569	0.071	0.038	53.521	0.049	0.026	53.061	0.006	0.003	50.000
Total	263.541	44.436	16.861	124.068	56.193	45.292	27.156	13.586	50.029	19.4958	10.440	53.550	8.6375	3.748	43.392

(1) *Abies* and *Picea* forests; (2) *Pinus koraiensis* forests; (3) *Larix* forests; (4) *Pinus sylvestris var. Mongolica* forests; (5) *Pinus tabulaeformis* and *Platycladus orientalis* (L.) *Franco* forests; (6) *Robinia* forests; (7) *Betula* forests; (8) *Populus and Salix* forests; (9) Hardwood forests; (10) *Quercus* forests; and (11) mixed broad-leaved forests.

posed by biomass carbon storages of arbor forests, shrub forests, woodlands, scattered trees and trees planted by the side of farm house and the roads, rivers and fields, which was also different from our study. The above factors all affected the differences in biomass carbon storages estimated by our study and that by Li and Lei [21]. Wang et al. [22] estimated forest biomass carbon storage in Liaoning Province based on 1999–2003 forest inventory data and mixed method. The forest biomass carbon storage estimated by Wang et al. [22] was 70.3 Tg C, which was almost 50% lower than our results. This difference may be due to the difference of models used for estimation, difference of forest type partition and time of forest inventory data acquirement. Because the area of biomass simple plots of one forest type was smaller as compared with the area of that, the model established based on the plots may not represent the real characteristics of the forest type. If more biomass sample plots were used to establish the model for biomass estimation, the accuracy of forest biomass estimation could be improved. The characteristics of different forest types were different. If we can establish the model for biomass estimation for every forest types, the accuracy of forest biomass estimation could be improved, too.

Xie [23] obtained a distribution map in the scale of 1 : 4000000 of soil organic carbon storages in China (1993–1995) [24] based on the Second Soil Inventory data and GIS (1993–1995). We distilled carbon storage for forest soil in Liaoning Province to be 532.162 Tg C, which was 19.2% lower than our results. This difference may be due to the complexity of soil characters, spatial variance, components and difference for time of sample plots collection. If more soil simple plots in one period were used to estimate soil carbon storage, the accuracy of soil carbon storage estimation can be improved.

Methods of forest storage estimation affected the results of estimates obviously. Rational methods should be adopted based on data obtained for estimates.

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