Research note

Carbon Storage and Density of Forest Ecosystems in Heilongjiang Province, China

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【Summary】

Accurately estimating carbon storage for forest ecosystems is important for understanding the role of forests in global warming and also in supporting decision-making processes in forest management. Using forest inventory data in combination with field data, we explored characteristics of carbon storage, density, and distribution for different forest ecosystems and their components in Heilongjiang Province, Northeast China. Results showed that total carbon storage was 4125.002 Tg C. The soil layer accounted for the most storage with 3205.764 Tg C or 77.7% of the total. This was followed by the canopy, litter, and shrub-grass layers with 800.965 (19.4%), 106.568 (2.6%), and 11.705 Tg C (0.3%), respectively. The average carbon density of forest ecosystems was 215.816 Mg C ha^{-1}, with the soil layer (167.722 Mg C ha^{-1}) the densest, followed by the canopy layer (41.906 Mg C ha^{-1}), litter (5.576 Mg C ha^{-1}), and shrub layers (0.612 Mg C ha^{-1}). Carbon storage in different forest ecosystems varied 37.87~1306.63 Tg C, while C density ranged 167.68~256.87 Mg C ha^{-1}, with the highest and lowest values observed in the soil and shrub-grass layers, respectively. That implies that the soil is the main body for forest carbon storage. The methods and data used for forest carbon storage estimation obviously affected results of the estimates. Rational methods should be adopted based on obtaining sufficient data for estimates. Middle-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 of forest ecosystems.

Key words: forest ecosystem, carbon storage, carbon density, estimation method.

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研究簡報

中國黑龍江省森林生態系統碳儲量估算

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摘 要

利用森林資源二類調查匯總資料和標準地實測資料，研究了中國黑龍江省森林生態系統的碳密度、碳儲量及其組分和分配特徵。結果表明：黑龍江省森林生態系統碳儲量為4125.002 Tg C，其中喬木層、灌草層、枯落物層和土壤層碳儲量分別為800.965、11.705、106.568和3205.764 Tg C，分別占總碳量的19.4、0.3、2.6和77.7%。黑龍江省森林生態系統碳密度為215.816 Mg C ha^{-1}，各層碳密度的大小順序為土壤層(167.722 Mg C ha^{-2}) > 喬木層(41.906 Mg C ha^{-1}) > 枯落物層(5.576 Mg C ha^{-1}) > 灌草層(0.612 Mg C ha^{-1})。不同類型森林生態系統的碳儲量介於37.874~1306.63 Tg C，碳密度在167.687~256.874 Mg C ha^{-1}之間，各林型分配特徵表現為土壤層最大、灌草層最小。結果說明土壤是森林生態系統碳儲量主要組成部分。另外，森林碳儲量估算方法及所用的數據對森林碳儲量估算結果有重大影響，估算時應在獲取足夠數據的基礎上採取盡可能穩健的方法。黑龍江省森林中中齡林分比重大，若對現有森林加以更好的管理，可以增加其碳吸存潛力。

關鍵詞：森林生態系統、碳儲量、碳密度、估算方法。

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INTRODUCTION

Global warming, which is mainly caused by 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 (Backéus et al. 2005), has become the most important global ecological and environmental problem faced by mankind today (Detwiler and Charles 1988, Dixon et al. 1994). Forests, which account for 2/3 of terrestrial carbon sequestration every year (Post et al. 1982), 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 (Woodwell et al. 1978). Accurately estimating forest ecosystem carbon budgets is important for understanding the role of forests in global warming and also in supporting decision-making processes in forest management (Liu et al. 2006).

Recently, scholars have done a lot of work in determining carbon storage and density of forest vegetation and soil (Fang et al. 2001, Bartel 2004). However, most studies focused on overall forest carbon storage on a global or national scale. Estimated results of forests in the same area can greatly differ because areas possess different bio-climatic types and diverse vegetation types. More attention has been paid to estimating the carbon storage for the canopy of forests, and less to understory plants, litter, and soil carbon. The carbon storage of forest ecosystems on a smaller scale should be comprehensively studied in greater detail.

In this study, carbon storage values of the canopy, shrub-grass, litter and soil layers of forests in Heilongjiang Province, China were estimated to obtain the carbon sequestration status of forests in Heilongjiang Province and provide a scientific reference for estimates of carbon storage by forest ecosystems and forest management which aims to enhance the accumulation of forest carbon.

MATERIALS AND METHODS

Study area overview and forest inventory data

Heilongjiang Province (121º11'~135º5'E, 43°25'~53°23'N) is located in the northern part of Northeast China. The total area of Heilongjiang Province is 45.4×10^4 km^2. The area has a temperate continental monsoon climate. The annual mean temperature in the area ranges -4~4℃. The main forest type is mixed broadleaf *Larix* and *Betula* forests.

Here, we used forest inventory data to estimate carbon storage of forest ecosystems in Heilongjiang Province, which were derived from the National Forest Resource Inventory database for China collected in 2004~2008. Forest area and timber volume by age class and forest type are documented at the provincial level in the database. Forests in this study did not include economic forests which are forests for non-timber products.

Plot setting and investigation

According to a typical sampling method, 110 sample plots (distributed in 11 forest types i.e., *Abies* and *Picea*, *Pinus koraiensis*, *Larix*, *Pinus sylvestris* var. *mongolica*, mixed coniferous, mixed broadleaf-coniferous, *Betula*, *Populus* and *Salix*, hardwood, *Quercus*, and mixed broadleaf forests) sized 20×20 m were set in the study area in 2009 and 2010. The 11 forest types were united by considering the area and comparability of forest types based on the forest types used in the forest inventory data which included the age class, forest origin, area, and volume of each forest type in Heilongjiang Province. The height and diameter at breast height (dbh) of trees (dbh > 2 cm) in each plot were measured. Three 5×5-m subplots were set up within each tree plot, from which live shrubs were harvested and weighed. One 1×1-m subplot within each shrub plot was established to harvest live grass. The grass was mixed and weighed. Three 20×20-cm subplots within each tree plot were established to collect all litter.

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. The carbon bulk density was then measured.

Vegetation biomass estimation

1) Canopy

Pan et al. (2004) established parameters by age class and forest type for converting forest volume to biomass based on 5415 samples. Some of the parameters are given in Table 1. The forest biomass density was calculated by applying formula (1) to each forest type:

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

where W (Mg ha^{-1}) is the forest biomass density, V (m^3 ha^{-1}) is the stocking per hectare contained in the forest inventory data, and a and b are parameters established by Pan et al. (2004).

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

Some of the forest types used in this study differed from the forest types in Table 1. Parameters used for biomass estimation of some forest types were the same. The

Table 1. Parameters (a and b) suitable for Heilongjiang 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

parameters for mixed coniferous forests were the same as these for *Abies* and *Picea* forests in Table 1. Parameters for mixed broadleaf-coniferous forests were the same as these of *P. koraiensis* and its mixed forests in Table 1. Parameters for *Betula* forests and *Populus* and *Salix* forests were the same as these of *Betula* and *Populus* forests in Table 1. Parameters for hardwood forests, *Quercus* forests, and mixed broadleaf forests were the same as these of oaks and other deciduous forests in Table 1.

2) Shrub

The biomass of shrubs in each plot was calculated by multiplying the average dry matter ratio of shrubs in Northeast China to the fresh weight of shrubs of each shrub plot, and the biomass per hectare was calculated based on this.

3) Grass

A certain number of samples was collected according to the weight proportion of the grass category. Samples were mixed, weighed, and placed in an oven to dry them to a constant weight, and their moisture content was calculated. This enabled the subsequent calculation of the biomass density and carbon ratio for grass.

4) Litter

All litter collected in each plot was placed in an oven to dry it to a constant weight. This enabled the subsequent calculation of the biomass density and carbon ratio for litter.

Carbon ratio of the soil

The carbon ratio of the soil (carbon content in 100 g of dry soil) was measured by the potassium dichromate and sulfuric acid oxidation method (Huang et al. 2008).

Calculation of carbon storage of forest ecosystems

Carbon storage of forest ecosystems is composed of the carbon storage for the canopy, shrub-grass, litter, and soil layers. Carbon storage values for the canopy, shrub-grass, and litter layers were calculated by multiplying the biomass to carbon ratio. Carbon ratios for the canopy and shrub layers were 0.5 which is commonly used (Fang et al. 2001, Pan et al. 2004). Carbon ratios for the grass, litter, and soil layers were directly measured in this study.

Carbon storage values of the shrub, grass, litter, and soil layers of each forest type in Heilongjiang Province were calculated by the vegetation type method (Zhou et al. 2000) based on the formula:

$$SOC_i = C_i \times S_i; \quad (2)$$

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

Finally, carbon storage for the forest ecosystem of each forest type was calculated by adding the carbon storage values for the canopy, shrub, grass, litter, and soil layers of each forest type together.

RESULTS

Carbon storage and its components for forest ecosystems in Heilongjiang Province

The total carbon storage for forest ecosystems in Heilongjiang Province was 4125.002 Tg C (Table 2). The carbon storage for the canopy, shrub-grass, litter, and soil layers accounted for 19.4, 0.3, 2.6, and 77.7% of the total. The soil layer accounted for the most storage with 3205.764 Tg C. This was followed by the canopy, litter and shrub layers with 800.965, 106.568, and 11.705 Tg C, respectively.

The carbon storage values for the canopy, shrub-grass, litter, and soil layers, and the entire ecosystem of different forest types ranged 4.295~275.265, 0.048~3.795, 1.629~29.799, 31.902~997.771, and 37.874~1306.63 Tg C, respectively. The carbon storage of mixed broadleaf forests of different layers was the greastest among all forest types, and it accounted for 30.55% of the total forested area in Heilongjiang Province.

Carbon density and its components for forest ecosystems in Heilongjiang Province

The average carbon density for forest ecosystems in Heilongjiang Province was 215.816 Mg C ha^{-1}, with the soil layer (167.722 Mg C ha^{-1}) being densest, followed by the canopy (41.906 Mg C ha^{-1}), litter (5.576

Table 2. Carbon storage (CS) and density (CD) of the canopy, shrub-grass, litter, and soil layers, and the entire ecosystem in different forests of Heilongjiang Province, China

Forest type	Area (10^4 ha)	Canopy 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	15.040	4.295	28.557	0.048	0.319	1.629	10.831	31.902	212.114	37.874	251.822
2	18.840	8.527	45.260	0.136	0.722	1.169	6.205	36.831	195.494	46.663	247.680
3	354.680	132.613	37.389	0.912	0.257	26.761	7.545	614.909	173.370	775.195	218.562
4	27.120	8.413	31.021	0.124	0.457	1.993	7.349	43.009	158.588	53.539	197.415
5	38.700	16.575	42.829	0.165	0.426	4.208	10.873	84.159	217.465	105.107	271.594
6	135.300	87.218	64.463	0.629	0.465	9.108	6.732	250.595	185.214	347.55	256.874
7	337.400	102.582	30.404	2.443	0.724	15.392	4.562	572.834	169.779	693.251	205.469
8	135.850	44.87	33.029	1.314	0.967	4.236	3.118	177.383	130.573	227.803	167.687
9	87.520	35.074	40.075	0.738	0.843	4.802	5.487	161.5	184.529	202.114	230.935
10	177.070	85.533	48.305	1.401	0.791	7.471	4.219	234.871	132.643	329.276	185.958
11	583.830	275.265	47.148	3.795	0.650	29.799	5.104	997.771	170.901	1306.63	223.803
Total	1911.350	800.965	41.906	11.705	0.612	106.568	5.576	3205.764	167.722	4125.002	215.816

1) *Abies* and *Picea* forests; 2) *Pinus koraiensis* forests; 3) *Larix* forests; 4) *Pinus sylvestris* var. *mongolica* forests; 5) mixed coniferous forests; 6) mixed broadleaf-coniferous forests; 7) *Betula* forests; 8) *Populus* and *Salix* forests; 9) hardwood forests; 10) *Quercus* forests; 11) mixed broad leaf forests.

Mg C ha^{-1}), and shrub layers (0.612 Mg C ha^{-1}) (Table 2).

Carbon densities of the canopy, shrub-grass, litter, and soil layers and the entire ecosystem of different forest types ranged 28.557~64.463, 0.257~0.967, 3.118~10.873, 130.573~217.465, and 167.687~271.594 Mg C ha^{-1}, respectively.

The highest carbon densities of the canopy, shrub-grass, litter, and soil layers and the entire ecosystem among different forest types were mixed broadleaf-coniferous forests, *Populus* and *Salix* forests, mixed coniferous forests, mixed coniferous forests, and mixed coniferous forests, respectively; the smallest carbon densities were for was *Abies* and *Picea* forests, *Larix* forests, mixed coniferous forests, mixed coniferous forests, and mixed coniferous forests, respectively.

Carbon sequestration function of the canopy for different forest types

Middle-aged forests accounted for a greater proportion of forests in Heilongjiang Province than forests in other age classes, the area and canopy carbon of which accounted for 42.2 and 47.3% of the total (Table 3). Canopy carbon densities of young forests, middle-aged forests, near-mature forests, mature forests, and over-mature forests ranged 10.546~33.179, 31.246~80.455, 30.386~80.682, 34.667~108.281, and 49.219~95.000 Mg C ha^{-1}, respectively (Table 3). The highest carbon densities of young forests, middle-aged forests, near-mature forests, and mature forests among all forest types were mixed coniferous, *P. koraiensis*, mixed broadleaf-coniferous, *P. koraiensis*. and *P. koraiensis* forests, respectively. The age of a forest type affected its canopy carbon sequestration. The canopy carbon densities of near-mature, mature, and over-mature forests of different forest types were almost always higher than these of young and middle-aged forests. Overall, the highest canopy carbon density of different age classes was

Table 3. Area, carbon storage (CS), and density (CD) for the canopy layer of different-aged forests of Heilongjiang Province, 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	6.080	1.190	19.572	7.04	2.256	32.045	1.28	0.560	43.750	0.64	0.289	45.156	0	0.000	0.000
2	13.720	4.005	29.191	3.52	2.832	80.455	0	0.000	0.000	1.28	1.386	108.281	0.32	0.304	95.000
3	83.320	12.439	14.929	148.61	62.832	42.280	51.44	21.885	42.545	43.8	20.593	47.016	27.51	14.864	54.031
4	4.780	0.793	16.590	13.71	4.768	34.778	5.44	1.653	30.386	2.55	0.884	34.667	0.64	0.315	49.219
5	7.360	2.442	33.179	23.35	9.068	38.835	6.4	3.926	61.344	0.63	0.345	54.762	0.96	0.794	82.708
6	29.110	7.733	26.565	82.85	60.331	72.820	17.59	14.192	80.682	5.75	4.962	86.296	0	0.000	0.000
7	98.660	10.405	10.546	135.17	42.235	31.246	63.29	29.432	46.503	31.96	16.317	51.054	8.32	4.193	50.397
8	71.430	8.793	12.310	31.27	14.502	46.377	16.29	10.325	63.382	9.88	6.828	69.109	6.98	4.422	63.352
9	25.270	6.391	25.291	40.9	17.463	42.697	14.32	7.717	53.890	5.75	2.672	46.470	1.28	0.831	64.922
10	35.420	7.047	19.896	59.34	30.376	51.190	45.63	28.493	62.444	18.82	10.267	54.554	17.86	9.350	52.352
11	147.010	36.035	24.512	261.49	132.428	50.644	119.17	75.939	63.723	42.76	23.571	55.124	13.4	7.292	54.418
Total	522.160	97.273	18.629	807.25	379.091	46.961	340.85	194.122	56.952	163.82	88.114	53.787	77.27	42.365	54.827

1) *Abies* and *Picea* forests; 2) *Pinus koraiensis* forests; 3) *Larix* forests; 4) *Pinus sylvestris* var. *mongolica* forests; 5) mixed coniferous forests; 6) mixed broadleaf-coniferous forests; 7) *Betula* forests; 8) *Populus* and *Salix* forests; 9) hardwood forests; 10) *Quercus* forests; 11) mixed broad leaf forests.

of near-mature forests, which was 3.1 times greater than that of young forests.

DISCUSSION

Contributions of the soil, shrub-grass, and litter layers to carbon sequestration of forests

The results of this study showed that the soil accounted for the highest proportion or 77.7% of all components of forest ecosystems in Heilongjiang Province. This implies that soil is the main body of forest carbon storage, which was proven by an earlier study (Dixon et al. 1994).

It was estimated that about 50 Pg C per year^{-1} organic carbon is returned to the soil by the decomposition of litter (Peng and Liu 2002). A study by Sheng and Yang (1996) showed that the organic and inorganic nutrient contents of the soil increase when the understory vegetation cover is > 70%, and biomass amounted to 4 Mg C ha^{-1} in fir plantations, especially for surface soil.

Changes in the amount of living forest litter can obviously affect soil carbon storage. This study showed that the higher of carbon density of litter of a forest type was, the higher of carbon density of the soil was. But litter and shrub-grass layers of forests can easily be damaged by human disturbance. So reducing human disturbance of forest ecosystems and strengthening protection of the shrub-grass and litter layers can help maintain and increase soil carbon storage. It is important to reduce the concentration of CO_2 in the atmosphere and slow global climate changes (Raich and Schlesinger 1992).

Influence of the estimation method on carbon storage of forest ecosystems

Fang et al. (2001) estimated forest biomass carbon storage in China according to biomass-volume linear models of different forest types which were established based on biomass simple plot data in the literature. That study did not consider the influence of forest age on the relation of forest volume and biomass. Pan et al. (2004) estimated forest biomass carbon storage in China based on modified biomass-volume linear models. The results showed that Fang et al. (2001) may have over-estimated forest biomass of China. Li and Lei (2010) estimated forest biomass carbon storage in 27 provinces and 4 municipalities directly under the Central

Government based on 2004~2008 forest inventory data and a biomass empirical model. The forest biomass carbon storage in Heilongjiang Province estimated by Li and Lei (2010) was 927.170 Tg C which was higher than our results (800.965 Tg C). The models used in the study were biomass empirical models which can be used to calculate the biomass of a forest type by multiplying the total volume by the average ratio of biomass and volume of all simple plots used in the study for the forest type, which differed from our study. Forests of 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 differed from our study. Forest biomass carbon storage values in the study were composed of biomass carbon storages of canopy forests, shrub forests, woodlands, scattered trees, and trees planted by the side of farm houses, roads, rivers, and fields, which also differed from our study. The above factors all affected differences in biomass carbon storage values estimated by our study and that of Li and Lei (2010). Jiao and Hu (2005) estimated forest biomass carbon storage in Heilongjiang Province based on 1999~2003 forest inventory data and models of Fang et al. (2001). The forest biomass carbon storage estimated by Jiao and Hu (2005) was 601.1 Tg C which was almost 25% lower than our results. That may have been due to differences in the of models used for estimation, and differences in forest type partition and the time that the forest inventory data were acquired. Because the area of the sample biomass plots of 1 forest type was smaller compared with the area of the total, the model established based on the plots might not represent the true characteristic of the forest type. If more sample biomass plots were used to establish the model for biomass estimation, the accuracy of forest biomass estimation would likely be better. The characterization of different forest types differed. If we could establish a model for biomass estimation of every forest type, the accuracy of forest biomass estimations would likely also be improved.

Xie (2004) obtained distribution of soil organic carbon storage values at a map scale of 1: 4,000,000 in China (1993~1995) (Data Sharing Infrastructure of Earth System Science, 2006) based on the 1993~1995 second soil inventory data and Geographic Information System (GIS). We distilled carbon storage for forest soils in Heilongjiang Province. The value was 2948.420 Tg C, which is 8.0% lower than our results. That may have been due to the complexity of soil characters, spatial variances, components, and differences in the time of sample plot collection. If more soil sample plots in 1 period were used to estimate soil carbon storage, the accuracy of soil carbon storage estimation would likely be improved.

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

CONCLUSIONS

The results showed that the total carbon storage for forests in Heilongjiang Province was 4125.002 Tg C. The soil layer accounted for the greatest storage of the total and was the main body of forest carbon storage. This was followed by the canopy, litter, and shrub layers. The average carbon density for the forest ecosystems was 215.816 Mg C ha^{-1}, with the soil layer the densest, followed by the canopy, litter, and shrub layers. Carbon storage in different forest ecosystems varied 37.874~1306.63 Tg C, while C density ranged 167.687~256.874 Mg C ha^{-1}, with the highest and lowest values observed in the soil and shrub-grass layers, respectively. This implies that the soil is the main body of forest carbon storage. Although carbon storage values for the litter and shrub-grass layers accounted for small proportions of carbon storage for forest ecosystems, they are important for maintaining and increasing carbon storage of forest soils. Methods and data used for forest carbon storage estimation obviously affected the results of the estimates. Rational methods should be adopted based on sufficient data obtained for estimates.

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