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Original Article

Special Topic on Ecological Assets and Ecosystem Services in the Qinghai-Tibet Plateau

Carbon storage of the forest and its spatial pattern in Tibet, China

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Abstract: The raising concentration of atmospheric CO_2 resulted in global warming. The forest ecosystem in Tibet played an irreplaceable role in maintaining global carbon balance and mitigating climate change for its abundant original forest resources with powerful action of carbon sink. In the present study, the samples of soil and vegetation were collected at a total of 137 sites from 2001 to 2018 in Tibet. Based on the field survey of Tibet's forest resources and 8th forest inventory data, we estimated the carbon storage and carbon density of forest vegetation (tree layer, shrub, grass, litter and dead wood) and soil (0-50 cm) in Tibet. Geostatistical methods combined with *K*riging spatial interpolation and Moran's I were applied to reveal their spatial distribution patterns and variation characteristics. The carbon density of forest vegetation and soil in Tibet were 74.57 t ha^{-1} and 96.24 t ha^{-1}, respectively. The carbon storage of forest vegetation and soil in Tibet were 344.35 Tg C and 440.53 Tg C, respectively. Carbon density of fir (*Abies* forest) was 144.80 t ha^{-1} with the highest value among all the forest types. Carbon storage of spruce (*Picea* forest) was the highest with 99.09 Tg C compared with other forest types. The carbon density of fir forest and spruce forest both increased with the rising temperature and precipitation. Temperature was the main influential factor. The spatial distribution of carbon density of forest vegetation, soil, and ecosystem in Tibet generally showed declining trends from western Tibet to eastern Tibet. Our results facilitated the understanding of the carbon

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sequestration role of forest ecosystem in the Tibet. It also implied that as the carbon storage potential of Tibet's forests are expected to increase, these forests are likely to serve as huge carbon sinks in the current era of global warming and climate change.

Keywords: Carbon storage; Carbon density; Spatial distribution; Forest ecosystems; Climate factors; Tibet

1 Introduction

As the main body of terrestrial ecosystems, the carbon stocks of forest ecosystems approximately accounts for 80% of above-ground carbon pool and 40% of the underground carbon pool in the global terrestrial ecosystem, respectively (Dixon 1994). Forest ecosystems play the most critical role in the carbon cycle (Qin et al. 1997). And their annual absorbed carbon accounts for about 2/3 of the carbon pool in terrestrial ecosystems (We et al. 2007). There are about 77% of the carbon storage of global terrestrial ecosystems contained in forest ecosystems (Sedjo 1994). On the other hand, forests will also emit massive carbon with deforestation, forest degradation and wood harvest (Ahmad et al. 2018). The change of carbon pool in forest will greatly affect the variation of carbon dioxide concentration in atmosphere (Lal 2004; Stinson et al. 2011).

Some scientists point out that uptake of carbon at the ocean's surface can't explain the imbalance between carbon released by the burning of fossil fuels and increase concentrations of carbon in the atmosphere. Generally, scientists called it missing sink for atmospheric CO2 (Zhou et al. 2000; Qin et al. 1997; Frank et al. 2015). The amount of CO_2 in the atmosphere and ocean can be precisely measured (Siegenthaler and Sarmiento 1993). However, the amount of carbon in terrestrial ecosystems is not clear for lack of an accurate awareness of its carbon dynamics (Tans et al. 1990; Keeling et al. 1996). Many scientists believe that the missing carbon was stored in terrestrial forests in the northern hemisphere (Zhou et al. 2000; Schimel et al. 2015), where temperate forests and boreal forests display the role of carbon sinks (Lal 2004; Stinson et al. 2011; Sedjo 1994; Houghton 2007). With more detailed research about carbon dynamics on basis of the national or regional data of forest resources inventory, it is contributed to a better knowledge of the function of forests in the global carbon balance (Yu 2014; Hennigar and Maclean 2010). At the same time, the clarity of the current status of carbon pools in major forest distributed areas is contributed to reduce greenhouse gas emissions and tackle global warming (Pan et al. 2011; Guo et al. 2014).

For its abundant forest resources, especially the plentiful original forest, the forest in Tibet occupies a unique place in protection and construction of ecology and response to climate change in China and the world. The places where these forests were dominantly distributed were the head water of many major rivers in China. They played important roles in maintaining the ecological balance of the river basin and developing the national economy. Therefore, it is very important to accurately estimate the carbon storage of Tibet's forests. There are some reports involved carbon storage of forest in Tibet. Liu et al. (2017) estimated that the carbon storage of tree layer in Tibet was 1067 Tg C using the biomass inventory method. Li et al. (2011) utilized weighted regression model to measure that carbon storage of forest was 953 Tg C. Ren et al. (2016) suggested that the carbon content of forest vegetation in Nyingchi and Qamdo were about 243 Tg C and 105.8 Tg C, respectively. However, these studies only involved the carbon pool of tree layer in forest, excluding shrubs, herbs, litter and other carbon pools. And little attention is paid to the soil pool, which is the largest carbon pool in forest ecosystems (Wu et al. 2007; Yang et al. 2014). Besides, although the carbon storage 7 prefecture-level region and whole Tibet were estimated on the base of statistical results of forest inventory data, it is hard to depict its spatial distribution pattern. A single biomass-stock volume linear model was established to estimate the biomass of the arbor layer in many studies (Fang et al. 2001). For a simple linear relationship existed in model and fixed carbon concentration, the accuracy of the results is still controversial (Wang et al. 2001; Wang et al. 2001). All of these made it difficult to fully know the whole carbon content of forest ecosystem and depict its spatial distribution patterns in Tibet. To remedy deficiencies of previous studies, 137 sampling sites were set up at the main forest distribution areas in Tibet. At each site, the ecosystem carbon density was calculated with detailed field survey based on biomass of tree, grass, shrub, litter, dead wood and soil (0-50cm). What's more, Geostatistical methods and Moran's *I* were applied to explore the spatial distribution characteristics of carbon density of forest ecosystems in Tibet. The purpose of present study is (1) to estimate carbon storage and carbon density of forest ecosystems in Tibet; (2) to investigate spatial distribution characteristics of carbon density of forest ecosystems in Tibet; (3) to explore the relationship between carbon density of forest ecosystem in Tibet and climate factors.

2 Material and Methods

2.1 Site description

The Tibet Autonomous Region is located in southwestern China (26°50'—36°53' N, 78°25'—99°6' E) with an average altitude of more than 4000 m. Tibet is the main body of Qinghai-Tibet Plateau with a total land area of 122×10⁶ ha (http://www.xizang.gov.cn/rsxz/qqjj/zrdl/201812/t20181221_34484.html). Tibet is mainly controlled by two climate systems: one is westerly of the northern hemisphere with less water vapor; the other is southwest monsoon of India ocean carrying massive precipitation air mass (Li et al. 2010). The climate systems caused two distinct seasons: wet season and dry season. Generally, the dry season is from October to April of the following year with rare precipitation high evaporation and dry air. The wet season is from May to September, characterized by relatively higher temperature and more rainfall. Precipitation during rainy season accounts for 90% of the annual rainfall (Cong et al. 2010). The average annual temperature is between -2.8°C and 11.9°C and the average annual precipitation ranges from 50 to 4000 mm (Guge Chime Dorje 2013). There are vast plateaus, majestic mountains, narrow plains and deep valleys in Tibet. For the unique climate conditions and complexity topography, the mountain regions form the special vertical climate change that is "one mountain at four seasons, and different weather within 10 km". The forest area is 4.4×10^4 km² under actual controlled area in Tibet. Mainly forest types are *Abies* forest, *Picea* forest, *Pinus yunnanensis* forest, *Pinus densata* forest, *Betula* forest, *Quercus semicarpifolia* forest, *Cupressus* forest, Soft broad-leaved stand forest, *Populus Larix gmelinii* forest, Broad-leaved mixed forest, Coniferous and broad-leaved mixed forest and Coniferous mixed forest. Most forests in Tibet are composed of *Abies* forest with area of 6.7×10^3 km² and *Picea* forest covering 1.2×10^4 km². Soil types are various for complicated topography, climate conditions and forest types. In study area, mainly soil types are yellow–brown earth, brown earth, gray-cinnamon soil, dark-brown earth and gray-dark-brown earth.

2.2 Sampling and measurements

The soil and vegetation were collected at 137 sampling sites from 2001 to 2018 (Fig. 1). The sample numbers of each forest type were presented in Table 1. At each sample point, 20 m × 50 m sample plots were established with three replicates. In each sample field, we recorded the tree species, diameter at breast height (>5 cm) and tree height. The sample trees were sampled following the DBH class distribution (Table 2). The sample numbers were determined according to the forest area and forest stocking of each species. And a total of 350 sample trees were felled. The branches and leaves of the dominant trees were separated from trunks with pruning shears. Stems were cut into 1 m sections. The roots were digged and randomly collected. Three 5 m × 5 m plots along the diagonal at the vertex, documented the main shrub species and coverage. All the shrubs were collected and measured. In each shrub plot, a 1 m × 1 m grass plot was built to collect the aboveground and underground parts of herbs and litter. We found that nearly 95% soil organic matter is distributed in soil depth of 0-40 cm and there are all bedrocks distributed in Tibet forest soil under 50 cm with field survey. Therefore, we could collect all the organic matter with sampling the soil of 0-50 cm. Soil sample (0-10 cm, 10-20 cm, 20-30 cm, 30-50 cm) were undertaken to conduct routine soil analysis at 3 representative plots with little anthropogenic interferences.

Table 1 The sample number for each forest types

Forest types	Sample number
Abies	38
Picea	42
Pinus yunnanensis	12
Pinus densata	14
Betula	3
Quercus semicarpifolia	5
Cupressus	6
Soft broad-leaved stand	5
Populus	2
Larix gmelinii forest	1
Broad-leaved mixed forest	1
Coniferous and broad-leaved mixed forest	2

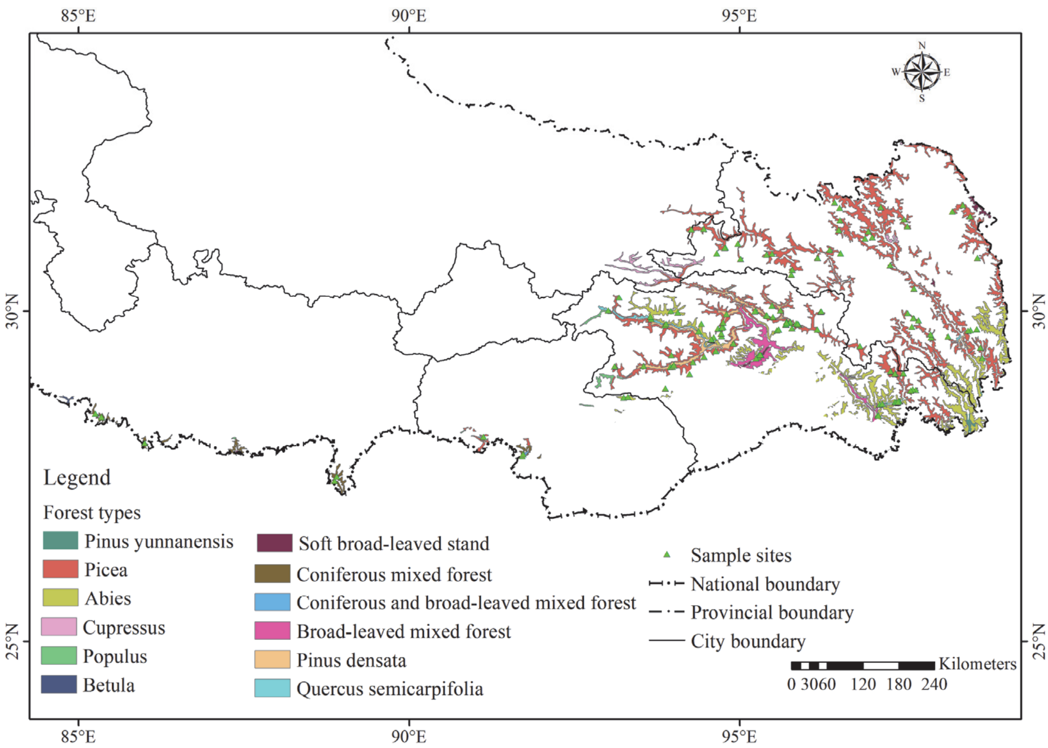

Fig. 1 Sampling sites and forest types in Tibet, China.

Table 2 The sampled tree numbers of each DBH (diameter breast height) class

Species	Sample number of each DBH (cm) class						Total sample number
	0-9.9	10-19.9	20-29.9	30-39.9	40-49.9	>50	
Abies	60	35	24	21	5	5	150
Picea	60	37	23	20	5	5	150
Pinus yunnanensis	20	12	8	7	3	0	50

All the samples of fresh weight were determined using an electronic balance. Then they were delivered to lab and were oven-dried at 70°C to constant weight for 24h, grinded to pass through a 0.2-mm screen. The carbon concentration of soil was measured with potassium dichromate-concentrated sulfuric acid (Walkley and Black 1934).

2.3 Statistical analysis

2.3.1 Estimation of forest vegetation carbon

The biomass of stem, branch, root and foliage in tree layer were calculated through the biomass equations based on the stem analysis (Appendix 1), respectively. The biomass of stem, branch, root and foliage multiplied the carbon concentration of each organ and then divided by plot area to get the carbon density of different layers. The total carbon density of tree layer was the sum of carbon density of each tree' s foliage, branch, stem and root, respectively, which was computed as follows:

$$D_t = (W_s \times C_s + W_b \times C_b + W_l \times C_l + W_r \times C_r)/S \quad (1)$$

D_t is the carbon density (t ha^{-1}) of tree layer; W_s, W_b, W_l and W_r are the total carbon biomass (kg) of stem, branch, leaf and root, respectively. C_s, C_b, C_l and C_r represent the carbon concentration (g/kg) of stem, branch, leaf and root, respectively. S (m^2) represents the plot area (m^2).

The dry weight of shrubs, grass, litter and dead wood multiplied their own carbon concentration respectively and divided by plot area. Then the carbon density of shrubs, grass, litter and dead wood were obtained. The total carbon density of vegetation was the sum of tree, shrubs, grass, litter and dead wood.

2.3.2 Estimation of soil carbon

The soil carbon density (0-50 cm) was calculated as follows:

$$D_s = \sum_{i=1}^{4} = R_i \times H_i \times \frac{\beta_i}{10} \quad (2)$$

D_s is the carbon density of total soil (0-50 cm). R_i

and H_i are the volume weight and carbon concentration of different soil depths (0-10 cm, 10-20 cm, 20-30 cm and 30-50 cm), respectively. β_i represents the soil depths of the *i* layer.

2.3.3 Estimation of forest ecosystem carbon

The carbon density of forest was the sum of vegetation and soil. Then it multiplied the area of forest to get the carbon storage of forest ecosystem.

2.3.4 Spatial distributions of forest ecosystem in Tibet

In present study, we used Moran's I index to explore the spatial autocorrelation of carbon density of vegetation and soil in Tibet. Moran's I index consisted of global Moran's I and local Moran's I index. The value of Moran's I ranged from -1 to 1. The value ">1" meant positive spatial autocorrelation, while "<1" represented that negative spatial autocorrelation and "0" suggested that spatial randomness ((Tu and Xia 2008).

The local Mora's I index was applied to identify local spatial cluster patterns and spatial outliers (Harries 2006). Its value ">1" indicated that the target value resembled its neighborhood and the locations are spatial clusters including high-high clusters (high values in a high value neighborhood) and low-low clusters (low values in a low value neighborhood). If a high negative local Moran's I value was high negative, it implied a possible spatial outlier. Spatial outliers contained high-low (a high value in a low value neighborhood) and low-high (a low value in a high value neighborhood) outliers.

Geostatistics was mainly based on the theory of regionalized variables, using variogram to study natural phenomena that had both randomness and structure or spatial correlation and dependence in spatial distribution (Goovaerts 1997). Kriging spatial interpolation was the core technology of geostatistics. It was modeled as a linear unbiased optimal estimation on the basis of the original data of the regionalized variables and the structural characteristics of the variogram (Goovaerts 1999). We utilized geostatistics to describe the spatial patterns of forest ecosystem by kriging. The experimental semivariogram was established based on theory of regionalized variables, which was computed as follows:

$$R_{(h)} = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(u_i + h) - Z(u_i)] \quad (3)$$

where $N(h)$ is the number of data pairs within a given class of distance and direction; where $Z(u_i)$ is the value of variable 1 at location u_i; $Z(u_i + h)$ is the value of variable 2 at a location separated by distance h from location u_i; h is the distance of sampling sites (Goovaerts 1999).

2.3.5 Relationship between the carbon density of fir and spruce and climate factors

As the dominant species of dark coniferous forest in Tibet, they were widely developed in the study area. They were the main contributors of forest carbon storage in Tibet with almost the same carbon storage, which were extremely important in evaluating the carbon sink capacity and carbon balance in Tibet's forests (Vogel et al. 2008; Alves et al. 2010; Malhi et al. 2010). Different altitudinal zones were selected as treatments to explore the relationship between the carbon density of fir and spruce and climate factors. We divided 7 altitudinal zones from 2900-4300 m for fir and 6 altitudinal zones from 3100-4300 m for spruce, respectively with the interval of 200 m. We used the climate data calculated by Wang et al. (2014) for the great similarity of our common study regions in Table 3.

2.4 Data source

The forest area was acquired from the data of the 8th Category Ⅱ Forest Resources Inventory in Tibet (within McMahon Line). The DEM data were derived from ASTER GDEM of Geospatial Data Cloud Platform of the Chinese Academy of Sciences. And its spatial resolution was both 30 m. The forest type data were national 1:100 million vegetation type maps from Resource and Environment Date Cloud Platform of Chinese Academy of Sciences. According to field survey of Tibet's forest resources, we depicted the forest areas. Geostatistical analysis was performed by ArcGIS 10.6. Descriptive statistics were carried out by SPSS version 12.0 software and all graphs were made in Origin 9.0.

Table 3 Climate conditions in different elevation gradient.

Elevation (m.a.s.l.)	2900-3100	3100-3300	3300-3500	3500-3700	3700-3900	3900-4100	4100-4300
MAT (°C)	10.3±1.6	9.25±0.7	9.4±1.2	7.86±1.4	6.4±1.5	9.55±2.6	1.4±0.8
MAP (mm)	769.4±85.2	499.7±56.8	499.5±36.0	455.1±26.7	449.2±26.3	409.9±24.6	331.9±26.7

Note: MAT represents mean annual temperature and MAP represents mean annual precipitation.

3 Results

3.1 Carbon storage and density of forest vegetation

The carbon storage and density of forest vegetation was presented in Table 4. The carbon storage and average density of vegetation layer in forests in Tibet was 344.35 Tg C and 74.57 t ha^{-1}, respectively. The carbon storage and density of different layer both ranged as: tree > shrub > dead wood > litter > grass. Tree layer had the highest carbon storage (281.0Tg C) and density (63.24 t ha^{-1}).

The carbon storage of *Abies* forest and *Picea* forest were the highest among these forest types in Tibet. *Abies* forest and *Picea* forest were the main contributor to carbon storage of forest vegetation in Tibet. It was important to enhance the protection of the *Abies* forest and *Picea* forest for their key roles in Tibet forest.

Fig. 2 showed that Moran's *I* of forest vegetation was 0.09 with moderate correlation. Local Moran's *I* showed that high-high clusters were mainly distributed in western direction of study area and low-low cluster were found in eastern direction. The higher carbon density of vegetation was found at west regions in eastern Tibet while lower carbon density was observed at eastern areas in eastern Tibet (Fig.2).

3.2 Carbon storage and density of soil

Table 5 showed that the carbon storage and density of soil in forests in Tibet were 440.53 Tg C and 96.28 t ha^{-1}, respectively. Compared with the other forest soil, the carbon storage of soil in *Picea* forest was the highest. The soil layer in coniferous mixed forest whose dominant species were *Abies* and *Picea* had the highest carbon density with 129.24 t ha^{-1}, higher than that in *Abies* forest (129.24 t ha^{-1}) and *Picea* forest (113.68 t ha^{-1}). The carbon density of soil layer in all the forest types presented the decline tendency with the increase of soil depths.

Fig. 3 showed that Moran's *I* of soil was 0.152 with greatly significant spatial autocorrelation, which indicated that the target value of the soil has a certain similarity with that of near sampling points. The high-high clusters were observed in southern Tibet and low-low clusters were mainly located in eastern Tibet. High carbon density of soil in Tibet was mainly located at western direction in eastern Tibet while diluted carbon density of soil was seen at eastern direction in eastern Tibet (Fig.3).

3.3 Carbon storage and density of forest ecosystem

The carbon storage of forest ecosystem was

Table 4 Carbon storage of vegetation layer in different forest types in Tibet, China.

Forest type	Area (×10^4 ha)	Carbon density (t ha^{-1})						Carbon storage (Tg C)					
		Trees	Shrubs	Grass	Litter	Dead wood	Total	Trees	Shrub	Grass	Litter	Dead wood	Total
Abies	67.62	121.28	11.06	0.74	2.30	9.42	144.80	82.01	7.48	0.50	1.55	6.37	97.92
Picea	119.85	63.68	13.70	2.95	1.18	1.17	82.68	76.33	16.42	3.53	1.42	1.40	99.09
Pinus yunnanensis	24.92	73.12	8.40	0.17	0.62	0.55	82.85	18.22	2.09	0.04	0.15	0.14	20.65
Pinus densata	31.65	88.75	0.61	0.60	2.27	1.58	93.81	28.09	0.19	0.19	0.72	0.50	29.69
Betula	14.42	30.45	5.03	2.13	2.56	1.75	41.92	4.39	0.73	0.31	0.37	0.25	5.98
Quercus semicarpifolia	35.48	50.61	12.97	0.62	3.91	0.00	68.10	17.96	4.60	0.22	1.39	0.00	23.95
Cupressus	57.6	34.23	6.31	2.55	1.65	0.84	45.58	19.72	3.63	1.47	0.95	0.49	26.25
Soft broad-leaved stand	10.06	20.35	2.81	0.15	0.58	0.00	23.88	2.05	0.28	0.01	0.06	0.00	2.40
Populus	7.49	31.85	4.49	0.16	0.46	0.16	37.13	2.39	0.34	0.01	0.03	0.01	2.78
Larix gmelinii forest	10.08	85.46	10.57	0.79	3.71	2.82	103.35	8.61	1.07	0.08	0.37	0.28	10.42
Broad-leaved mixed forest	9.72	53.95	3.13	1.15	2.45	0.00	60.67	5.24	0.30	0.11	0.24	0.00	5.90
Coniferous and broad leaved mixed forest	19.63	45.79	9.68	0.37	0.83	0.98	57.65	8.99	1.90	0.07	0.16	0.19	11.32
Coniferous mixed forest	8.63	80.92	3.97	2.79	1.37	0.55	89.60	6.98	0.34	0.24	0.12	0.05	7.73

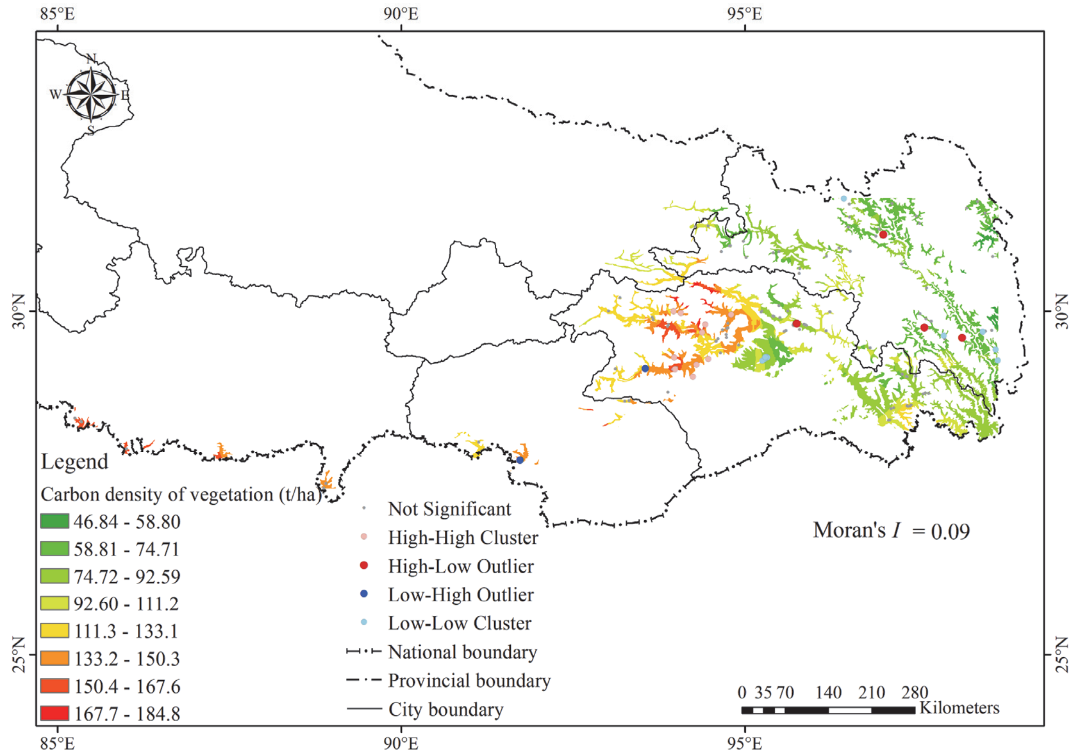

Fig. 2 Carbon density and its spatial distributions of vegetation layer in forests in Tibet, China.

Table 5 Carbon storage of soil layer in different forest types in Tibet, China

Forest type	Area (×10⁴ ha)	Carbon density(t ha⁻¹)					Carbon storage (Tg C)				
		0-10 cm	10-20 cm	20-30 cm	30-50 cm	Total	0-10 cm	10-20 cm	20-30 cm	30-50 cm	Total
Abies	67.62	45.87	27.73	22.00	33.64	129.24	31.02	18.75	14.87	22.75	87.39
Picea	119.85	42.07	28.95	19.98	22.67	113.68	50.42	34.70	23.95	27.17	136.24
Pinus yunnanensis	24.92	38.70	16.79	12.31	12.36	80.15	9.64	4.18	3.07	3.08	19.97
Pinus densata	31.65	32.88	15.85	11.15	13.45	73.34	10.41	5.02	3.53	4.26	23.21
Betula	14.42	43.95	27.26	19.85	34.35	125.41	6.34	3.93	2.86	4.95	18.08
Quercus semicarpifolia	35.48	36.67	18.97	12.14	16.43	84.21	13.01	6.73	4.31	5.83	29.88
Cupressus	57.6	45.92	26.03	19.23	24.16	115.34	26.45	14.99	11.08	13.92	66.44
Soft broad-leaved stand	10.06	26.98	19.41	16.38	23.49	86.26	2.71	1.95	1.65	2.36	8.68
Populus	7.49	15.64	9.11	5.54	7.81	38.09	1.17	0.68	0.41	0.58	2.85
Larix gmelinii forest	10.08	33.31	12.49	19.45	24.89	90.14	3.36	1.26	1.96	2.51	9.09
Broad-leaved mixed forest	9.72	37.35	19.68	13.18	16.23	86.43	3.63	1.91	1.28	1.58	8.40
Coniferous and broad-leaved mixed forest	19.63	37.84	20.44	17.92	19.64	95.84	7.43	4.01	3.52	3.86	18.81
Coniferous mixed forest	8.63	41.73	30.62	25.27	35.41	133.04	3.60	2.64	2.18	3.06	11.48

784.88 Tg C with the biomass of vegetation and soil accounting for 44.2% and 55.8%, respectively (Table 6). The average carbon density of forest ecosystem was 170.88 t ha⁻¹. *Picea* forest had the highest carbon storage (235.3 Tg C) and *Abies* forest had the maximum carbon density (274.04 t ha⁻¹).

Fig. 4 suggested that Moran's *I* of ecosystem was 0.163 with great significant autocorrelation ($p < 0.01$). It suggested that the target value of the ecosystem resembled the neighbor sampling sites. The high-high clusters were found in the middle of southern Tibet and low-low clusters were distributed in eastern Tibet (Fig. 4). The western regions in eastern Tibet were characterized with elevated carbon density while the carbon density of eastern regions in eastern Tibet was relatively low (Fig. 4).

3.4 Relationship between the carbon density of fir and spruce and climate factors

Fig. 5 showed that the carbon density of fir and spruce increased by 0.49 t ha⁻¹ per 1mm and 15.06

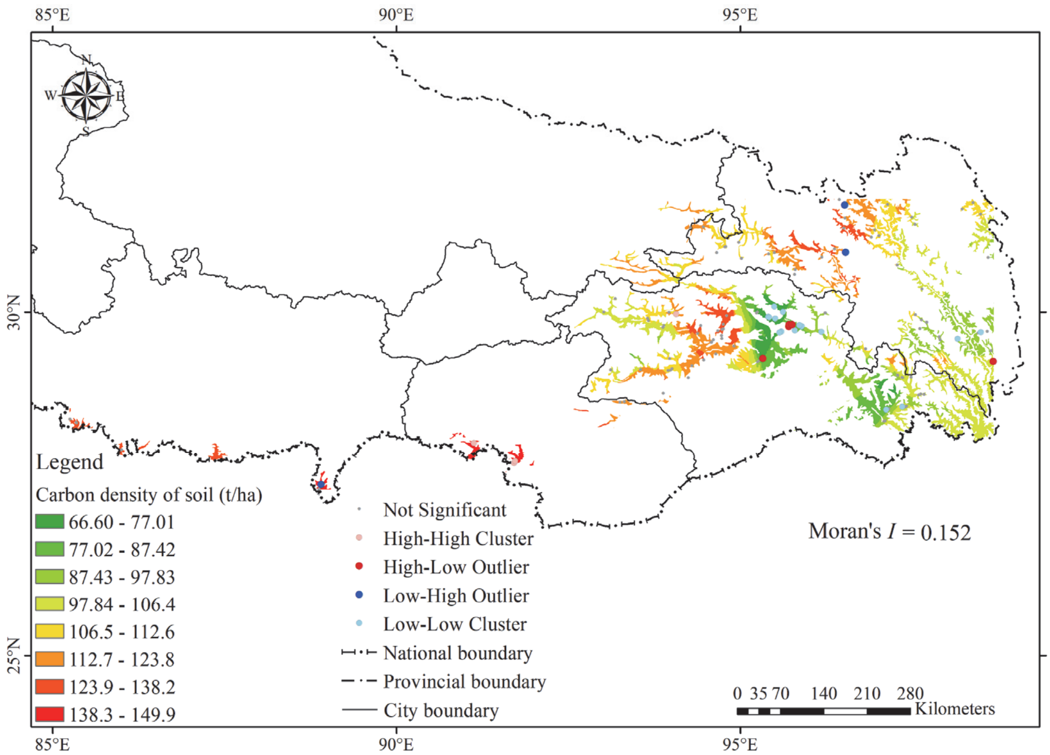

Fig. 3 Carbon density and its spatial distributions of soil layer in forests in Tibet, China

Table 6 Carbon storage of forests in different forest types in Tibet, China.

Forest type	Area (×10⁴ ha)	Carbon density (t ha⁻¹)	Carbon storage (Tg C)
Abies	67.62	274.04	185.31
Picea	119.85	196.36	235.33
Pinus yunnanensis	24.92	163.00	40.62
Pinus densata	31.65	167.14	52.90
Betula	14.42	167.33	24.13
Quercus semicarpifolia	35.48	152.31	54.04
Cupressus	57.6	160.92	92.69
Soft broad-leaved stand	10.06	110.14	11.08
Populus	7.49	75.22	5.63
Larix gmelinii forest	10.08	193.49	19.50
Broad-leaved mixed forest	9.72	147.10	14.30
Coniferous and broad-leaved mixed forest	19.63	153.49	30.13
Coniferous mixed forest	8.63	222.64	19.21

t ha⁻¹ per 1°C. And the carbon density of spruce increased by 0.17t ha⁻¹ per 1mm and 6.71t ha⁻¹ per 1°C. The Carbon density of fir increased faster than that of spruce, which suggested that fir had the greater potential capacity of carbon sink than spruce.

4 Discussion

4.1 Carbon storage and density of forest vegetation, soil and ecosystem

The carbon storage of forest vegetation was 344 Tg C, with the proportion of trees, shrubs, grass, litter and dead wood accounting for 81.6%, 11.4%, 2.0%, 2.2% and 2.8%, respectively. It suggested that the carbon storage of shrubs, grass, litter and dead wood couldn't be neglected when further estimating the carbon storage of forest vegetation in Tibet. The difference in carbon density in tree layer caused the difference in carbon density of different forest types. Table 7 showed that tree layer in Tibet had higher carbon density compared with other province in China for the reason that the mature and over mature coniferous

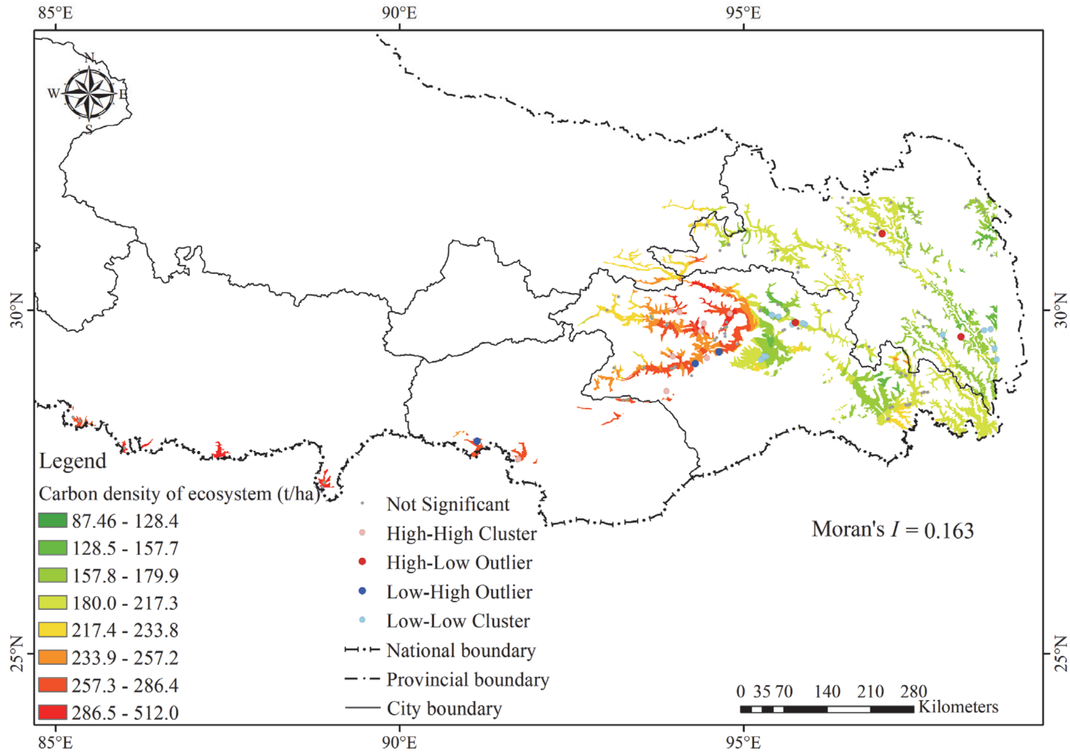

Fig. 4 Carbon density and its spatial distributions of forest ecosystem layer in forests in Tibet, China.

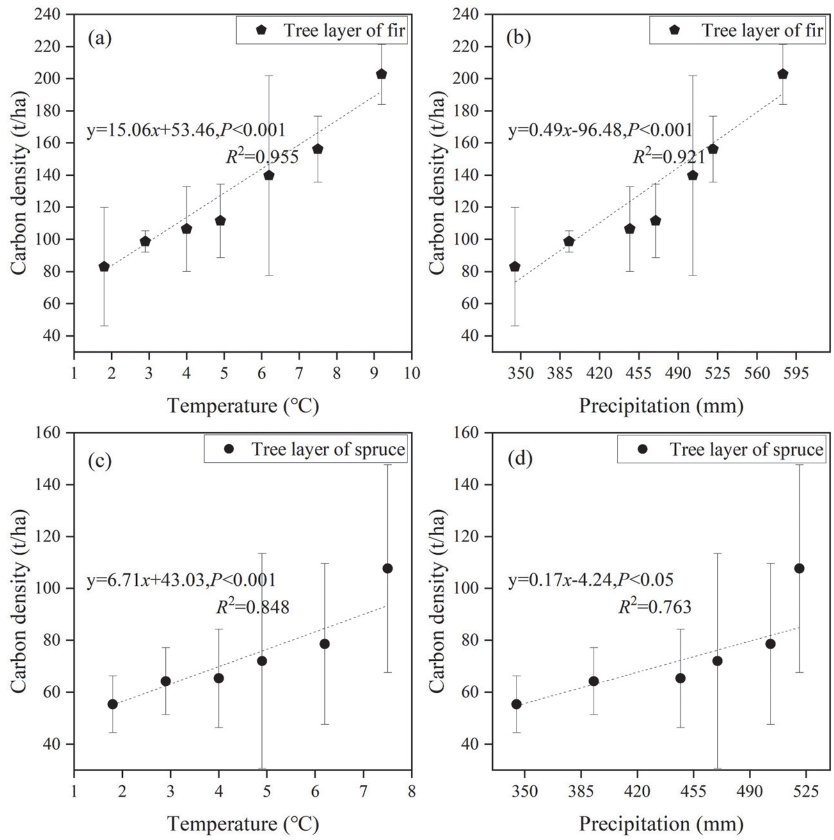

Fig. 5 The relationship between carbon density of tree layer in fir spruce and climate factors. The error bars show the SE of the mean.

Table 7 Carbon storage and density in different forest ecosystem in China and other countries

Area	Carbon storage (Tg C)				Carbon density (t ha^{-1})				Reference
	Forest ecosystem	Soil	Vegetation	Dead wood	Forest ecosystem	Soil	Vegetation	Dead wood	
China	28120	21023	6200	892.00	258.83	194.04	57.07	8.21	Zhou et al. (2000)
Sichuan, China	2927	2394	491	41.14	232.81	190.45	38.04	3.27	Huang (2008)
Jilin, China	1820	1331	444	45. 60	225.30	164. 66	55.00	5.64	Wang et al. (2011)
Zhejiang, China	887	656	204	10.84	145.22	108.89	27.34	1.79	Dai et al. (2017)
Inner Mongolia, China	3237	2450	764	23.63	184.50	144.40	40.40	2.9	Huang et al. (2016)
Tibet, China	784	441	344	9.67	170.81	96.24	74.57	1.428	Present study
Russia	323000	249000	74000	-	364.00	281.00	83.00	-	Kolchugina and Vinson (1993)
Canada	223000	211000	12000	-	251.00	212.00	39.00	-	Pekka (1992)
Continental U.S.A	41000	26000	15000	-	170.00	108.00	62.00	-	Birdsey Richard A (1992)
Europe	34000	25000	9000	-	122.00	90.00	32.00	-	Pekka et al. (1992)
Australia	51000	33000	18000	-	128.00	83.00	45.00	-	Glfford (1992)

forest were dominantly distributed in Tibet. However, its carbon storage in Tibet was lower than these regions for its relative lower forest area. In previous studies about carbons storage of forest ecosystems, they always just focused on the carbon pools of vegetation, soil and litter, neglected the dead wood. Dead wood played an indispensable role in energy flow, carbon sequestration and forest succession in th e forest ecosystem (Gough C M et al. 2007). Our results suggested that carbon storage of dead wood was not diluted, which could not be ignored when estimated the carbon storage of forest ecosystem. Liu et al. (2017) reported that carbon stock of tree layer in Tibet was 1064 Tg C. Li (2011) estimated that the carbon storage of forest including tree layer, scatted trees, "four-sides" trees and shrubbery in Tibet were 953 Tg C. These results were both much higher than our values (280. 98 Tg C). One possible reason might be that we only calculated the arbor forest within the actual area, not the whole region. If added the forest carbon beyond the actual area, the value was about 529.37 Tg C, which was close to Li (2011)'s results if only considering the tree layers' carbon storage. We thought the carbon storage of tree layer in Liu et al. (2017) was a little high. It might be caused by using different estimated methods of carbon storage. Zhou and Zhao (2004) estimated that carbon stock of vegetation in Tibet was 329.64 Tg C, lower than our result. The carbon stock of tree layer in Tibet has increased within past nearly ten years. The implementation of an intensive program of forestation and management to enrich the forest resource in Tibet may explain the raising C stock in Tibet.

Forest soil was the largest carbon pool in the ecosystem and its carbon storage was about 1.7-8.8 times higher than that of tree layer (Zhou et al. 2000; Huang 2008; Wang et al. 2012; Gao et al. 2014; Wang 2014). The carbon storage of soil in Tibet was the lowest compared with other regions (Table 7). The soil with depth of 0-10cm was the major carbon pool in soil. Some investigations indicated that the surface soil was fragile and easily affected by human activities, which determined whether the soil surface was carbon sink or carbon source (Huang et al. 2005; Zhang et al. 2006). Therefore, reducing the anthropogenic influence to the surface soil was contributed to maintain and increase the size of carbon pool of soil.

The soil contained o ver two-thirds of the carbon in global forest ecosystems (Dixon et al. 1994). Numerous soil organic carbons were stocked in soils of tundra, pre-tundra and taiga regions. Lal et al. (2005) found that the regions with higher ratio of soil: vegetation C density had higher carbon sequestration and accumulated more carbon. Therefore, a conclusion might be drawn that the ratio of carbon density of forest soil (including litter layer) to that (including car shrub and grass layer) in forest vegetation could reflect the function about the carbon sink of forest ecosystem (Lal 2005). According to Dixon et al. (1994), the ratio of soil: vegetation C density in China was 1.19 while that in Tibet was 1.29 in the present study. It was higher than the national average values, which indicated that the function of carbon sink in Tibet's forest was important. It was noteworthy that the carbon storage of forest ecosystem was within the actual control line with greatly significance.

Dixon et al. (1994) documented that the carbon stock of global forest ecosystem was 1146 Pg C and forest vegetation and soils contained 359 and 787 Pg C, respectively. Zhou et al. (2000) estimated that the carbon storage of forest ecosystem in China was 28100 Tg C. The carbon storage of the forest ecosystem in Tibet (784.88 Tg C) accounted for 2.8% in that of China. With the comparison of other province in China, Tibet forest had relatively low carbon storage (Table 7), which was also much lower than that of Canada, Alaska, Continental U.S.A, Europe, Australia and Russia (Table 7) for the huge difference exited in soil carbon density. Although Tibet forests had lowest carbon density in soil, the carbon density of vegetation was much higher than these regions and close to Russia, partly because Tibet contained massive natural and mutule coniferous forest. It implied that Tibet vegetation had great potential of carbon sequestration.

4.2 Spatial distributions of forest ecosystem in Tibet

Fig. 2 showed that most forests distributed in eastern Tibet (Qamdo and Nyingchi). The possible reason for higher carbon density in eastern Tibet was that it had suitable climate conditions with influence of southwest monsoon for forest growing up. In western Tibet, there was little forest in western Tibet for the higher elevation and more severe climate.

Ge et al. (2013) estimated forest carbon storage in Nyingchi was 2.43 × 10^8t and the average forest carbon density was 76.01 t ha^{-1}. Ren et al. (2016) reported that carbon storage of forest in Qamdo was about 1.058×10^8 t and the average carbon density was 67.31 t ha^{-1}. These studies partly supported our result that the carbon density of soil, vegetation and ecosystem all showed the decline trend from Nyingchi to Qamdo (Figs. 2 to 4). We discussed the differences between the two regions to explore what caused the decreasing tendency. Table 8 showed that Nyingchi had better climate conditions with higher temperature, less frost-free hours and more precipitation and sunshine days, which was beneficial for trees growing. The occurrence of the high value areas of carbon density of soil and vegetation was mainly due to the distribution of natural mature fir forest in these areas, where there were little human disturbance and relatively complete preservation of native vegetation. It was conducive to the accumulation of carbon sinks (Cui et al. 2016; Fang 2004). Tibet's forest resources came from long-term development succession and mainly were in primitive state. For the small annual temperature difference and large daily temperature difference, it was beneficial to accumulate organic matters with photosynthesis under high temperature during the day and reducing respiration under low temperature at night (Liu et al. 2017). Low-value spatial outliers appeared near high-value agglomeration areas. More severely anthropogenic interference such as grazing and felling were the possible reasons. High-value spatial outliers were found in vicinity of low-value agglomeration areas. It might be related to local great climatic conditions and topography. The immense natural forest in Tibet was preserved relatively well. By exploring spatial distributions of forest ecosystem, it could be helpful to provide scientific suggestions for implementation of forestation measures.

4.3 Relationship between the carbon density of fir and spruce and climate factors

Fig. 5 showed that the carbon density of fir and spruce both increased with raising temperature and precipitation, which was consist with Saeed et al. (2019)'s work. They found an increasing trend in carbon density of fir with raising elevation. With global warming, the carbon density of Tibet would elevate for its wide distribution of dark coniferous forest. It was important to maintain and improve the capacity of forest's carbon sink with strengthening the protection of fir and spruce and reducing deforestation and human activities. Previous studies suggested that temperature and precipitation were

Table 8 The difference of climate conditions between Nyingchi and Qamdo

Regions	Climate types	Temp. (°C)	Precipitation (mm)	Frost-free period (h)	Sunshine days	Topography	References
Nyingchi	Plateau temperate monsoon humid climate	11.2	650	2022	180	Plateau and wide valley alpine	Liu et al. 2000
Qamdo	Temperate humid climate	7.6	400-600	2319-2776	80-127	Mountainous regions	Yang et al. 2006

the key factors affecting distribution of the carbon storage and carbon density of the ecosystem (Lv and Sun, 2004; Zhao and Zhou, 2004; Huang et al. 2009). Many studies consistently suggested that the carbon storage of forests declined with altitude increasing (Leuschner et al. 2007; Girardin et al. 2010). It might be caused by producing less carbon by foliage for the decreased temperature with raised altitude (Leuschner et al. 2007; Kitayama and Aiba, 2002). In addition, the reasons might be that low temperature limited nutrient accumulation process in soil and the availability of soil nutrients by plants (Raich et al. 2006; Kitayama and Aiba 2002; Stewart 2000). Cheng and Luo (2003) measured that the carbon density of tree layer of fir was 158 t ha^{-1} in Gongga Mountain at an elevation of 3000 m, which is lower than our results (193.01 t ha^{-1}) at elevations between (2900-3100 m) in Nyingchi County. According to the weather station near the Gongga mountain, its annual MAT (mean annual temperature) and MAP (mean annual precipitation) were 4°C and 1906.9 mm. MAT and MAP of these sites with elevation ranged from 2900-3100 m was 9.2°C and 583 mm, respectively. Present sites had the higher temperature and lower precipitation. The difference in carbon density between the two regions with the same altitude might be mainly caused by temperature factors instead of precipitation. The alpine timberline of fir in Gongga Mountain reached 3700 m asl. However, in our study, the fir was distributed at 4100 m asl and the spruce even climbed to 4300 m asl. MAT in timberline at the Gongga Mountain is -0.55°C lower than our present study (4.15°C) and MAP was and 1806.3mm higher that in present sites (524.2 mm). It might indicate that higher temperature and lower precipitation lead to higher timberline. Partial correlation analysis was used to further explore the factors limited the carbon density of fir and spruce. The results showed that when the MAP factor was controlled, partial correlation coefficients between MAT and carbon density of fir and spruce were 0.922 (p <0.01) and 0.818 (p <0.05) with significant correlations. When the MAT factor was controlled, partial correlation coefficients between MAP and carbon density of fir and spruce were 0.144 (p>0.05) and -0.497 (p>0.05) without significance. A conclusion might be drawn that MAT significantly influenced the carbon density of forest.

Under cold and humid climate conditions, especially in high mountains, temperature mainly limited tree's growth (Camarero JJ 2015). And excessive precipitation will increase the amount of clouds, further reducing sunshine, causing temperature decreased. Precipitation indirectly affected trees' growth with influencing temperature (Takahashi 2005). In high-altitude areas, especially near the forest line, the soil moisture was relatively high and the rainfall was abundant. Precipitation seemed not to be the main factor restricting the growth and survival of plant. However, Körner (1999) pointed out that with the high soil moisture and abundant rainfall, water-shortage state may still exist in the plant body in the timberline. For its low temperature, the water absorption in soil and diversion of water in the trunk were limited (Ryan et al. 2005), and lower transpiration also reduced the water tension (Smith et al. 1984; Magnani 995). At the same time, due to the hydraulic restriction existed caused by the change of tree height (Ryan MG et al. 2006), the leaves might occur the phenomenon of water stress for that the change of tree height would cause the hydraulic restriction. Studies suggested that even in high-altitude areas with abundant rainfall, wood plant may still suffer water stress on the certain (James et al. 2006). The absorption and transmission of water might be restricted for the variable tree height and low temperature occurred in the growing season (Li et al. 2007).

5 Conclusions

Based on the field survey, we estimated the carbon density and storage of soil, trees, shrubs, grass, litter and dead wood of the main forest types in Tibet. The carbon storage and carbon density of forest vegetation layer were 344.35 Tg C and 74.57 t ha^{-1}, respectively. The carbon storage and carbon density of the forest soil layer (0-50 cm) in Tibet were 440.53 Tg C and 96.237 t ha^{-1}, respectively. The 0-10 cm soil carbon storage and carbon density were the highest. The soil carbon density decreased with the increase of soil depth. The carbon storage and density of forest ecosystem in Tibet was 784.88 Tg C and 170.18 t ha^{-1}, respectively. Carbon density of fir (*Abies* forest) was 144.80 t ha^{-1} with the highest value among all the forest types. Carbon storage of spruce (*Picea* forest) was the highest with 99.09 Tg C compared with other forest types. The carbon density of fir forest and spruce forest both increased with the raising temperature and precipitation. Temperature was the main limiting factor. The spatial distribution of carbon density of forest vegetation, soil, and ecosystem in Tibet generally showed decline trends from western Tibet to eastern Tibet. Our results were contributed to understand the carbon sequestration role of forest ecosystem in the Tibet. It also implied that as forests in Tibet were likely to serve as huge carbon sinks in the current era of global warming and climate change for the expectation of increasing carbon storage. In present study, we just focused on the current carbon stocks of forests in Tibet. Therefore, we will explore their dynamics change of the carbon storage in the future work to have a deeper and comprehensive understanding about carbon sequestration of forest ecosystem in Tibet.

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