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SOIL AGGREGATES, DISTRIBUTION CHARACTERISTICS AND ORGANIC CARBON PROTECTION MECHANISM OF *PINUS MASSONIANA* FORESTS OF DIFFERENT AGES

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Abstract

Soil aggregates are an important component of soil and a special organic–inorganic complex. It is an important method of soil carbon sequestration, having positive effects on stabilizing productivity and coping with climate change. This paper, by taking the soil of *Pinus massoniana* forests of different ages as the object, researched the soil aggregates' distribution characteristics and carbon sequestration mechanism. The results show that for the 20-year-old *Pinus massoniana* forest, the content of soil aggregates decreases with the decrease of aggregates' particle size in different soil depths; for the 60-year-old *Pinus massoniana* forest, the overall percentage content of soil aggregates is similar to that of the 40-year-old *Pinus massoniana* forests in terms of distribution, but has some differences in the value. The percentage of aggregates with a particle size of 2.00 mm changes significantly, from approximately 16.00% to more than 20.00% (except for the 60-80 cm soil layer). The soil aggregates with different particle sizes are mainly dominated by aggregates with a particle size of 10.00 mm, followed by aggregates with a particle size of 2.00 mm. The new organic matter in *Pinus massoniana* forests promotes the formation of coarse aggregates, and the particulate organic matter in coarse aggregates helps the formation of fine aggregates. The coarse aggregates can physically protect the newly added organic carbon in *Pinus massoniana* forests, but the protection has a saturation limit. With increasing forest age, the saturated limit of coarse aggregates would be broken under the combined action of internal and external forces, and fine aggregates would then be released. The research results will provide theoretical and methodological support for the study of aggregates' organic carbon and promote the sustainable development of forest soil carbon sequestration and emission reduction technology.

Key words: Soil aggregates; Organic carbon; Carbon fixation; Protection mechanism.

Introduction

The soil aggregate is the basic unit of soil structure, the size, shape, void distribution and composition of which affects not only the physical properties of soil, such as voidage, water holding capacity, permeability and erosion durability but also the function of soil, such as water and nutrient supply, oxygen and heat transfer (Luzuriaga *et al.,* 2005; Wang *et al.,* 2010). Therefore, soil aggregates are an important index to measure soil structure, and they are the centre of soil fertility regulation. As an important component of soil, soil aggregates have long been used as a substitute index of soil structural stability (Zhu *et al.,* 2013; Wang *et al.,* 2010). Soil aggregates play three major roles in soil, namely, ensuring and coordinating water, fertilizer, gas and heat in soil; influencing the types and activities of soil enzymes; and maintaining and stabilizing the soil (Dai *et al.,* 2011). Nearly 90% of soil organic carbon in the loose arable layer soil is in aggregates (Sun *et al.,* 2011; Anonymous *et al.,* 2006). The spatial isolation between organisms and organic carbon caused by the physical protection of soil aggregates is one of the main stabilization mechanisms of soil organic carbon (Zhang *et al.,* 2014). As agricultural activities mainly occur in the surface soil, the study of organic carbon in surface soil aggregates is of great significance to reveal the effect of human disturbance on organic carbon (Yan *et al.,* 2007).

The organic carbon content in soil accounts for approximately two-thirds of the terrestrial biosphere's carbon pool, while the yearly amount of carbon stored in soil and released in the form of CO_2 accounts for approximately 4% of the total soil organic carbon (Zhang *et al.,* 2017). Therefore, organic carbon in soil is both a carbon sink and a carbon source (Ali *et al.,* 2016). As a result of long-term and large-scale human production activities, the carbon cycle balance between the soil carbon pool and atmospheric carbon has been damaged, and a large amount of soil organic carbon has been oxidized and released into the atmosphere in the form of CO_2, increasing the emission of greenhouse gases (Hafner *et al.,* 2012). Increasing the fixation of soil organic carbon is an effective measure to reduce greenhouse gas emissions, which would bring medium- and long-term benefits (Huang *et al.,* 2018). The stability of soil organic carbon is mainly affected by the degradation resistance of organic carbon, the physical and chemical properties of soil, environmental conditions and soil decomposer biocenosis (Liu *et al.,* 2016). A comprehensive understanding of the stabilization mechanism of soil organic carbon is of great significance for estimating the fixation potential of soil organic carbon and formulating appropriate soil management measures to improve the fixation of organic carbon and give full play to the ecological function of soil organic carbon (Mu *et al.,* 2015).

Forests and forest soils are the largest carbon storage systems in terrestrial ecosystems and play an irreplaceable role in regulating and balancing the global carbon cycle and slowing down the increase in greenhouse gas concentrations (Zhou *et al.,* 2010). *Pinus massoniana* is the most common and largest-scale forest species in South China, and the soil of *Pinus massoniana* forests plays an important role in soil organic carbon fixation (Mu *et al.,* 2015). Therefore, this research takes the soil of *Pinus massoniana* forests of different ages as the research object. By integrating methods of systematic sampling, determination of aggregate destruction rate and average weight diameter, and dichromate oxidation, the physical mechanism of soil carbon fixation of *Pinus massoniana* forests was studied, and the key factors affecting the soil organic carbon fixation of *Pinus massoniana* forests were discussed. This paper provides a scientific reference for the soil carbon sequestration potential of *Pinus massoniana* forests and their ecological status in mitigating climate change to strengthen the management of *Pinus massoniana* artificial forests and provide scientific support for global carbon sequestration and carbon sinks.

Materials and Methods

Study region: The research area is located in the experimental forest of Guizhou Academy of Forestry in Guiyang city, Guizhou Province (26°31’N-26°34’N, 106°43’E-106°46’E), located in the subtropical monsoon climate zone in Southwest China (Fig. 1), with an annual average temperature of 15.3°C, a high annual temperature of 35.1°C, a low annual temperature of -7.3°C, and an average annual precipitation of 1129.5 mm. The soil is predominantly yellow soil interlaced with limestone, dolomite, sandstone, and shale, and the main vegetation types are coniferous forests composed of *Pinus massoniana* and Cunninghamia lanceolata. The forest floor is covered with shrubs and herbs, including Rhus chinensis Mill, Rhododendron simsii Planch, Camellia oleifera Abel, Coriaria nepalensis Wall, Schefflera octophylla (Lour.) Harms, Pyracantha fortuneana (Maxim.) Li, Lithocarpus glaber (Thunb.), Imperata cylindrica (Linn.) Beauv, Lophatherum gracile, Polygonatum odoratum (Mill.) Druce, Pteris multifida Poir, and Dicranopteris linearis. Snow and ice disasters are the main disturbance factors of vegetation in this area.

Fig. 1. Distribution of sampling plots (Guiyang City, Guizhou Province, southwest of China).

Research methods: Three areas of *Pinus massoniana* forests aged 20, 40 and 60 years and two areas of *Pinus massoniana* + broad-leaved forests were selected as the research object, with each area containing three sample plots of 20 m×20 m. The tree age was determined by afforestation records and growth cones. The sample soil should not be too wet or too dry to be easily removed and not easily deformed. In each sample plot, three *Pinus massoniana* trees were selected randomly the organic layer was removed and a soil profile was dug with a depth of 100 cm and 120 cm away from each *Pinus massoniana* tree. Approximately 2 kg of soil samples were taken from five layers of each profile: 0-20 cm (layer 1), 20-40 cm (layer 2), 40-60 cm (layer 3), 60-80 cm (layer 4), and 80-100 cm (layer 5). The soil samples were put into an iron box and brought back to the laboratory. Meanwhile, soil bulk density was determined with the cutting-ring method. In the laboratory, soil samples were gently broken up into small pieces with diameters of 10-12 mm to remove roots and rocks, and the soil structure was maintained as much as possible. The samples were placed on the floor and dried (2 weeks). The dried soil samples were screened with a 2 mm screen for subsequent analysis.

Aggregates were air dried by dry screening, and aggregate destruction rate was calculated as (>0.25 mm air-dried aggregates - >0.25 mm water-stable aggregates)/>0.25 mm air-dried aggregates × 100%. The calculation method for mean weight diameter is as follows: weight percent of water-stable aggregates of each particle level (the weight percentage of aggregates of each level in total sample weight) × average diameter of its level, then add together (Du *et al.*, 2011). The relationships between the aggregate destruction rate, mean weight diameter and organic carbon content were compared. The organic carbon content was determined by the potassium dichromate external heating method (Bolliger *et al.,* 2008).

Results and Analysis

Spatial distribution of dry screening soil aggregates of *Pinus massoniana* forests with different ages: Three areas of *Pinus massoniana* forest at 20-, 40- and 60-years-old were selected, with each area containing three sample plots and 3 soil profiles were collected from each plot. Soil samples were collected from five layers of each soil profile, that is, 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm, and the contents of soil aggregates with different particle sizes in soil samples were analysed. The soil aggregates of a 20-year-old *Pinus massoniana* forest showed significant differences (Table 1). First, from a particle size of 10 mm to <0.20 mm, the content of soil aggregates with different particle sizes changed greatly. For the 20-year-old *Pinus massoniana* forest, the content of soil aggregates decreased with decreasing particle size at different soil depths, and at each soil depth, the variation in the content of aggregates with different particle sizes was similar to the distribution of soil aggregate content, decreasing with decreasing particle size. In the 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm soil layers, the average values of soil aggregates with different particle sizes were between 1.74-28.12%, 1.55-39.59%, 0.75-47.71%, 0.98-42.56% and 0.85-43.53%, respectively. It can be observed that with increasing soil depth, the aggregates tend to become large particles.

Table 1. Profile characteristics of soil aggregate of 20 years aged *Pinus massoniana* forestlands (%) (n=9).

Aggregate size (mm)		10.00	7.00	5.00	2.00	1.00	0.45	0.20	<0.20
0-20	Variability	38.73	6.07	9.32	64.87	5.81	2.01	2.50	0.80
	Minimum	19.18	10.25	12.33	0.00	6.59	3.05	2.52	0.61
	Maximum	38.78	18.41	22.53	26.11	14.92	7.28	6.52	3.38
	Mean	28.12	14.80	14.97	20.53	10.41	5.21	4.24	1.74
	Skewness	0.14	-0.20	2.23	-2.54	0.20	-0.15	0.18	0.66
	k urtosis	-0.57	0.52	5.76	6.86	0.98	-1.06	-1.82	-0.03
20-40	Variability	112.25	5.82	4.44	20.00	3.04	1.21	0.66	0.67
	Minimum	25.84	6.69	7.09	12.65	5.68	2.72	2.11	0.63
	Maximum	61.38	14.26	14.02	26.81	11.54	6.35	4.59	3.25
	Mean	39.59	11.02	11.41	20.07	8.99	4.07	3.32	1.55
	Skewness	0.80	-0.34	-1.02	0.27	-0.27	0.97	0.13	1.06
	kurtosis	1.52	0.09	1.20	0.16	0.93	1.36	-0.69	1.44
40-60	Variability	58.74	4.50	3.26	6.99	4.10	1.01	1.44	0.17
	Minimum	37.85	7.52	6.82	12.29	4.46	1.78	1.28	0.22
	Maximum	64.27	14.18	12.70	19.91	10.87	4.55	4.93	1.32
	Mean	47.71	11.11	10.11	17.15	7.44	3.09	2.64	0.75
	Skewness	1.15	-0.15	-0.41	-0.79	0.06	0.06	0.83	0.16
	kurtosis	2.20	-0.53	-0.04	-0.55	-0.53	-1.30	-0.06	-1.48
60-80	Variability	76.70	3.61	4.30	10.01	2.66	0.78	0.47	0.47
	Minimum	35.24	7.89	7.60	13.70	5.37	2.11	1.45	0.22
	Maximum	59.48	14.59	13.68	24.14	10.49	5.01	3.41	2.02
	Mean	42.56	12.27	11.65	19.41	7.66	3.07	2.40	0.98
	Skewness	1.22	-1.52	-0.98	-0.54	-0.01	1.40	0.24	0.52
	kurtosis	0.16	3.79	0.16	0.18	0.00	2.30	-1.20	-1.22
80-100	Variability	37.27	3.25	6.25	5.35	3.28	0.65	0.70	0.28
	Minimum	33.91	10.14	9.91	15.92	5.77	1.40	1.55	0.25
	Maximum	51.97	15.25	17.96	22.43	11.73	4.32	4.01	2.02
	Mean	43.53	12.75	11.86	18.99	7.33	2.48	2.21	0.85
	Skewness	-0.15	-0.46	2.16	0.38	2.10	1.51	1.56	1.37
	kurtosis	-1.21	-1.26	5.14	-1.25	5.04	3.62	1.93	2.28

Table 2. Profile characteristics of soil aggregate of 40 years aged *Pinus massoniana* forestlands (%) (n=9).

Aggregate size (mm)		10.00	7.00	5.00	2.00	1.00	0.45	0.20	<0.20
0-20	Variability	135.86	6.99	3.24	15.67	9.69	18.46	12.81	7.78
	Minimum	0.00	6.65	10.60	15.49	9.72	7.22	6.37	1.53
	Maximum	34.61	15.76	15.78	28.71	20.61	20.83	17.85	10.41
	Mean	14.81	11.73	13.69	22.16	13.24	10.24	10.21	3.91
	Skewness	0.60	-0.59	-0.66	-0.08	1.76	2.32	1.18	1.84
	kurtosis	-0.71	0.77	-0.94	0.00	4.48	5.46	1.72	3.68
20-40	Variability	124.57	19.43	7.23	15.41	11.45	10.48	8.96	5.94
	Minimum	5.31	1.55	8.22	16.78	7.12	3.49	5.62	0.54
	Maximum	38.89	14.65	18.11	30.16	18.14	14.45	14.26	8.32
	Mean	19.62	10.71	12.27	22.20	12.08	9.71	9.66	3.76
	Skewness	0.55	-1.31	1.08	0.73	0.26	-0.59	0.19	0.55
	kurtosis	-0.40	1.00	2.85	1.33	0.01	0.62	-1.39	0.23
40-60	Variability	260.52	17.42	5.29	16.36	23.25	17.61	11.96	3.23
	Minimum	6.78	6.98	10.24	14.65	2.10	1.50	1.58	0.52
	Maximum	52.55	19.80	16.99	26.72	16.79	14.13	11.00	6.01
	Mean	27.85	13.76	13.17	20.43	9.29	6.88	6.04	2.58
	Skewness	0.15	0.11	0.39	0.08	0.24	0.41	0.49	1.09
	kurtosis	-1.31	-0.70	-0.61	-0.46	-0.76	-0.75	-1.31	0.35
60-80	Variability	191.43	11.90	7.34	26.49	17.60	15.16	8.49	4.31
	Minimum	7.94	6.91	7.70	14.34	2.92	0.29	1.77	0.59
	Maximum	51.32	17.44	15.27	28.84	16.83	13.56	11.09	7.13
	Mean	34.85	14.39	12.53	20.94	7.79	3.70	3.87	1.93
	Skewness	-0.74	-1.35	-0.74	0.48	1.25	2.45	2.27	2.39
	kurtosis	0.29	1.85	-0.61	-1.12	1.94	6.66	5.73	6.09
80-100	Variability	201.12	20.51	10.40	47.73	16.96	2.28	3.39	29.08
	Minimum	7.14	8.76	5.91	11.41	3.84	1.51	1.68	0.48
	Maximum	60.32	21.92	16.75	35.03	17.60	6.37	7.35	17.19
	Mean	35.54	15.30	11.90	21.12	7.37	2.55	2.96	3.25
	Skewness	-0.44	-0.22	-0.71	0.83	2.28	2.44	2.09	2.70
	kurtosis	2.30	-1.12	0.66	1.13	5.84	6.54	4.33	7.46

The soil aggregate profile structure of a 40-year-old *Pinus massoniana* forest is shown in Table 2. In the 0-20 cm soil layer, the percentage of aggregates with a particle size of 2.00 mm reached 22.16% (average value), which was significantly higher than that of aggregates with other particle sizes (3.91-14.81%). In the 20-40 cm soil layer, the percentage of aggregates with a particle size of 2.00 mm (22.20%) was also the highest among the particle sizes studied, while the percentage of aggregates with a particle size of 10.00 mm increased to 19.62% compared with that of the 0-20 cm soil layer. In the 40-60 cm soil layer, the percentages of aggregates with particle sizes of 10.00 mm and 2.00 mm were among the largest, but the percentage of 2.00 mm aggregates exceeded that of 10.00 mm aggregates in the next layer. In the 60-80 cm and 80-100 cm soil layers, the percentage of aggregates with a particle size of 10.00 mm continued to increase, reaching 34.85% and 35.54%, respectively, while the percentage of aggregates with a particle size of 2.00 mm was basically stable at approximately 20%. In terms of variability, the percentage content of aggregates with a particle size of 10.00 mm is the largest in all soil layers, which is above 100, significantly higher than that of aggregates with other particle sizes.

The soil aggregate profile of a 60-year-old *Pinus massoniana* forest is shown in Table 3. The overall percentage content of its soil aggregates is similar to that of 40-year-old *Pinus massoniana* forests in terms of distribution but has some differences in value. First, in the same soil layer, the percentage contents of aggregates with particle sizes of 10.00 mm and 2.00 mm were significantly higher than those of aggregates with other particle sizes. Second, the percentage of aggregates with particle size of 10.00 mm is higher, especially in soil layers of 0-20 cm and 20-40 cm, from approximately 20% to more than 30%, while the percentage of aggregates with particle size of 2.00 mm is decreased from more than 20% to less than 20%. The variation degree of the percentage of aggregates with a particle size of 10.00 mm is also very large, reaching more than 100, while the variation of the other particle size aggregates is all below 60 and relatively stable.

Table 3. Profile characteristics of soil aggregate of 60 years aged *Pinus massoniana* forestlands (%) (n=9).

Aggregate size (mm)		10.00	7.00	5.00	2.00	1.00	0.45	0.20	<0.20
0-20	Variability	386.83	2.12	2.48	58.80	6.19	7.14	51.41	57.36
	Minimum	5.65	7.22	6.30	9.41	3.01	1.27	1.57	0.67
	Maximum	67.79	12.23	10.54	35.40	11.93	9.75	22.07	26.23
	Mean	36.21	9.33	8.77	15.77	7.46	5.27	8.70	8.49
	Skewness	-0.06	0.76	-0.37	2.55	0.17	0.41	1.37	1.80
	kurtosis	-0.62	1.14	-1.62	7.09	1.28	-0.41	0.52	3.95
20-40	Variability	119.23	6.73	3.87	5.40	3.40	5.66	21.56	21.40
	Minimum	18.57	6.65	8.15	12.11	5.84	2.71	3.45	1.57
	Maximum	51.28	16.35	12.83	18.60	11.34	9.35	16.43	16.23
	Mean	32.06	10.57	10.13	15.86	8.51	5.94	8.82	8.10
	Skewness	0.42	1.21	0.61	-0.42	0.45	0.12	0.47	0.27
	kurtosis	-0.63	3.47	-1.74	-1.04	-0.65	-1.69	-1.14	-0.31
40-60	Variability	180.16	1.35	11.13	9.57	6.45	12.18	13.30	10.02
	Minimum	18.18	9.30	7.21	12.31	4.60	1.85	2.52	1.40
	Maximum	55.81	12.73	18.36	20.87	11.25	13.08	12.36	9.11
	Mean	36.74	11.22	10.21	16.69	7.79	4.45	7.17	5.73
	Skewness	-0.04	-0.37	2.13	0.17	0.00	2.27	0.40	-0.35
	kurtosis	-1.55	-1.04	5.25	-1.43	-1.77	5.65	-1.40	-1.78
60-80	Variability	238.56	4.89	3.31	12.44	7.19	5.15	32.17	17.91
	Minimum	8.70	8.30	6.70	10.00	3.35	1.93	1.99	0.99
	Maximum	63.56	14.28	12.73	20.96	12.90	9.12	18.35	13.12
	Mean	39.53	11.61	10.32	16.58	6.89	3.40	5.93	5.76
	Skewness	-0.65	-0.10	-0.90	-0.91	1.33	2.42	1.78	0.62
	kurtosis	1.47	-1.69	0.87	0.15	3.17	6.37	2.26	-0.73
80-100	Variability	206.30	6.31	2.40	8.60	4.19	4.96	33.73	34.64
	Minimum	13.36	6.47	7.61	11.81	3.50	1.16	1.38	0.96
	Maximum	59.06	14.87	12.89	20.78	9.75	8.41	19.67	19.62
	Mean	46.60	11.78	9.50	15.06	5.67	2.67	4.46	4.27
	Skewness	-1.77	-1.06	1.32	0.84	1.00	2.64	2.81	2.76
	kurtosis	3.48	1.69	2.35	0.25	0.43	7.37	8.10	7.91

Vertical characteristics of wet screening soil aggregates of *Pinus massoniana* forests with different ages: This research discussed the vertical distribution of wet screening soil aggregates of *Pinus massoniana* with different ages, by measuring aggregates with particle sizes of >5 mm, 5-2 mm, 2-1 mm, 1-0.5 mm and 0.5-0.2 mm from soil profiles of *Pinus massoniana* forests at the ages of 20, 40 and 60 years. The wet screening soil aggregate profile of a 20-year-old *Pinus massoniana* forest is shown in Fig. 2. The Figure shows that the percentage of aggregates with particle size of 2-1 mm is relatively low, and the data are relatively concentrated; but the difference between the percentages of aggregates with particle sizes of >5 mm and 5-2 mm and that of particle size of 1-0.5 mm and 0.5-0.2 mm is smaller. The percentage of aggregates with particle sizes of >5 mm ranges from 3.39% to 55.63%, with an average value of 29.47%; the percentage of aggregates with particle sizes of 5-2 mm is between 4.72%-48.03%, with an average value of 25.57%; the percentage of aggregates with particle sizes of 2-1 mm is between 3.50%-29.08%, with an average value of 9.35%; for particle sizes of 1.00-0.50 mm is 7.98%-40.80%, and 19.19%, respectively; and 0.50-0.20 mm is 3.89%-38.84% and 17.06%, respectively.

Similar to that of the 20-year-old *Pinus massoniana* forest, the percentage of aggregates with particle sizes of 2-1 mm was also the lowest, but there were differences in data convergence (Fig. 3). Meanwhile, the difference between the percentage of aggregates with particle sizes of >5 mm and 5-2 mm and that of particle sizes of 1-0.5 mm and 0.5-0.2 mm is further reduced. The percentage of aggregates with particle sizes of >5 mm is between 4.89%-69.52%, with an average value of 36.41%; the percentage of aggregates with particle sizes of 5-2 mm is between 5.29%-68.20%, with an average value of 20.64%; the percentage of aggregates with particle sizes of 2-1 mm is between 2.38%-19.70%, with an average value of 7.32%; for particle sizes of 1.00-0.50 mm, the percentage content is between 4.37%-30.15%, and average value is 13.30%; and the Figure for 0.50-0.20 mm are 3.92%-59.99% and 24.03%, respectively.

The wet screening soil aggregate profile of a 60-year-old *Pinus massoniana* forest is shown in Fig. 4. Similar to that of the 40-year-old *Pinus massoniana* forest, the percentage of aggregates with particle sizes of 2-1 mm was also the lowest, but data convergence was reduced further. The difference between the percentage content of aggregates with particle sizes of >5 mm and 5-2 mm and that of aggregates with particle sizes of 1-0.5 mm and 0.5-0.2 mm is further reduced. The percentage content of aggregates with particle sizes of >5 mm is between 2.73%-73.94%, with an average value of 35.06%; the percentage of aggregates with particle sizes of 5-2 mm is between 4.46%-26.12%, with an average value of 13.32%; the percentage of aggregates with particle sizes of 2-1 mm is between 0.14%-10.82%, with an average value of 6.10%; for particle sizes of 1.00-0.50 mm, the percentage content is between 5.99%-51.90%, and average value is 16.78%; and the Figure for 0.50-0.20 mm are 4.19%-71.93% and 28.75%, respectively. In general, there are certain rules for soil aggregates with different particle sizes of *Pinus massoniana* forests with different ages. The content of aggregates with particle sizes of 2-1 mm is the lowest, and the data are relatively concentrated. With increasing forest age, the content of aggregates with particle sizes >5 mm decreased gradually, while that of soil aggregates with 0.5-0.2 mm particle sizes increased gradually.

Vertical variation in soil aggregates' organic carbon of *Pinus massoniana* forests with different ages: Soil aggregates are the basic units of soil structure, and their quantity and quality play an important role in soil quality. A good soil aggregate structure is beneficial for storing more soil organic carbon. Aggregates of different sizes play different roles in nutrient maintenance, supply and transformation. Organic carbon decreases sharply as the soil depth increases. In the 0-20 cm soil layer, the organic carbon content in soil aggregates with different particle sizes is between 34.966-39.95 g/kg, with an average value of 37.34 g/kg; in the 20-40 cm soil layer, the organic carbon content in soil aggregates with different particle sizes is between 24.50-27.11 g/kg, with an average value of 25.54 g/kg; in the 40-60 cm soil layer, the Figures are 17.60-22.60 g/kg and 19.35 g/kg, respectively; the Figures are 13.56-19.98 g/kg and 17.21 g/kg for the 60-80 cm layer and 13.55-17.36 g/kg and 15.73 g/kg for the 80-100 cm layer. After 10 years of accumulation, the organic carbon in the soil aggregates increased (Fig. 5). However, the aggregate organic carbon content in the 40-60 cm soil layer was somewhat reduced, which may be because the roots of *Pinus massoniana* trees were deep and were mainly concentrated in the 40-60 cm soil layer. This indirectly shows that the activities of tree roots can change the rhizosphere soil environment, increase the activities of soil microorganisms, change the biogeochemical process of soil organic carbon, and thus reduce the content of soil organic carbon.

There are obvious profile characteristics for the organic carbon in soil aggregates with different particle sizes of 40-year-old *Pinus massoniana* forests (Fig. 6). With increasing soil depth, the organic carbon in aggregates decreases sharply. In addition, compared with 10- and 20-year-old *Pinus massoniana* forests, the content of aggregate organic carbon was also reduced significantly. For the 40-year-old *Pinus massoniana* forest, in the 0-20 cm soil layer, the organic carbon content in soil aggregates with different particle sizes is between 20.05-22.00 g/kg, with an average value of 20.93 g/kg; in the 20-40 cm soil layer, the organic carbon content in soil aggregates with different particle sizes is between 17.01-19.03 g/kg, with an average value of 18.22 g/kg; in the 40-60 cm soil layer, the organic carbon content in soil aggregates with different particle sizes is between 13.67-15.58 g/kg, with an average value of 14.36 g/kg; in the of 60-80 cm soil layer, the organic carbon content in soil aggregates with different particle sizes is between 10.34-11.66 g/kg, with an average value of 11.00 g/kg; in the 80-100 cm soil layer, the organic carbon content in soil aggregates with different particle sizes is between 6.90-8.68 g/kg, with an average value of 7.00 g/kg. The average organic carbon content of aggregates with different particle sizes is very close, which is approximately 14 g/kg, but that Figure for aggregates with a particle size of 0.20 mm is slightly higher, reaching 15.20 g/kg.

Overall, the aggregate organic carbon content of the 60-year-old *Pinus massoniana* forest was higher than that of the 40-year-old *Pinus massoniana* forest. In the 40-60 cm, 60-80 cm and 80-100 cm soil layers, the differences between aggregate organic carbon contents were reduced and no longer obvious (Fig. 7). For 60-year-old *Pinus massoniana* forest, in the 0-20 cm soil layer, the organic carbon content in soil aggregates with different particle sizes is between 22.12-24.50 g/kg, with an average value of 23.19 g/kg; in the 20-40 cm soil layer, the organic carbon content in soil aggregates with different particle sizes is between 18.55-20.69 g/kg, with an average value of 19.71 g/kg; in the 40-60 cm soil layer, the organic carbon content in soil aggregates with different particle sizes is between 15.10-17.36 g/kg, with an average value of 16.43 g/kg; in the 60-80 cm soil layer, the organic carbon content in soil aggregates with different particle sizes is between 14.27-16.17 g/kg, with an average value of 15.19 g/kg; in the soil layer of 80-100 cm soil layer, the organic carbon content in soil aggregates with different particle sizes is between 14.63-15.58 g/kg, with an average value of 14.89 g/kg. The average organic carbon content of aggregates with different particle sizes is increased to above 17.00 g/kg, only for aggregates with particle size of 10 mm, the average organic carbon content of which is 16.98 g/kg, slightly lower than 17.00 g/kg.

Relationship between soil depth and soil aggregates' organic carbon of *Pinus massoniana* forests with different ages: The average organic carbon content in soil aggregates of *Pinus massoniana* forests increases with soil depth but is greatly different among *Pinus massoniana* forests with different ages. The average organic carbon content was the largest in the soil aggregates of the 20-year-old *Pinus massoniana* forest, followed by the 10-year-old *Pinus massoniana* forest (Fig. 8).

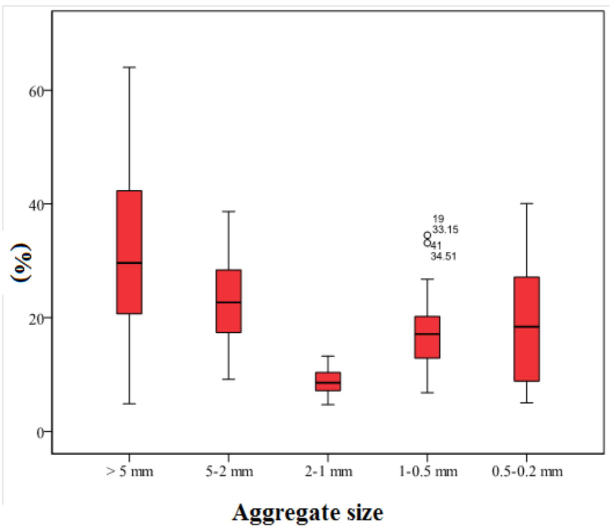

Fig. 2. Situation of soil wet sieve aggregate in the 20 years aged *Pinus massoniana* forestland.

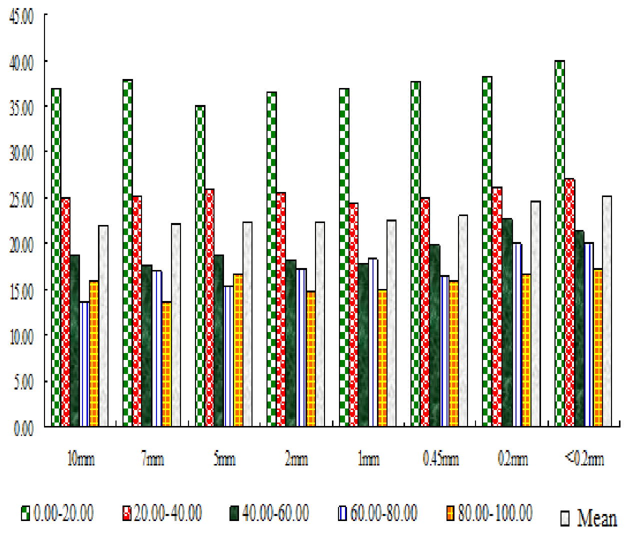

Fig. 5. Characteristics of soil organic carbon in 20 years aged *Pinus massoniana* Forestland.

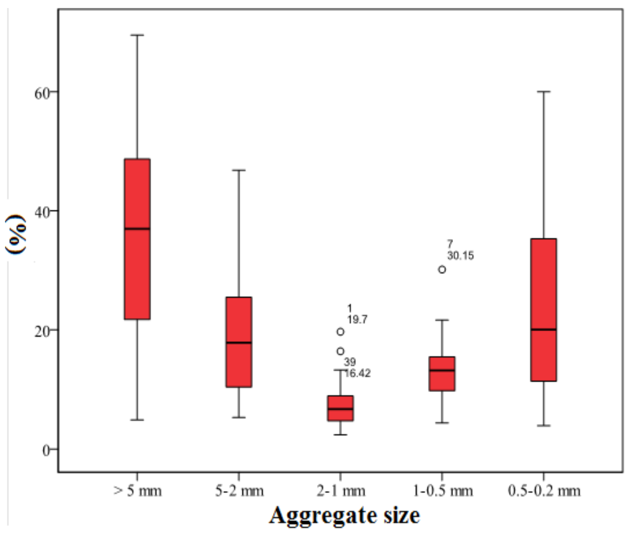

Fig. 3. Situation of soil wet sieve aggregate in the 40 years aged *Pinus massoniana* forestland.

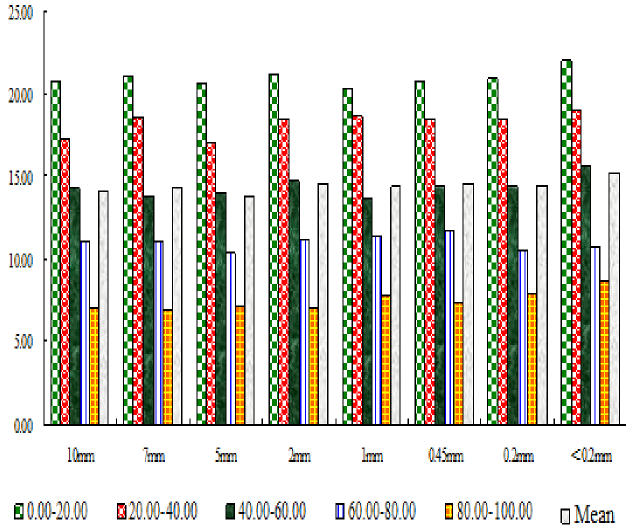

Fig. 6. Characteristics of soil organic carbon in 40 years aged *Pinus massoniana* Forestland.

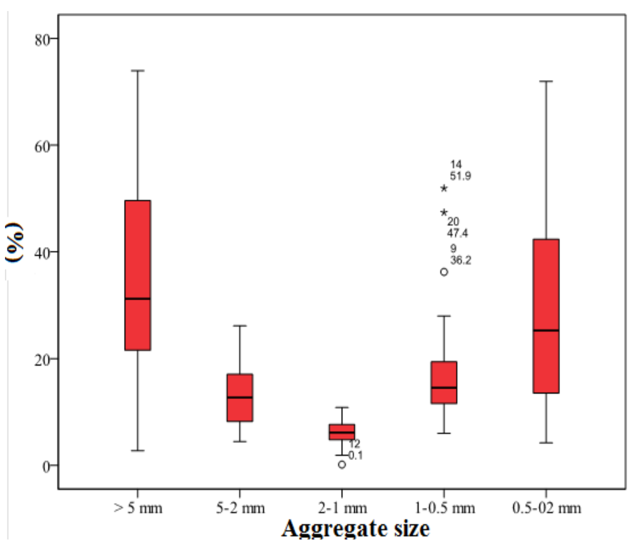

Fig. 4. Situation of soil wet sieve aggregate in the 60 years aged *Pinus massoniana* forestland.

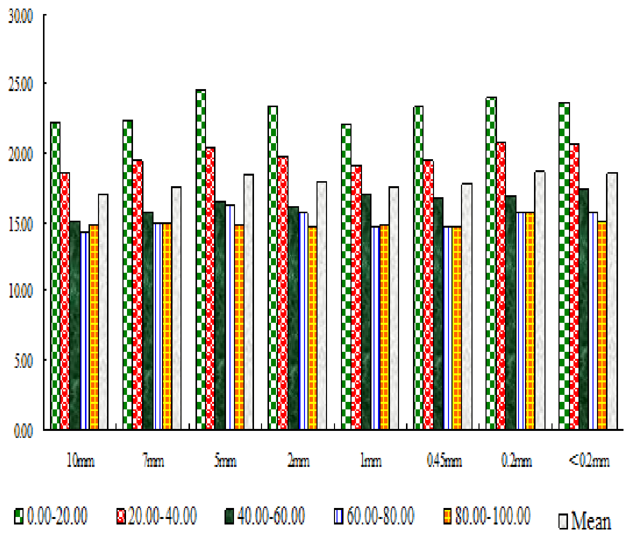

Fig. 7. Characteristics of soil organic carbon in 60 years aged *Pinus massoniana* forestland.

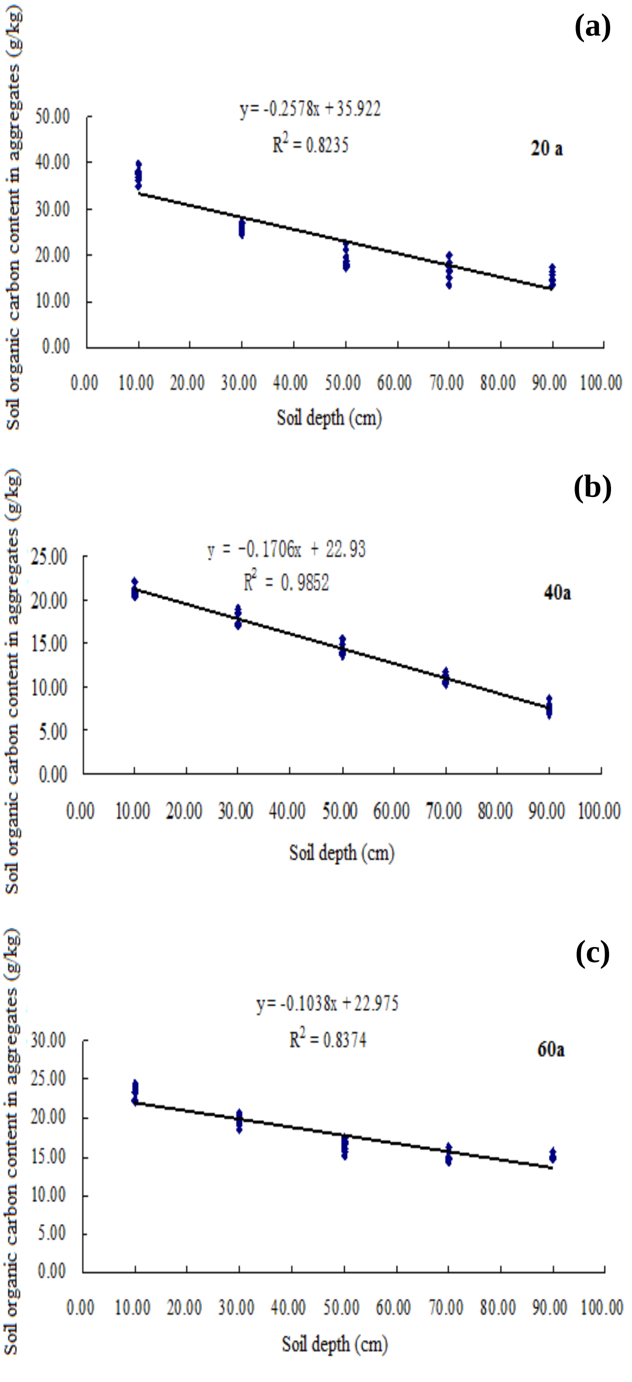

Fig. 8. Relationship between soil depth and soil aggregates organic carbon of *Pinus massoniana* forests with different ages.

Discussion

Comparison of organic carbon characteristics of soil aggregates of *Pinus massoniana* with different ages: There are significant differences among aggregates with different particle sizes in the same soil layer and among aggregates with the same particle size in different soil layers. In the 0-20 cm soil layer, with the decrease in particle size, the variability first decreases and then increases. Compared with the 10-year-old *Pinus massoniana* forest, the changes in soil aggregates of the 20-year-old *Pinus massoniana* forest were larger. Similarly, from particle sizes of 10 mm to <0.20 mm, the contents of soil aggregates with different particle sizes also change greatly. For the 10-year-old *Pinus massoniana* forest, the soil aggregate content did not change obviously with decreasing particle size. For the 20-year-old *Pinus massoniana* forest, the content of soil aggregates decreased with decreasing particle size at different soil depths. Overall, the percentage content of soil aggregates of the 60-year-old *Pinus massoniana* forest was similar to that of the 40-year-old *Pinus massoniana* forest in terms of distribution but had some differences in value. In the same soil layer, the percentage contents of aggregates with particle sizes of 10.00 mm and 2.00 mm are significantly higher than those of aggregates with other particle sizes (Zheng *et al.*, 2018). The percentage content of aggregates with particle sizes of 10.00 mm was higher than that of the 40-year-old *Pinus massoniana* forest, especially in the 0-20 cm and 20-40 cm soil layers, where it increased to 30% from 20%. However, the percentage content of aggregates with particle sizes of 2.00 mm decreases from 20% to below 20%. Compared with the soil aggregate distribution of the 60-year-old *Pinus massoniana* forest, the percentage content of aggregates with particle sizes of 10.00 mm in the surface layer (0-20 cm) of the 100-year-old *Pinus massoniana* forest decreased, while there was no substantial change in the 10.00 mm aggregates in the deeper soil layers. However, the percentages of aggregates with a particle size of 2.00 mm changed significantly, from approximately 16.00% to more than 20.00% (except for the 60-80 cm soil layer). Soil aggregates with different particle sizes are mainly dominated by aggregates with a particle size of 10.00 mm, followed by aggregates with a particle size of 2.00 mm (Guo & Zhou, 2010).

Soil aggregates are an important part of soil, affecting various physical and chemical properties of the soil and the geochemical behaviour of soil elements and substances (Liu *et al.*, 2008). Soil aggregates and organic carbon are inseparable, with the former being the carrier of the latter and the latter being the cementing material of the former (Shedayi *et al.*, 2016). As the main structural unit of soil, the soil aggregate is an important determinant of soil organic matter and nutrient salt metabolism. Traditionally, soil aggregates are divided into macroaggregates and microaggregates (Zhang *et al.*, 2012). Macroaggregates mainly refer to the part of soil with particle sizes larger than 0.25 mm, while microaggregates refer to the part with particle sizes smaller than 0.25 mm (Islam & Weil, 2000; Golchin & Asgari, 2008). Different land uses could result in changes in vegetation cover, and the composition and structure of soil aggregates would also change. The profile of soil aggregate organic carbon of the 20-year-old *Pinus massoniana* forest was similar to that of the 10-year-old *Pinus massoniana* forest, decreasing dramatically as the soil depth increased. For the 40-year-old *Pinus massoniana* forest, the organic carbon of aggregates with different particle sizes has very obvious profile characteristics, with aggregates' organic carbon decreasing sharply as soil depth increases, and compared with that of the 10-year-old *Pinus massoniana* forest and the 20-year-old *Pinus massoniana* forest, its organic carbon content also decreases significantly. The organic carbon content in soil aggregates of the 60-year-old *Pinus massoniana* forest is slightly higher than that of the 40-year-old *Pinus massoniana* forest, with differences between organic carbon contents in soil layers of 40-60 cm, 60-80 cm and 80-100 cm narrowing and no longer obvious. Similar to the profile of soil aggregates' organic carbon of the 60-year-old *Pinus massoniana* forest, the organic carbon content of the 100-year-old *Pinus massoniana* forest increased further.

Physical protective mechanism of aggregates on organic carbon: The formation of aggregates is conducive to the accumulation of soil organic carbon in the soil and physically protects the organic matter from being degraded or reduced by edaphon. Six and Elliott (2000) developed a conceptual model centred on the "turnover of macroaggregates". Specifically, fresh organic matter promotes the formation of macroaggregates, and the particulate organic matter within macroaggregates contributes to the formation of microaggregates; that is, with the decomposition of particulate organic matter and other interference processes, macroaggregates break up and release microaggregates. The model indicates that the macroaggregates have faster turnover than the microaggregates, so the organic carbon in the microaggregates is relatively constant. However, macroaggregates can fix more organic carbon, providing conditions for the preservation of organic carbon in microaggregates. Zhang *et al*., (2020) further emphasized that the particulate organic matter (POM) enclosed by macroaggregates creates conditions for the formation of microaggregates, while the particulate organic matter enclosed by microaggregates gains more physical protection, which is of great significance for the stability of organic carbon.

The results of this study show that there are differences among the soil aggregates of *Pinus massoniana* forests of different ages subject to different soil depths, particle sizes and ages. The organic carbon contents of soil aggregates with different particle sizes have obvious profile characteristics, decreasing with increasing soil depth. The difference between the organic carbon contents of soil aggregates with different particle sizes is small. However, due to the great difference among the percentage content of soil aggregates with different particle sizes, there are also great differences among the organic carbon contents of soil aggregates with different particle sizes.

Conclusion

The new organic matter in *Pinus massoniana* forests promotes the formation of coarse aggregates, and the particulate organic matter in coarse aggregates helps the formation of fine aggregates. The coarse aggregates can physically protect the newly added organic carbon in *Pinus massoniana* forests, but the protection has a saturation limit. With increasing forest age, the saturated limit of coarse aggregates would be broken under the combined action of internal and external forces, and fine aggregates would then be released. The particulate organic matter enclosed by coarse aggregates creates conditions for the formation and stability of fine aggregates, while the particulate organic matter enclosed by fine aggregates is more physically protected by coarse aggregates. The two types of aggregates coordinate and jointly promote the physical stability of organic carbon.

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