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Vertical and seasonal variations of soil carbon pools in ginkgo agroforestry systems in eastern China

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ABSTRACT

Agroforestry provides opportunities to decrease the levels of carbon dioxide (CO_2) released into the atmosphere by increasing the carbon (C) stored in agricultural systems. In agroforestry systems, soil C pools serve as the most important and stable C sink, but there is limited information on the vertical and seasonal variations of soil C pools. In this study, the vertical and seasonal variations of soil organic C (SOC) and its labile pools were measured in five planting systems: a pure ginkgo (*Gingko biloba.* L) planting system, a pure wheat (*Triticum aestivum* L.) field, a pure metasequoia (*Metasequoia glyptostroboides* Hu et Cheng) seedling system, a ginkgo and wheat agroforestry system, and a ginkgo and metasequoia seedling agroforestry system. Among these systems, the ginkgo and wheat system had a significantly higher SOC content than the other systems throughout the year, particularly at depths of 0–10 cm and 10–20 cm. Additionally, the pure ginkgo and pure metasequoia systems had lower SOC contents than the other planting systems, and this decrease was attributed to the relatively limited tree litter input and lower fine root biomass. Microbial biomass C (MBC) and soil readily oxidizable C (ROC) exhibited similar vertical and seasonal variations and reached minimum values in winter. The highest MBC and ROC contents were observed in the ginkgo and wheat system at a depth of 0–10 cm, i.e., 127.3 mg kg^{-1} and 4.49 g kg^{-1}, respectively. The highest water-soluble organic carbon (WSOC) content was observed in summer at a depth of 0–10 cm, i.e., 472.2 mg kg^{-1}. A Pearson correlation analysis indicated that soil properties were significantly correlated with SOC and labile C fractions. The results suggested that an agroforestry system resulted in a greater increase in the soil C sink; in particular, the ginkgo and wheat system achieved the best results. Basic soil properties played key roles in soil carbon formation. These results provide important information about SOC and labile C fraction dynamics resulting from planting systems and depth variations and strengthen our understanding of soil C sequestration in agroforestry systems.

1. Introduction

The global soil carbon (C) pools contain 2500 gigatons (Gt) of carbon, which is three times higher than the atmospheric carbon pool and 4.5 times higher than the biotic carbon pool (Lal, 2004). In the context of global warming, dramatic climate changes have been caused by greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2) emissions. Thus, the carbon sink capacity of soil has received extensive attention by international researchers because a higher soil C sequestration capacity results in more atmospheric CO_2 being taken up, soil fertility being enhanced, and soil quality being improved (Wiesmeier et al., 2014; Zhao et al., 2018). Forests store the majority of organic C in terrestrial ecosystems as a result of C sequestration, and soils store the majority of organic C in forest ecosystems (Lorenz and Lal, 2010; Scharlemann et al., 2014). Hence, forest soil carbon pools are important C sinks that are crucial for ecosystem functioning and the global C budget.

However, various factors affect the stability of soil carbon pools; in particular the formation and decomposition of soil organic carbon (SOC) are key ecological processes (Hiltbrunner et al., 2013). For example, land use changes may increase the amounts of CO_2 released into the atmosphere by influencing SOC decomposition, and different types of vegetation usually provide litter with different physical and chemical properties by influencing SOC formation (Bárcena et al., 2014; Gosheva et al., 2017; Román-Sánchez et al., 2018). Moreover, climate, fertilization, and soil bulk density and aggregate ability strongly affect forest soil carbon pools (Brar et al., 2013; Franzluebbers, 2005; Miller et al., 2004). Thus, it is important to implement sustainable and adaptive forest management practices to better manage forests sustainably to cope with future climate change challenges. Agroforestry systems,

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which combine trees with agricultural crops and/or livestock, supply a large number of ecosystem services and environmental benefits (Hergoualc'h et al., 2012). Moreover, agroforestry can increase the amount of C stored in agricultural systems while still allowing the growth of food crops (Montagnini and Nair, 2004). For example, perennial trees in agroforestry systems can fix CO_2 through photosynthesis and can serve as important C sinks, and plant residues and dead branches that are retained on the soil surface are crucial for soil C input and improvements in soil aggregation (Chen et al., 2017; Oelbermann et al., 2006). Moreover, perennial trees in agroforestry systems can be deeply rooted, which is beneficial for SOC accumulation in deep soil layers (Cardinael et al., 2015).

In general, SOC pools can be divided into labile and recalcitrant C pools. The recalcitrant C pool is relatively stable and has a longer turnover time (Chen et al., 2016). In contrast, soil labile C pools, such as microbial biomass C (MBC), water-soluble organic C (WSOC), and readily oxidizable C (ROC), are more sensitive indicators of changes in land management practices because of their key roles in soil nutrient accumulation and energy supply in soil microbial activities (Shao et al., 2015; Yu et al., 2017). Crop residue incorporation is an important measure for improving air quality, mitigating climate change and increasing SOC input (Dikgwatlhe et al., 2014). Previous studies have demonstrated that crop residues with different properties produced various effects on the composition of soil C fractions and the stability of soil aggregates (Langenbruch et al., 2014). Perennial plants generally participate in SOC formation by providing organic C to soil via branch pruning, root turnover and exudation, and leaf litter (Khalid et al., 2007). Agroforestry systems, which consist of perennial and annual plants, can supply primary organic C to soil and can have a positive effect on the SOC content. Labile C pools are strongly time-sensitive, and seasonal changes may play a vital role in nutrient availability and microbial activity.

Gingko (*Gingko biloba.* L), a 'living fossil' that is native to China, is widespread around the world because of its beautiful appearance and strong adaptability (Major, 1967). In China, ginkgo is usually intercropped with crops, seedlings, and vegetables. In ginkgo agroforestry systems, gingko leaves, crop residues, and root exudation are the major sources of soil C input (Guo et al., 2018; Khalid et al., 2007). Previous studies focused mainly on the distribution of soil C in the topsoil (< 20 cm). However, information on the labile fraction dynamics is urgently needed for sub-soil layers. Thus, the primary aim of this study was to quantify the distribution of labile C fractions to a soil depth of 1 m in a ginkgo agroforestry system. Five typical planting systems were selected: a pure ginkgo planting system, a pure wheat (*Triticum aestivum* L.) field, a pure metasequoia (*Metasequoia glyptostroboides* Hu et Cheng) seedling system, a ginkgo and wheat agroforestry system, and a ginkgo and metasequoia seedling agroforestry system. Three objectives were established: (1) characterize the differences in the soil C pools among the various planting systems; (2) quantify the SOC contents and labile C fractions in different layers (0–10, 10–20, 20–40, 40–60, and 60–100 cm); and (3) analyze the correlation among soil labile C pools and basic soil properties.

2. Materials and methods

2.1. Study area

This study was conducted in Yellow Sea Forest Park (32°33′–32°57′ N, 120°07′–120°53′ E), Dongtai City, Jiangsu Province. This site is located in the alluvial plain in the middle and lower reaches of the Yangtze River. The area has a subtropical warm humid monsoon climate that is hot and rainy in summer and cold and dry in winter. The annual average temperature is 15.6 °C, annual precipitation is 1044 mm, the annual average frost-free period is 237 days, and the annual sunshine duration is 2209 h. The local soil is characterized as alkaline sandy loam soil.

2.2. Experimental design and soil sampling

Through a preliminary investigation, five popular planting systems were selected for the experiment: a pure ginkgo planting system (G), a pure wheat field (W), a pure metasequoia seedling system (M), a ginkgo and wheat agroforestry system (GW), and a ginkgo and Metasequoia seedling agroforestry system (GM). These systems are referred to as G, W, GW, M, and GM based on the first letter. The ginkgo forest was planted in 2002, and the agroforestry systems were established in 2004 using a row and plant spacing of 2 × 8 m. A pure ginkgo planting system with a row and plant spacing of 2 × 8 m was gradually intercropped with an interrow crop. Adjacent pure ginkgo planting systems with a row and plant spacing of 3 × 3 m were selected in this study. Metasequoia seedlings were planted in 2010 with a row and plant spacing of 0.8 × 0.8 m. Maize was planted as a rotation crop after wheat. Based on information provided by local farmers, fertilizers are applied twice per year, i.e., in mid-May and mid-October. Compound fertilizer was applied, i.e., a total of approximately 0.9 t·ha^{-1}, divided equally into two applications.

Soil samples were collected in 2016 during four typical months representing the four seasons: March, July, October, and January. In each planting system, three plots with a dimension of 100 m^2 were randomly selected for soil sampling. On each sampling date, soil samples were collected at depths of 0–10, 10–20, 20–40, 40–60, and 60–100 cm. Soil drilling (4-cm diameter) was used to collect the soil samples from five selected locations in each plot, based on an S-shaped curve, and the samples were combined to form a composite sample according to the inquartation method. A total of 75 samples was collected on each sampling date; the samples were placed on ice in a cooler and then transported to the laboratory. The three cutting ring method was used to collect soil samples from each plot on the first sampling date to determine the bulk density.

2.3. Soil analysis

Soil bulk density was detected using a gravimetric method. Briefly, the original soil was retrieved with a cutting ring, and the dry soil weight was measured, after which the soil bulk density was calculated. Soil pH was measured using a pH meter at a 1:2.5 soil/water (w/v) ratio. Total N was determined using the Kjeldahl method, total P was determined using a molybdenum colorimetric method, and total K was determined using an acid solution and flame photometric method. Soil ammonium-N (AN, indigo blue colorimetric method) and nitrate-N (NN, dual band ultraviolet spectrophotometry) were extracted with 2 M KCl (w/v = 1:5, 180 r, 1 h) and were determined using UV spectrophotometry (Lu, 1999; Shibata et al., 2011). The basic soil properties are shown in Table 1.

SOC was determined using a modified Walkley and Black method. Briefly, 0.5 g of soil was digested using 5 mL of 0.8 M 1/6$K_2Cr_2O_7$ and 5 mL of concentrated H_2SO_4 at 175 °C for 10 min, after which the extracts were titrated with standardized $FeSO_4$, and the SOC content was calculated according to potassium dichromate consumption (Gao et al., 2017).

MBC was determined using the chloroform fumigation-extraction method (Vance et al., 1987). Briefly, fresh sampled soil (equivalent to 5 g of oven-dried soil) was fumigated with chloroform for 24 h at 25 °C after sieving (< 2 mm), followed by extraction with 0.5 M K_2SO_4 for 30 min on a shaker (180 r). Non-fumigated soil was also extracted with 0.5 M K_2SO_4 for 30 min. MBC was determined using a liquid TOC analyzer (Elementar, Germany). MBC was calculated as 2.22 × (C extracted from fumigated soil - C extracted from non-fumigated soil) (Liu et al., 2012; Wu et al., 1990).

WSOC was determined by shaking fresh soil (equivalent to 5 g of oven-dried soil) at a soil/water (w/v) ratio of 1:5 on a shaker at room temperature for 30 min, followed by centrifuging at 3000 rpm for 10 min. The supernatant was filtered through a membrane filter (pore

Table 1
Bulk density and contents of the main soil nutrients (mean ± standard deviation, n = 3) in the 0–100-cm layer of the five planting systems. BD: bulk density, TP total phosphorus, TK total potassium, AN ammoniacal nitrogen, and NN nitrate nitrogen.

Planting system	Soil depth	BD g·cm^{-3}	TP g·kg^{-1}	TK mg·kg^{-1}	AN mg·kg^{-1}	NN mg·kg^{-1}
G	0–10	1.19 ± 0.06	0.39 ± 0.01	5.50 ± 1.25	7.09 ± 0.94	2.14 ± 0.43
	10–20	1.25 ± 0.01	0.38 ± 0.02	6.43 ± 1.92	7.88 ± 1.19	2.60 ± 0.37
	20–40	1.34 ± 0.06	0.32 ± 0.01	6.28 ± 1.90	7.80 ± 0.75	2.92 ± 0.05
	40–60	1.44 ± 0.01	0.28 ± 0.06	4.91 ± 1.65	4.43 ± 1.65	2.42 ± 0.29
	60–100	1.37 ± 0.02	0.31 ± 0.01	4.20 ± 0.55	3.12 ± 0.94	1.74 ± 0.69
W	0–10	1.19 ± 0.07	0.46 ± 0.01	8.20 ± 0.45	2.90 ± 1.88	4.94 ± 0.76
	10–20	1.27 ± 0.08	0.45 ± 0.02	8.04 ± 0.91	1.94 ± 1.57	2.33 ± 0.26
	20–40	1.43 ± 0.04	0.34 ± 0.02	8.09 ± 0.93	2.62 ± 0.99	3.83 ± 0.37
	40–60	1.47 ± 0.02	0.33 ± 0.01	7.87 ± 0.95	2.96 ± 0.41	6.51 ± 0.71
	60–100	1.47 ± 0.02	0.32 ± 0.02	7.59 ± 0.13	3.25 ± 0.75	6.88 ± 0.85
M	0–10	1.28 ± 0.09	0.45 ± 0.02	5.48 ± 1.04	4.93 ± 0.90	2.27 ± 0.18
	10–20	1.28 ± 0.11	0.46 ± 0.03	4.77 ± 1.15	6.40 ± 0.93	4.58 ± 0.79
	20–40	1.47 ± 0.02	0.34 ± 0.05	4.25 ± 1.12	3.11 ± 0.89	3.72 ± 0.36
	40–60	1.50 ± 0.03	0.31 ± 0.03	6.59 ± 1.69	1.54 ± 0.50	2.01 ± 0.64
	60–100	1.43 ± 0.07	0.32 ± 0.01	7.82 ± 0.37	1.60 ± 0.58	1.64 ± 0.95
GW	0–10	1.14 ± 0.09	0.50 ± 0.02	2.61 ± 0.87	6.62 ± 2.14	1.69 ± 0.42
	10–20	1.15 ± 0.03	0.48 ± 0.04	5.00 ± 1.15	6.82 ± 1.53	3.32 ± 0.54
	20–40	1.40 ± 0.02	0.33 ± 0.02	5.25 ± 0.85	4.08 ± 1.00	2.68 ± 0.18
	40–60	1.45 ± 0.02	0.34 ± 0.03	4.81 ± 0.67	3.34 ± 0.65	1.91 ± 0.22
	60–100	1.36 ± 0.08	0.32 ± 0.01	3.67 ± 0.27	2.63 ± 0.33	1.26 ± 0.27
GM	0–10	1.27 ± 0.03	0.39 ± 0.02	3.12 ± 1.22	11.22 ± 1.7	1.27 ± 0.27
	10–20	1.32 ± 0.04	0.37 ± 0.03	4.75 ± 0.51	10.71 ± 1.5	2.19 ± 0.76
	20–40	1.46 ± 0.03	0.31 ± 0.03	4.40 ± 1.43	4.68 ± 0.07	1.74 ± 0.72
	40–60	1.49 ± 0.02	0.28 ± 0.03	4.11 ± 1.56	2.27 ± 0.51	1.16 ± 0.93
	60–100	1.45 ± 0.02	0.30 ± 0.02	4.19 ± 0.74	2.92 ± 0.63	1.20 ± 0.61

size: 0.45 mm) using vacuum filtration with circulating water. WSOC was determined using the liquid TOC analyzer.

ROC was determined using a colorimetric method proposed by Blair et al. (1995) and Li et al. (2010). Air-dried soil (2 g) was placed in a 50-mL centrifuge tube and 25 mL of 333 mmol·L^{-1} $KMnO_4$ solution was added, shaken at 120 rpm for 1 h, and centrifuged for 5 min at 2000 *g*. The vacuity contrast group received the same treatment. The supernatant was diluted 250-fold, and the absorbance at 565 nm was determined. The amount of ROC was calculated according to the difference between the sample and the vacuity contrast group assuming that 1 mmol·L^{-1} $KMnO_4$ oxidizes 1 mg C.

2.4. Statistical analyses

Statistical analyses were conducted using SPSS (IBM Inc., Chicago, Illinois, USA). The data in this paper are presented as the mean ± standard deviation (n = 3). Basic soil properties, SOC, and labile C pools (ROC, WSOC, and MBC) were analyzed using one-way ANOVA and Duncan's multiple range test at a 5% level of significance. A repeated-measures ANOVA was conducted to test for differences in SOC, ROC, WSOC and labile C pools (ROC, WSOC, and MBC) among planting systems using season as the repeated variable.

3. Results

3.1. SOC contents across planting systems

As the soil depth increased, SOC changed substantially in the five planting systems (Fig. 1). The SOC content was significantly higher in the upper two soil layers (0–10 and 10–20 cm) but was relatively low throughout the bottom three layers ($P < 0.05$). The SOC content in the 0–10 and 10–20-cm layers of the GW system was significantly higher than those in the other systems throughout the year ($P < 0.05$). However, no significant differences were observed in summer for the bottom three layers ($P > 0.05$). Among the four seasons, there were significant differences in the mean SOC content ($P < 0.05$) of the GW and G systems. In the G system, the mean SOC content in spring was 192%, 216%, and 217% higher than that in summer, autumn, and winter, respectively. The highest mean SOC content was mostly observed in the GW system, i.e., 10.58 g·kg^{-1}, 5.85 g·kg^{-1}, and 7.21 g·kg^{-1} in spring, summer, and winter, respectively. The lowest mean SOC contents were observed in the R system in spring and in the G system in the three other seasons. The repeated-measures ANOVA showed significant interactions between season and planting system in all sample layers (Table 2).

3.2. ROC contents across planting systems

The ROC content was relatively stable along the soil depth chronosequence in winter but decreased with an increase in soil depth in the three other seasons (Fig. 2). Except in winter, the ROC content was significantly higher in the upper two soil layers (0–10 and 10–20 cm) than in the bottom three layers ($P < 0.05$). The ROC content in the 0–10-cm layer of the GW system was significantly higher than in the other systems throughout the year ($P < 0.05$). However, no significant differences were observed in the 20–40, 40–60, and 60–100-cm layers throughout the year except in spring ($P > 0.05$). The average spring and summer ROC contents, based on all sampling layers in the GW system, were 2.17 and 2.87 g·kg^{-1} higher, respectively, than those in the other planting systems. In addition, higher ROC contents were observed in the G system (2.19 g·kg^{-1}) in autumn and the GM system (0.97 g·kg^{-1}) in winter. The repeated-measures ANOVA showed significant interaction effects of planting system and season on ROC at the 10–20 and 60–100-cm depths (Table 2).

3.3. WSOC contents across planting systems

The trend of the WSOC content in each system was similar (Fig. 3), i.e., significant seasonal changes ($P < 0.01$) were observed, but no significant difference among the soil layers was detected ($P > 0.05$). The WSOC content was highest in summer, followed by spring and autumn, and lowest in winter. In spring, the WSOC content was significantly higher in the GW, G, and W systems when compared with the GM and M treatments at depths of 0–10, 20–40, and 40–60 cm. The average WSOC content of the GW, G, and W treatments was 132%–150% higher than that measured in the GM and M treatments. In

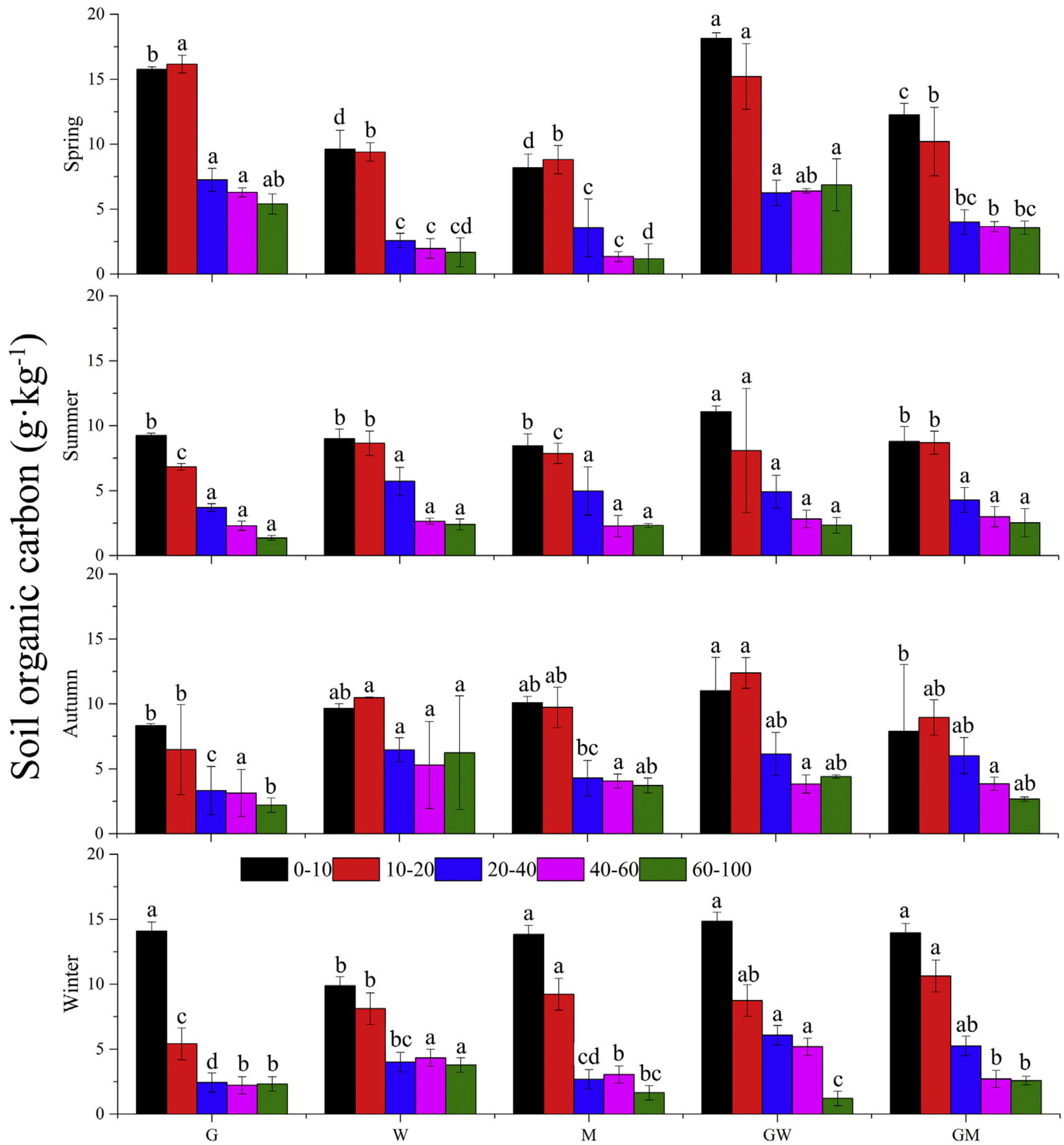

Fig. 1. Seasonal variations in SOC at different depths (0–10, 10–20, 20–40, 40–60, and 60–100 cm) in different planting systems. Different lowercase letters indicate significant differences among planting systems for the same soil layer and season based on Duncan's multiple comparison test at $P < 0.05$.

Table 2
Results of a repeated-measures ANOVA testing for differences in soil organic carbon (SOC), readily oxidizable carbon (ROC), water soluble organic carbon (WSOC), and microbial biomass carbon (MBC) among planting systems using season as the repeated variable. PS: planting system, S: season.

Source of variation		SOC			ROC			WSOC			MBC		
		df	F	P	df	F	P	df	F	P	df	F	P
PS	0–10 cm	4	12.144	0.010	4	2.750	0.089	4	2.524	0.107	4	0.944	0.478
S		3	35.594	0.000	3	54.005	0.000	3	208.301	0.000	3	18.282	0.000
PS × S		12	6.509	0.000	12	1.541	0.164	12	1.158	0.355	12	0.437	0.935
PS	10–20 cm	4	3.671	0.043	4	6.407	0.008	4	1.170	0.380	4	0.774	0.566
S		3	13.804	0.000	3	258.460	0.000	3	473.766	0.000	3	18.955	0.000
PS × S		12	5.082	0.000	12	10.275	0.000	12	0.971	0.465	12	0.503	0.896
PS	20–40 cm	4	15.050	0.000	4	0.880	0.510	4	2.297	0.131	4	1.016	0.444
S		3	1.930	0.146	3	21.177	0	3	250.247	0.000	3	10.397	0.001
PS × S		12	3.682	0.002	12	1.242	0.302	12	1.651	0.130	12	1.151	0.359
PS	40–60 cm	4	9.007	0.002	4	1.047	0.431	4	2.724	0.091	4	1.273	0.343
S		3	5.368	0.004	3	20.026	0.000	3	210.904	0.000	3	30.726	0.000
PS × S		12	5.059	0.000	12	1.658	0.128	12	2.444	0.023	12	2.903	0.037
PS	60–100 cm	4	3.846	0.038	4	0.821	0.541	4	0.177	0.945	4	0.638	0.647
S		3	7.219	0.001	3	23.792	0.000	3	61.130	0.000	3	9.400	0.000
PS × S		12	4.909	0.000	12	4.683	0.000	12	0.441	0.933	12	0.974	0.494

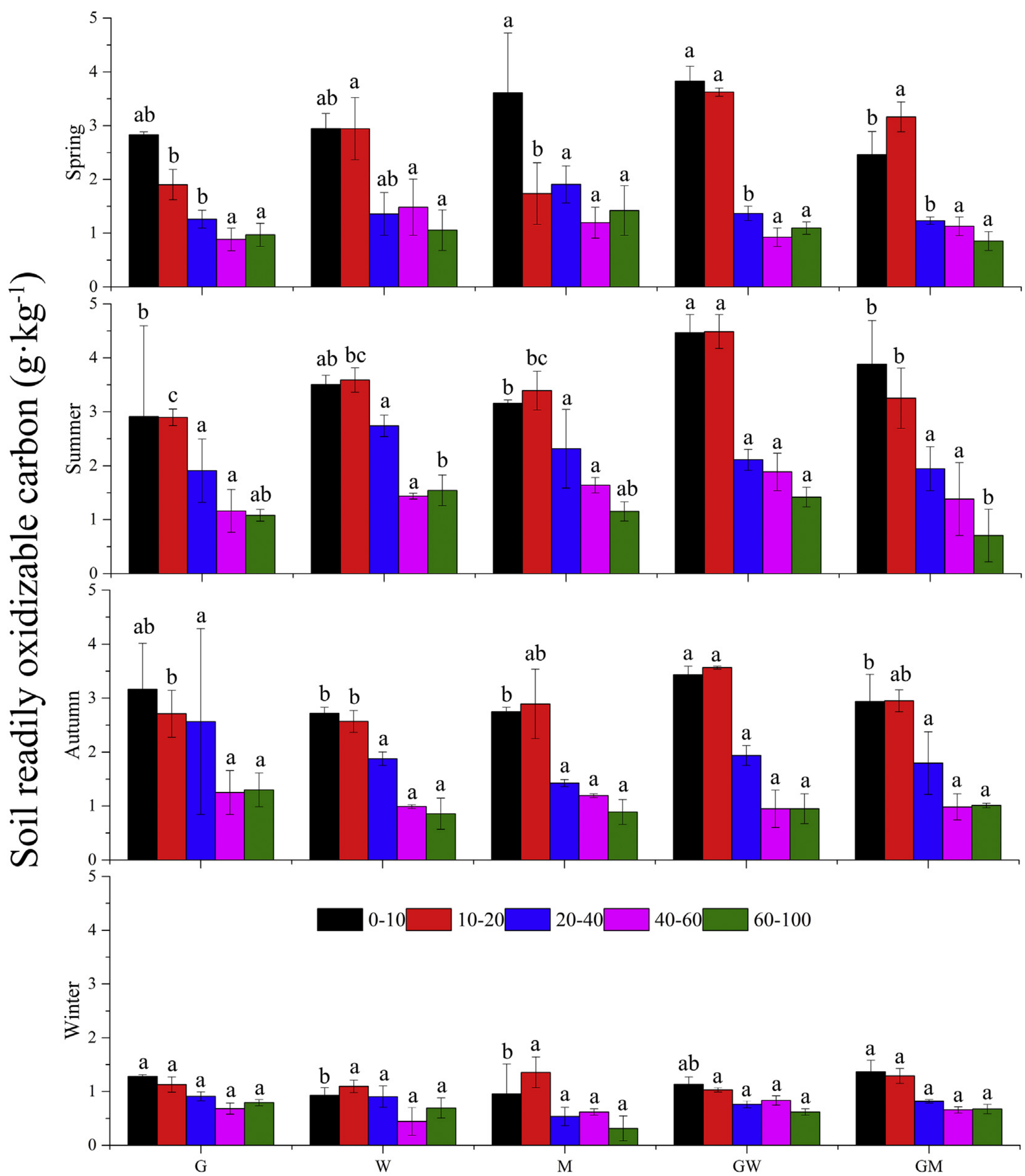

Fig. 2. Seasonal variations in ROC at different depths (0–10, 10–20, 20–40, 40–60, and 60–100 cm) in different planting systems. Different lowercase letters indicate significant differences among planting systems for the same soil layer and season based on Duncan's multiple comparison test at $P < 0.05$.

summer, no significant differences were observed in all layers among the five systems, and the highest WSOC content was measured in the GW system. In autumn, the WSOC content was significantly higher in the GW and M treatments when compared with the G, W, and GM treatments at a depth of 20–40 cm, and the highest average WSOC content was measured in the GW treatment. A significant interaction between planting system and season was only observed in the 40–60-cm layer (Table 2).

3.4. MBC contents across planting systems

Changes in MBC along the soil depth chronosequence were different from those of the three other C pools (Fig. 4). The ANOVA results showed that the MBC contents in the G and GM systems were significantly higher than those of the other systems at depths of 0–10, 20–40, and 40–60 cm in spring. In general, the highest MBC content was observed in the GW system, i.e., 127.3 mg kg^{-1}, which was significantly higher than that in the M system in summer at a depth of 0–10 cm. There were no significant variations in the soil MBC content among the five systems across subsoil layers in summer, autumn, and winter (10–100 cm). The ANOVA results showed that the seasonal dynamics of the MBC content were significant ($P < 0.01$). The MBC content was much lower in winter than at other times of the year and was highest in autumn. Across all soil layers, the MBC content in autumn was 6–11 times higher than that in winter. A significant interaction between planting system and season was only observed in 40–60-cm layer (Table 2).

3.5. Correlations between soil properties and soil C pools

Correlations among soil organic fractions and soil properties across the five planting systems were analyzed at a depth of 0–100 cm (Table 3). Significantly positive correlations were observed among SOC and total porosity, AN, and NN ($r = 0.365$, 0.297, and 0.637, respectively, $P < 0.01$). pH was negatively correlated with SOC and ROC ($r = -0.440$ and -0.233, $P < 0.01$ and $P < 0.05$, respectively).

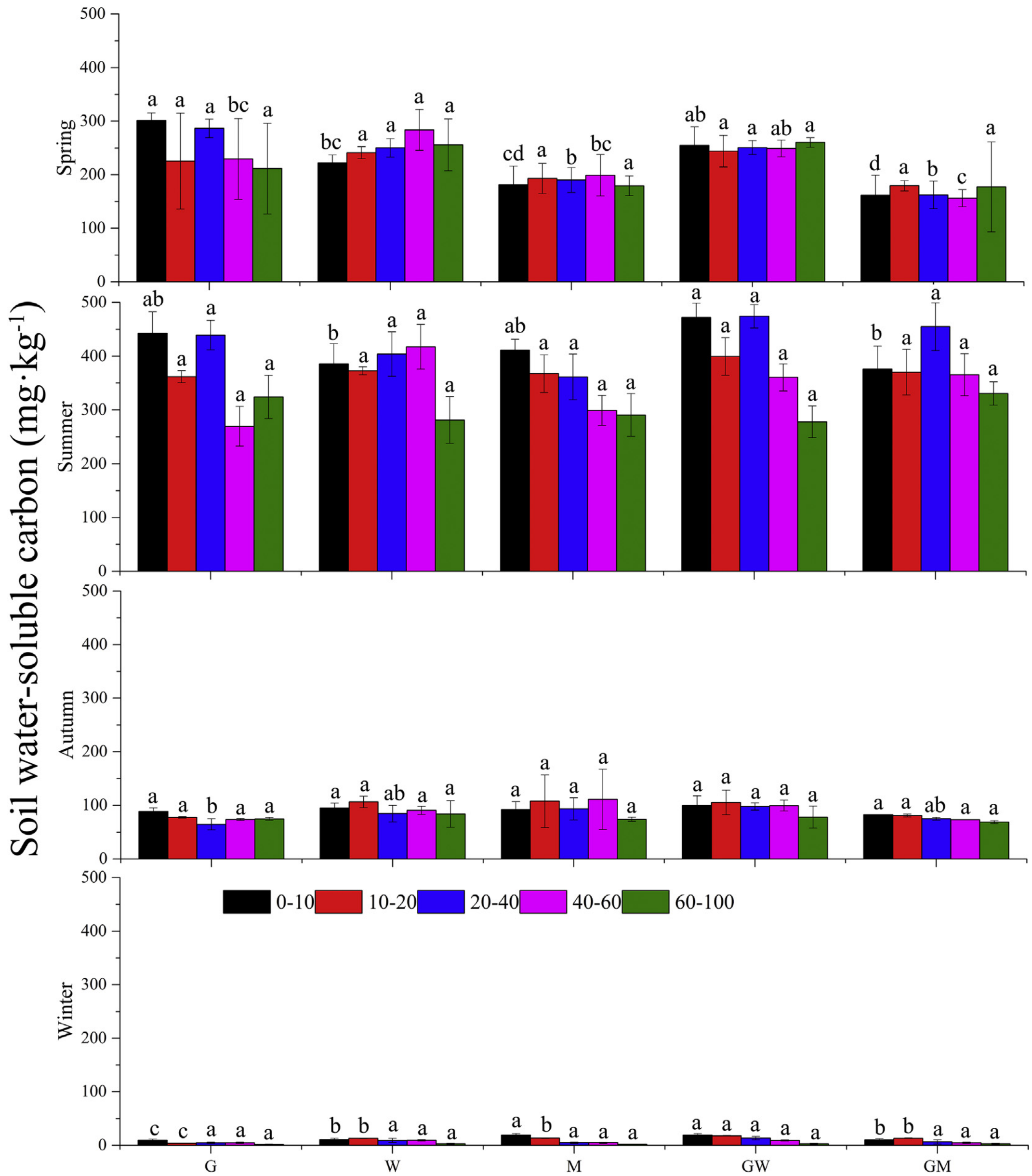

Fig. 3. Seasonal variations in WSOC at different depths (0–10, 10–20, 20–40, 40–60, and 60–100 cm) in different planting systems. Different lowercase letters indicate significant differences among planting systems for the same soil layer and season based on Duncan's multiple comparison test at $P < 0.05$.

There was a significant correlation between ROC and other soil properties. In addition, WSOC was positively correlated with all soil properties ($P < 0.05$), and MBC was positively correlated with all soil properties except AN.

4. Discussion

Tree components, understory plant components, and soil C pools in agroforestry systems can be considered of great importance for decreasing carbon dioxide in the atmospheric C pool (Hergoualc'h et al., 2012). Soil C is the most stable pool that receives organic inputs (leaf litter, root exudates, and straw) from trees and intercrops (Marone et al., 2017). Among the five studied planting systems in the present study, the highest mean SOC content in spring, summer, and winter was measured in the ginkgo and wheat system. A significantly higher SOC content was measured in the ginkgo and wheat system than in the other systems at depths of 0–10 and 10–20 cm throughout the year (Fig. 1). Several previous studies also showed that the influence of different land uses on the SOC content was the greatest in the topsoil (0–20 cm) (Fang et al., 2012; Tesfaye et al., 2016). In general, the higher surface SOC content in the ginkgo and wheat system can be attributed to soil litter inputs, which are mainly concentrated at the surface, and wheat fine root decomposition, especially because the maximum wheat rooting depth is 20 cm (Zhao et al., 2018). This is in line with the results presented by Chang et al. (2012), who proposed that fine root systems might play a key role in SOC distribution and accumulation at different depths. However, Zhang et al. (2016) reported that root decomposition had negative effects on plant growth and soil C inputs due to the release of phytotoxic compounds and the breeding of soil-borne pathogens. The locally applied summer maize no-tilling sowing method may contribute to the increase in the surface SOC content, while litter residue availability and the decomposition rate have been reported to decrease with an increase in soil depth (Hassan et al., 2016; Li et al., 2018). The aboveground biomass in pure ginkgo and metasequoia systems can be greater than that in a wheat field, while the relatively limited tree litter input may decrease the SOC content. With respect to belowground

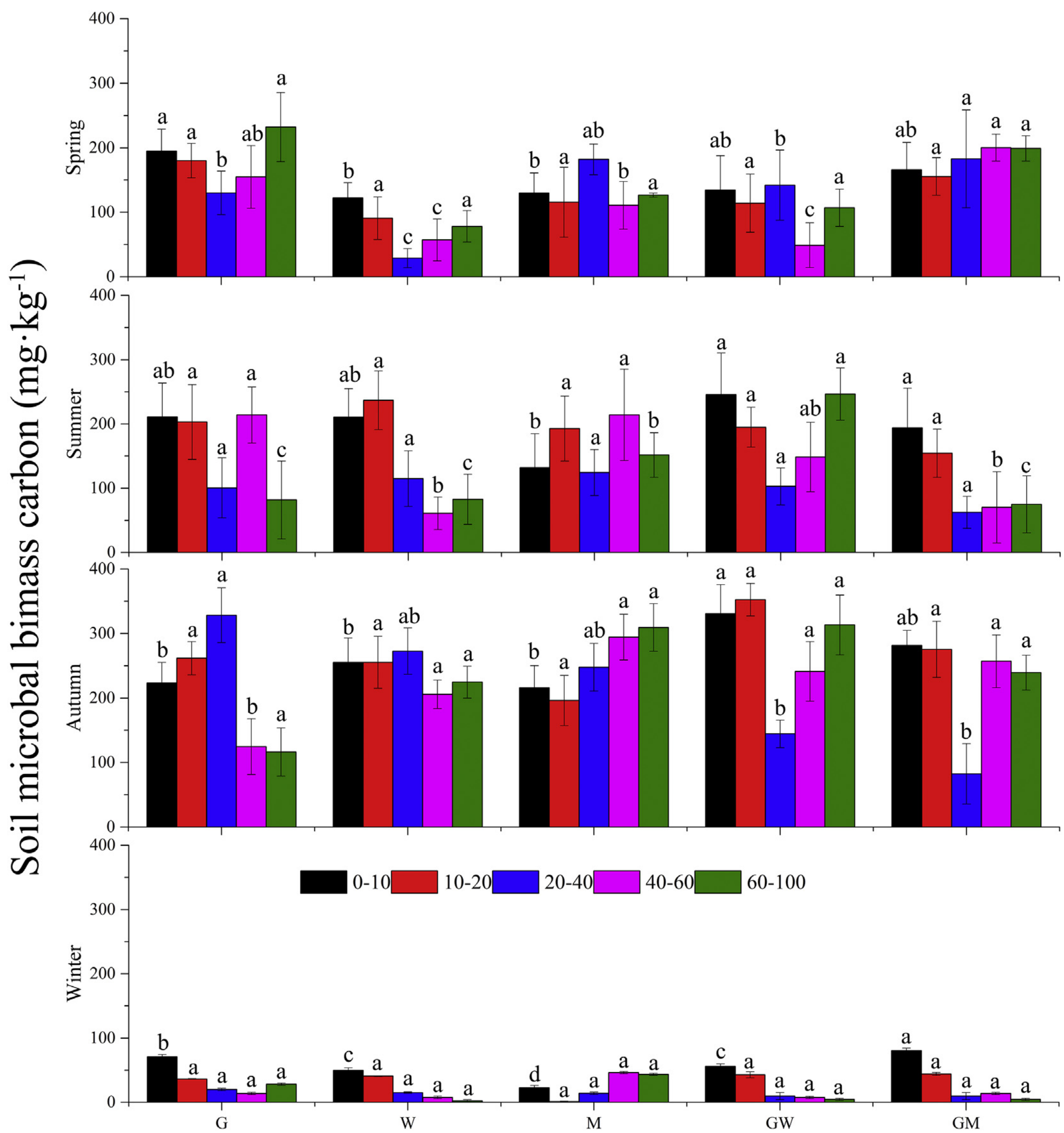

Fig. 4. Seasonal variations in MBC at different depths (0–10, 10–20, 20–40, 40–60, and 60–100 cm) in different planting systems. Different lowercase letters indicate significant differences among planting systems for the same soil layer and season based on Duncan's multiple comparison test at $P < 0.05$.

biomass, a greater fine root biomass of annual crops in a pasture system was observed relative to a plantation system (Li et al., 2017).

In accordance with previous studies, the SOC content was greatly influenced by seasonal variations (Wuest, 2014; Liu et al., 2015). The SOC content along the soil depth chronosequence showed a similar distribution tendency in all planting systems, i.e., a sharp decline below the 10–20-cm layer. Below a depth of 20 cm, no significant differences were observed in the SOC content in the bottom three layers in summer (Fig. 1), whereas slight differences were observed in the other seasons. This may be related to the following: the main sources of deep SOC are probably root exudates in systems that contain perennial plants and translocation from topsoil in systems that contain annual crops (Gao et al., 2017). Another explanation for this phenomenon is the presence of more dynamic microorganisms in the upper soil that play a pivotal role in soil C cycling. Higher SOC contents were measured in the subsoil of the wheat system and the ginkgo and wheat system. This may be attributed to the relatively high annual precipitation (1044 mm), relatively high soil moisture content and the high hydraulic conductivity, which result in high organic C translocation to deep soil layers (Zhao et al., 2014). The high SOC content in spring in the pure ginkgo system

Table 3
Correlation coefficients (r) between soil organic carbon and basic soil properties at a depth of 0–100 cm across the five planting systems.

	Soil temperature	Water content	Total porosity	Ammoniacal nitrogen	Nitrate nitrogen	pH
SOC	0.145	−0.098	0.365**	0.297**	0.637**	−0.440**
ROC	0.547**	0.483**	0.631**	0.241*	0.574**	−0.233*
WSOC	0.796**	0.377**	0.526**	0.288**	0.687**	0.354**
MBC	0.540**	0.580**	0.503**	−0.093	0.365**	0.247*

* Significant differences at the 0.05 probability level.
** Significant differences at the 0.01 probability level.

was probably due to the fallen leaves from the previous autumn that decomposed rapidly as a result of the warm spring.

MBC, ROC, and WSOC are important components of soil labile C pools. In this study, the MBC content in the surface layer in summer and autumn was significantly higher in the ginkgo and wheat system than in the other systems. In perennial tree-based cropping systems, i.e., the ginkgo and wheat system in this study, a large proportion of root biomass (mainly fine roots and root hairs) is mainly distributed in the topsoil and thus creates larger labile C pools compared to systems that contain only annual crops (Culman et al., 2010; Hurisso et al., 2014; Rasse et al., 2005). Kaul et al. (2010) demonstrated that MBC was 42% higher in perennial tree-based systems than in mono-cropped systems. This indicated that wheat mechanization seeding technology reduced the MBC content by affecting the moisture content and soil aeration of wheat fields (Beare et al., 1994; Salinas-García et al., 2002), and less fresh organic matter inputs decreased the MBC content by reducing essential energy substrates for microbial survival in mono-planting systems (Fontaine et al., 2007).

In accordance with previous studies that showed the variation trend of WSOC differed from that of other labile C fractions, the WSOC content did not vary significantly among planting systems (Sharma et al., 2014). In addition, the WSOC content did not vary significantly with increasing soil depth across the five planting systems ($P > 0.05$). A significantly higher WSOC content was measured in summer than in the other seasons in the five planting systems ($P < 0.05$). A previous study indicated that a rapid increase in the soil WSOC content depended on the input of soluble plant residues, and the WSOC content rapidly returned to a low level due to the rapid decomposition of soluble residues (Franchini et al., 2001). Another reason explaining the rapid decrease in autumn is the high amount of rain in summer, which greatly impacted WSOC leaching. This is in accordance with the explanation proposed by Jiang et al. (2006), i.e., that the WSOC content is mainly controlled by precipitation. Compared with the MBC and WSOC contents, a higher ROC content in all systems may be due to the relatively slower turnover rate of ROC than that of the other labile C fractions (Xiao et al., 2015). The ROC content exhibited a decreasing trend along the soil depth chronosequence, which might be due to the spatial distribution of crop straw that was concentrated on the soil surface (Liao et al., 2007).

Soil labile C exhibited seasonal variation, and a comparatively lower value of soil labile C was consistently observed in winter. Possible reasons include the low soil temperature and weakened activity of microorganisms in winter. The highest ROC and WSOC contents were observed in summer. This was possibly due to the high quality organic matter inputs that promoted microbial activity and then increased the labile carbon pools (Cheng et al., 2008; Jia et al., 2010). The highest MBC content was observed in autumn, which is consistent with previous studies that indicated fertilizer application before sowing may accelerate plant residue decomposition and promote microbial activity (Jiang et al., 2006; Liu et al., 2015). Moreover, changes in soil physical and chemical properties and root exudates can certainly affect microbial quantity and activity (Chen et al., 2004). A previous study reported that rhizodeposition exerted an important impact on the MBC content (Sanaullah et al., 2011). Different planting systems result in different C inputs into the soil, and agroforestry systems apparently result in the highest C input to the soil (Smith, 2008).

Significantly positive correlations were observed among soil labile C fractions and soil properties. WSOC and ROC are believed to be closely connected to organic matter decomposition driven by microbes (Marschner and Bredow, 2002). Furthermore, soil water and temperature play important roles in plant and microbial growth by acting as a medium or by influencing microbial activities (Joergensen et al., 1990). pH was negatively correlated with SOC and ROC, which is in accordance with a previous study (Hurisso et al., 2014).

5. Conclusions

In this study, vertical and seasonal variations of SOC and labile C fractions were compared among ginkgo agroforestry systems in eastern China. Our results indicated that planting system significantly affected the vertical and seasonal distribution of SOC and the labile C pools (ROC, WSOC, and MBC). Among the five planting systems, the ginkgo and wheat system had a significantly higher SOC content throughout the year. In addition, the greatest differences in SOC were observed in surface soil, and considerable variations were also observed in deeper soil layers. The results suggest that agroforestry systems result in greater increases in soil C sinks; in particular, the ginkgo and wheat system achieved the best results. MBC and ROC showed similar vertical and seasonal variations, and the highest WSOC content was observed in summer at a depth of 0–10 cm. Pearson's correlation results showed that the basic soil properties of these labile pools played key roles in the formation of soil C. Overall, this study provides valuable information on the seasonal and vertical dynamics of SOC in eastern China that may contribute to our understanding of SOC sequestration. Although the timescale of this study was limited, this year-long study clarifies that the soil labile carbon pools in agroforestry are dependent on time and depth and encourages further research using a much longer timescale.

Compliance with ethical standards

Conflict of interest

The authors declare that they have no conflict of interest.

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