



Changes in soil moisture and organic carbon under deep-rooted trees of different stand ages on the Chinese Loess Plateau

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ABSTRACT

Deep-rooted plants have increasingly been introduced after cropland abandonment with the implementation of the 'Grain-for-Green' program on the Chinese Loess Plateau (CLP). However, the temporal patterns of soil moisture content (SMC) and soil organic carbon (SOC) with stand ages and the potential role of deep roots driving these patterns within deep profiles are still poorly understood. Here, we investigated variations in fine root distribution, SMC, and SOC content and density in 0–500 cm soil profiles under two deep-rooted plant systems with different stand ages (black locust plantation, *Robinia pseudoacacia* L.; and apple orchard, *Malus pumila* Mill.), evaluated their soil moisture deficit (SMD) and SOC sequestration effect relative to cropland, and attempted to characterize the role of deep roots in driving these variations. The results confirmed severe SMD in all soil layers within the 0–500 cm profile under black locust plantations, relative to cropland, but noting some SMC recovery under the 38-year-old black locust plantation. In contrast, depth-averaged (0–500 cm) SMC increased notably during the initial 5 years and then declined continuously over time under apple orchards. These results suggest the temporal pattern of SMC varies with deep-rooted systems. The SOC density of the 100–500 cm layer accounted for more than half of the entire profile, and SOC accumulation mostly occurred at depths below 300 cm under the two deep-rooted systems, which indicates the great importance of deep soils for carbon sequestration. The temporal patterns of deep SOC were different from those in surface soils. Obvious carbon losses were detected within the 20–500 cm soil profile under the 38-year-old black locust plantation. The linkages between SMC and SOC content were typically stronger under black locust plantations than under apple orchards. The influence of roots on SMC was stronger under apple orchards than under black locust plantations. Suitable land management practices are recommended to restore the fragile ecosystem of the CLP. Overall, our findings provide new insights for sustainable vegetation restoration in restored ecosystems.

1. Introduction

Vegetation restoration is one of the most effective measures to alleviate soil and water losses (Huang et al., 2003; Wang et al., 2015a), prevent land degradation (Liu et al., 2008), and improve biodiversity (Elbakidze et al., 2011), soil quality (Mobley et al., 2015) and ecological environments. Vegetation restoration after farmland abandonment has been confirmed to alter soil functions and quality by changing the litter input, plant species composition, and the physical, chemical and

biological properties of soils (Bárcena et al., 2014a; Deng et al., 2014; Laganier et al., 2010).

The Chinese Loess Plateau (CLP) is a typical water-limited region and has suffered severe soil erosion that has intensified the fragility of the local ecology (Fu et al., 1989; Jia et al., 2017). A large-scale "Grain-for-Green" program (GGP) initiated across the CLP since 1999 has dramatically altered the landscape, with the conversion of croplands on sloping land into woodlands, shrublands, or grasslands. Black locust (*Robinia pseudoacacia* L.), an exotic N-fixing tree species, was introduced

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and is one of the most extensively planted tree species on the CLP owing to its strong drought and poor nutrient resistance, as well as its high survival and rapid growth rates (Jin et al., 2011; Rice et al., 2004). Furthermore, apple tree cultivation was encouraged by the government to increase the incomes of local households to partly offset the economic losses resulting from the areal decrease of cropland with the implementation of the GGP. By 2016, the apple crop on the CLP had grown significantly, with coverage and apple yield accounting for 25.2% and 26.3% of global totals, respectively (Wang et al., 2020). Both black locust and apple trees are characterized by deep roots. Expansive plantations of these deep-rooted trees are expected to have inevitably altered hydrological processes (Jackson et al., 2005) and carbon sequestration dynamics (Farley et al., 2005; Yang et al., 2020) of deep soil layers. Hence, an improved understanding of the responses of soil moisture and carbon sequestration to the expansive plantations of these deep-rooted trees is urgently needed to provide insights into sustainable water resource, ecosystem service, and vegetation management practices.

Soil moisture content (SMC) could be affected by the expansive plantations of deep-rooted trees (Jia et al., 2017; Jin et al., 2011; Yang et al., 2012). The balance between soil moisture supply and consumption by plants is of great importance for sustainable and healthy ecosystems, especially in water-limited regions. Increasing attention has been paid to the response of SMC to afforestation following cropland abandonment over time with some negative effects found. For example, SMC declines after tree planting (Yaseef et al., 2010) and severe desiccation is observed in deep soil layers on the CLP (Jia et al., 2017; Yang et al., 2020). This can primarily be attributed to excessive soil moisture depletion accompanied by long-term weak replenishment of deep layers from precipitation which typically recharges the shallow layers (0–200 cm deep) (Chen et al., 2008; Suo et al., 2018). Furthermore, intensive vegetation planting exceeding the limited soil water availability also aggravates water scarcity in deep soils. Deep-rooted plants consume more deep soil moisture than conventional cropland due to their well-developed and deeper root systems and higher evapotranspiration rates (Jia et al., 2017; Li et al., 2019; Yang et al., 2020), and therefore can suffer severe drought stress with soil desiccation (Zhang et al., 2020). However, the temporal variation patterns of SMC within the deep soil profile with stand age are species- and sites- specific and vary with plant growth intensity under deep-rooted tree plantations. For example, SMC within the deep profile progressively declined with increasing stand age under afforested black locust plantations in areas where the mean annual precipitation (MAP) was less than 500–550 mm (Liang et al., 2018) and under apple orchards in a semi-humid region on the CLP (Li et al., 2019). However, Li et al. (2021) synthesized 5668 observations on the CLP from peer-reviewed publications and demonstrated the deep SMC (0–1000 cm) continuously decreased during the first 20 years but then remained relatively stable after 20-year growth under planted forests. Jia et al. (2017) observed that depth-averaged (0–500 cm) SMC declined gradually in the first 20–25 years of growth and then recovered with increasing stand age over 25 years of growth in black locust plantations on the CLP. A similar temporal pattern of SMC was also reported under apple orchards, with SMC recovering after 29 years of growth within the 0–1000 cm soil profile (Liu et al., 2020b). These conflicting reports indicate further research efforts are urgently needed to determine the soil moisture dynamics over time throughout deep profiles on the CLP under the continuous expansive plantations of deep-rooted trees after cropland abandonment.

Soils hold the largest carbon pool in terrestrial ecosystems and soil organic carbon (SOC) is a key characteristic of soil quality (Batjes, 1996; Lal, 2004). Reports on the temporal patterns of SOC in response to tree planting after cropland abandonment indicate inconsistent results. For example, SOC increased in the surface soil layer (0–20 cm) after *Robinia pseudoacacia* L. afforestation on the CLP (Liu et al., 2018), but initially (0–30 years) decreased and then gradually increased with stand age to net carbon gains in later stages in the 0–20/30 cm layer after tree planting in northern Europe (Bárcena et al., 2014a). Li et al. (2019)

demonstrated that converting long-term cropland to apple orchards failed to cause significant deep SOC changes on the CLP. Likewise, no obvious mineral soil carbon pool changes in the 10–50 cm soil layer were observed under poplar plantations with increasing stand age in the United States (Sartori et al., 2007). However, most current studies mainly focus on temporal variations in SOC in the upper 100 cm but ignore deeper soils where plant roots can exert a significant influence on SOC dynamics. Deep soils typically have a low SOC content, yet a notable quantity (> 50%) of SOC is still stored in deep soil layers (below 100 cm) (Han et al., 2018; Harper and Tibbett, 2013; Li et al., 2020). Furthermore, deep soils exhibit a different carbon cycling process than topsoil (Bernal et al., 2016; Harper and Tibbett, 2013) and are more susceptible to variations in the external environment (e.g., water stress, anthropogenic perturbation) than previously thought (Bernal et al., 2016; Dietzen et al., 2017; Shahzad et al., 2018). Therefore, the temporal patterns of SOC might be distinct when incorporating the previously overlooked deeper soil layers (Dietzen et al., 2017; Harper and Tibbett, 2013; Li et al., 2020).

Deep SOC dynamics are primarily mediated by below-ground root residues and rhizodeposition (Davidson et al., 2011; Hirte et al., 2018), which contribute to the magnitude and vertical distribution patterns of SOC. In water-limited regions, translocation rates for nutrient-rich materials from top soils to deep layers are low, and therefore the main carbon sources in deep layers are root-introduced C via root exudation (e.g., enzymes, organic acids), mycorrhizal associations, and root tissue mortality (Davidson et al., 2011; Gao et al., 2017). Nevertheless, the increase in below-ground roots does not always foster SOC accumulation but can lead to SOC losses in deep soil layers over time. Specifically, the root penetration gradually breaks the soil aggregates and improves oxygen diffusion rates of soils (Mueller et al., 2016). The stimulated soil microbial activities resulting from the labile C inputs can enhance SOC mineralization, known as the “priming effect” in plant-soil systems (Blagodatskaya et al., 2011). Furthermore, root exudates (i.e., oxalic acid) also lead to carbon losses by liberating mineral-protected organic compounds (Keiluweit et al., 2015). Indeed, the persistence of microorganisms has been confirmed in soils to depth of 180 cm in a forested montane watershed in Colorado, USA (Eilers et al., 2012), as well as in deeper soils (to depth of 20 m) in a semi-arid region on the CLP (Liu et al., 2020a). Overall, it is unclear how deep SOC on the CLP will respond over time to the expansive plantation of deep-rooted trees after cropland abandonment.

Therefore, objectives of this study were to: (1) investigate the temporal patterns and the degree of soil moisture deficit within deep soil profiles; (2) determine if temporal patterns of SOC in deep soil layers are similar to those of shallow layers with increasing stand age; and (3) analyze the linkages among SMC, SOC, and root parameters for deep-rooted trees with different stand ages on the CLP. Black locust plantations and apple orchards with different stand ages were selected within a gully watershed on the CLP for this study, the results of which are expected to help determine optimal management practices for the sustainable management of fragile ecosystems around the world.

2. Materials and methods

2.1. Study site

The study site is located in the Wangdonggou watershed (35°12' N – 35°16' N, 107°40' E – 107°42' E; total area 8.3 km²), Changwu County, Shaanxi Province, China (Fig. 1). This small watershed is in the gully regions of the CLP, which is characterized by a continental monsoon climate, a mean annual temperature of 9.0 °C, and annual precipitation of 571 mm (average from 1968 to 2018), most (more than 58%) of which falls between July and September (Duan et al., 2016). The soils are developed from wind-deposited loess and are classified as Cambisols according to the World Reference Base for Soil Resources (WRB) (Wang et al., 2017). The cropland, apple orchard, woodland, and grassland

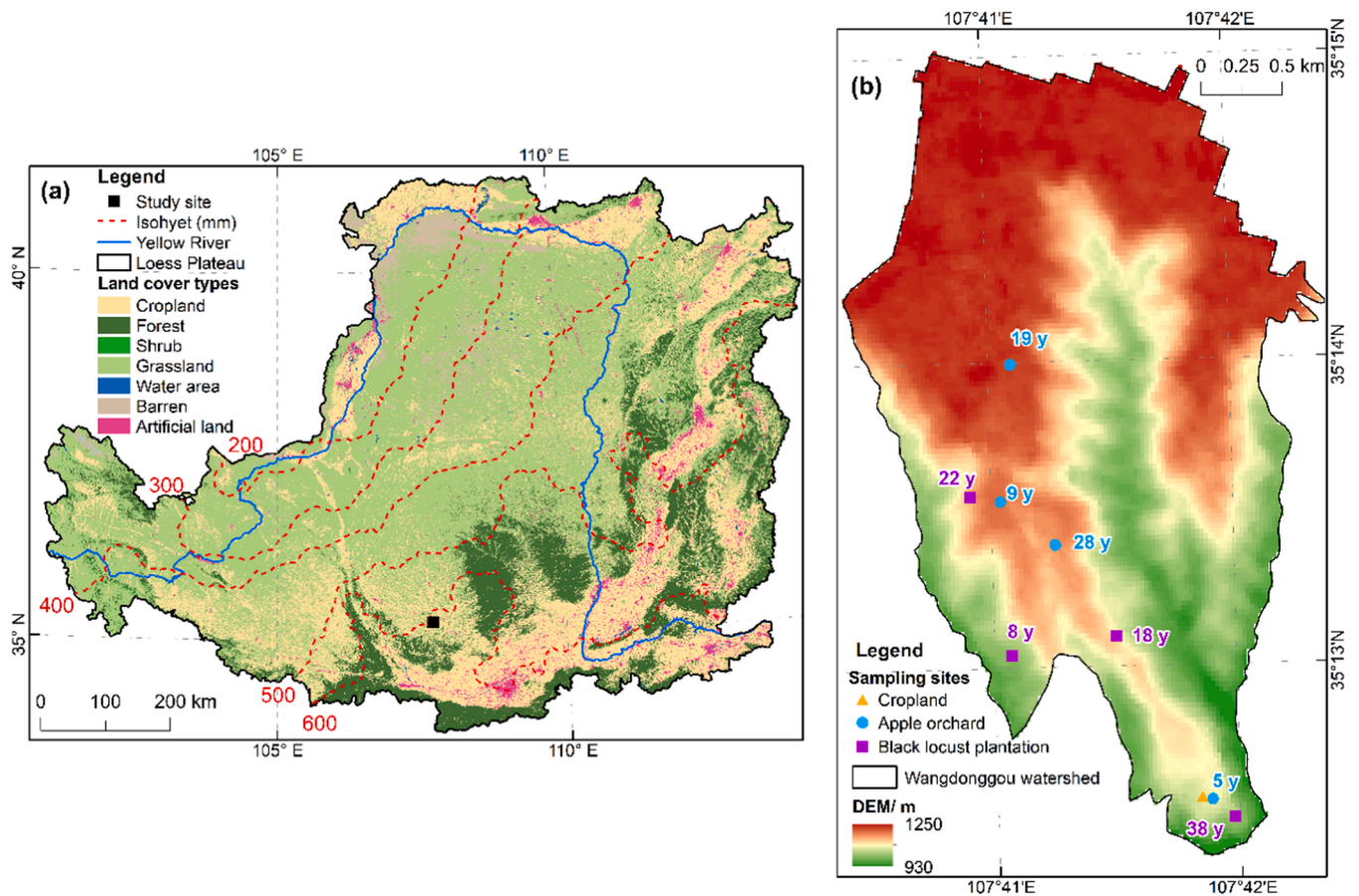


Fig. 1. Location of the study area (a) and soil sampling sites (b) in the Wangdonggou watershed.

represent the predominant land use types in this region. The water source for vegetation growth is precipitation without irrigation in this region.

2.2. Field survey and soil sampling

A space-for-time substitution (chronosequence) approach was used to select sampling sites with various stand ages to serve as alternatives of time series for predicting the long-term SMC and SOC dynamics (Blois et al., 2013; Bárcena et al., 2014b) under deep-rooted trees after cropland abandonment.

Two representative deep-rooted plant ecosystems, black locust (*Robinia pseudoacacia* L.) plantations and apple orchards (*Malus pumila* Mill.), were selected in Wangdonggou watershed to evaluate their moisture deficit and SOC sequestration capacity. The black locust trees were planted since the mid-1970s in Wangdonggou watershed for reducing soil and water losses and subsequently planted for restoring ecological environment with the implementation of a series of soil and water conservation measures, especially the GGP. While, the oldest age for apple trees in the study area is usually no more than 30. Specifically, the old apple trees are usually cut down and replaced by crops for minimizing economic losses because the quantity and quality of fruits declines when the age of apple trees is greater than 25. Based on the field investigation, four available black locust forest stands aged 8, 18, 22, and 38 years (subsequently referred to BL8, BL18, BL22, and BL38, respectively) and four available apple orchard stands aged 5, 9, 19, and 28 years (subsequently referred to AO5, AO9, AO19, and AO28, respectively) were selected for this study. The stand ages of the black locust plantations were determined by consulting official records and confirmed by checking tree rings using a Pressler increment borer. Ages of apple orchards were determined from owner records. All selected

black locust plantations and apple orchards had been converted from cropland. Therefore, a long-term (> 60 years) cultivated slope cropland (spring maize, *Zea mays* L.) was selected as the reference site (control) to represent the pre-afforestation SMC and SOC profile conditions. All the selected sampling sites, their absolute distances not larger than 3.1 km, had the same parent materials (Duan et al., 2016; Wang et al., 2017) and are located at the sloping land in the small watershed. Particle size measurements showed distribution of soil clay and silt contents in the soil profiles was fairly consistent among all sampling sites (Fig. S1). Moreover, the selected sampling sites had similar topological conditions (altitude, slope gradients and aspects) and land use history (Table 1 and S1). Therefore, it was assumed that initial soil profile conditions across all sites were the same before revegetation and that any changes in soil moisture and organic carbon could primarily attributed to the establishment of deep-rooted plants after cropland abandonment.

The spring maize is seeded in April and harvested in September and the apple trees generally bloom in late March with apples harvested in October. Mineral (N, P, and K) fertilizers and manure were conventionally applied in croplands and apple orchards each year; the black locust plantations did not receive any fertilizer. Croplands and apple orchards were tilled each year with all aboveground residues removed (Wang et al., 2017). The anthropogenic perturbation of black locust plantations was less than for cropland and apple orchards. The understory vegetation within the black locust plantations was dominated by wheatgrass (*Agropyron cristatum* (Linn.) Gaertn.), Dahurian bush clover (*Lespedeza daurica* (Laxm.) Schindl.), green bristlegrass (*Setaria viridis* (Linn.) Beauv), etc.

In August 2019, three typical plots were established as replicates for cropland, four ages of black locust plantation, and four ages of apple orchard, following a randomized design. The plot size was 10 m × 10 m for black locust plantations and apple orchards and 1 m × 1 m for

Table 1
Characteristics of sampling sites in the Wangdonggou watershed of the Chinese Loess Plateau.

Land use types	Stand age (y)	Altitude (m)	DBH (cm)	Tree height (m)	Planting density (trees ha ⁻¹)	Litter biomass (Mg ha ⁻¹)	Dominant plant species
Black locust plantation	8	1007.3	5.42 ± 0.3	3.30 ± 0.1	5500	6.11 ± 1.1	<i>Robinia pseudoacacia</i> L.
	18	1088.4	11.70 ± 0.6	11.33 ± 0.4	2567	7.18 ± 1.4	
	22	1099.7	12.74 ± 0.7	12.78 ± 0.4	1700	8.02 ± 1.2	
	38	1034.6	18.57 ± 2.1	15.7 ± 0.5	533	9.68 ± 1.3	
Apple orchard	5	1060.1	4.25 ± 0.2	3.05 ± 0.1	625	–	<i>Malus pumila</i> Mill.
	9	1141.0	10.66 ± 0.4	3.38 ± 0.2	667	–	
	19	1178.0	15.01 ± 1.3	3.78 ± 0.2	833	–	
	28	1132.4	15.76 ± 0.2	3.69 ± 0.1	1000	–	
Cropland	> 60	1059.3	–	–	–	–	<i>Zea mays</i> L.

cropland. The root depth of the maize was shallow (Zhu et al., 2018) and we mainly focused on the soil moisture and organic carbon dynamics within deep soil profiles; therefore, the roots of maize were not taken into account and only roots under black locust plantations and apple orchards were collected in our study. Disturbed soil samples were collected at 20-cm intervals to a depth of 500 cm using a hand auger (90 mm in diameter) from three randomly selected soil cores (0.5–1.5 m distant from trees) within each sampling plot. A small amount of each soil sample was collected using aluminum boxes while sampling and then transported to the laboratory for soil moisture measurements. Another subsamples were stored in airtight plastic bags and then all replicates were mixed together to form one composite sample for the same soil layer per plot. The remaining subsamples from black locust plantations and apple orchards were washed carefully with tap water over a 0.25 mm sieve to collect fresh roots. Dead roots were recognized based on color (dark for dead roots vs. white for living roots) and discarded. Fine (≤ 2 mm) and coarse roots (> 2 mm) were separated from each other using a vernier caliper with only fine roots included in our further analysis. All isolated fine roots were oven-dried at 65 °C and then weighed to determine the dry root biomass. Root dry weight density (RDWD, g cm⁻³) was then calculated by dividing the dry weight of fine roots by the corresponding soil volume. All composite soil samples were air-dried at room temperature for soil particle size and SOC content analyses.

One 1 m × 1 m quadrat was set for each sampling plot within the black locust plantations, with all ground litter in quadrats collected to determine litter biomass in black locust plantations of different stand ages. At the time of sampling, the latitude, longitude, and elevation of sampling sites were recorded with a global positioning system (GPS) device. For each sampling plot, the slope gradient and aspect, diameter at breast height, tree height, tree density (trees ha⁻¹), and dominant vegetation species were recorded. Detailed information for the sampling sites is provided in Table 1 and S1.

Undisturbed soils are needed to measure the soil bulk density (BD), but the acquisition of such samples for deep soils was difficult. Therefore, one soil profile to a depth of 100 cm was dug in the center of each black locust plantation, apple orchard, and cropland to collect undisturbed soil samples. Specifically, undisturbed soils were collected from depths of 0–20, 20–40, 40–60, 60–80, and 80–100 cm (three replicates for each soil layer) using a stainless steel cutting ring (volume, 100 cm³).

2.3. Laboratory analyses

Soil particle size composition was analyzed by laser diffraction using a Mastersizer 2000 (Malvern Instruments, Malvern, England). Clay (< 0.002 mm), silt (0.002–0.05 mm), and sand (0.05–2 mm) were identified according to the United States Department of Agriculture classification. SOC content was determined using the Walkley and Black dichromate oxidation method (Nelson and Sommers, 1982). SOC density (SOCD, kg m⁻²) was converted from SOC content based on the following equation:

$$SOCD_i = SOC_i \times BD_i \times (1 - CF_i) \times D_i \times 0.01 \quad (1)$$

where $SOCD_i$, SOC_i , BD_i , and D_i denote SOC density (kg m⁻²), SOC content (g kg⁻¹), bulk density (g cm⁻³), and thickness (cm) of the i_{th} layer of soils, respectively. CF_i represents the volume percentage (%) of coarse fragments (> 2 mm) in the i_{th} soil layer, and this proportion could be considered zero and ignored (Han et al., 2018). The average BD value of the 60–100 cm soil layer was applied when calculating the SOC density in the 100–500 cm soil layer because no obvious differences were observed for BD values below 60 cm soil depth for each vegetation type in the study are (Zhang et al., 2013).

The soil moisture deficit (SMD) and SOC sequestration effect (SOCSE) relative to control values in deep soils were determined to evaluate how soil moisture and SOC change with the expansive plantation of deep-rooted trees. The SMD and SOCSE were calculated as follows:

$$SMD_{j,k} = \frac{SMC_{j,k} - SMC_{0,k}}{SMC_{0,k}} \quad (2)$$

$$SOCSE_{j,k} = \frac{SOCD_{j,k} - SOCD_{0,k}}{SOCD_{0,k}} \quad (3)$$

where $SMD_{j,k}$ and $SOCSE_{j,k}$ are the SMD and SOCSE of the k_{th} layer of the j_{th} vegetation type, respectively. $SMC_{j,k}$ and $SMC_{0,k}$ denote the SMC (%) of the k_{th} layer of the j_{th} vegetation type and control, respectively. $SOCD_{j,k}$ and $SOCD_{0,k}$ denote the SOC density (kg m⁻²) of the k_{th} layer of the j_{th} vegetation type and control, respectively.

2.4. Statistical analysis

One-way analysis of variance (ANOVA) was used to analyze the effects of deep-rooted tree systems (i.e., black locust plantation and apple orchard) with different stand ages and cropland on the RDWD, SMC, and SOC content and density. Two-way ANOVA was conducted to explore the interactive effects of stand age and soil depth on the RDWD, SMC, and SOC content and density, as well as the SMD and SOCSE, for black locust plantations and apple orchards. Differences were considered significant at $p < 0.05$ with a post-hoc least significant difference (LSD) test. The relationships among the SMC, SOC density, and root parameters were evaluated by nonparametric Spearman's test. All statistical analyses were conducted in SAS SystemV8 (SAS Inc., Cary, NC, USA).

3. Results

3.1. Characterization of root parameters

The RDWD differed with stand age and soil depth for both black locust plantations and apple orchards ($p < 0.01$; Table 2, Fig. 2). The overall RDWD tended to decrease with increasing soil depth, despite fluctuations throughout the 0–500 cm soil profiles under both tree species (Fig. 2). The fine roots were mostly concentrated in the upper

Table 2

Two-way ANOVA summary for the effects of stand age and soil depth on soil silt and clay content, root dry weight density, soil moisture content, and soil organic carbon content and density in black locust plantations and apple orchards.

	Source of variations/factors	Stand age		Soil depth		Stand age × soil depth	
		F value	Cont. (%) ^a	F value	Cont. (%)	F value	Cont. (%)
Black locust plantation	Root dry weight density	4.80**	1.05	41.5**	72.8	2.18**	11.5
	Soil moisture content	74.0**	38.2	2.12**	8.75	1.50*	18.6
	Soil organic carbon content	78.1**	3.82	200**	78.3	12.5**	14.6
	Soil organic carbon density	87.0**	4.92	172**	77.8	10.0**	13.6
Apple orchard	Root dry weight density	22.7**	11.1	10.2**	39.8	1.41*	16.6
	Soil moisture content	561**	76.2	8.20**	8.91	1.79**	5.84
	Soil organic carbon content	42.8**	3.58	119**	80.2	5.27**	10.6
	Soil organic carbon density	43.7**	3.31	135**	81.8	5.42**	9.84

Asterisks represent significant correlations (*, $p < 0.05$; **, $p < 0.01$). Significant contributions at $p < 0.05$ or $p < 0.01$ are bolded.

^a Cont. is an abbreviation for contribution, indicating the percentage of each factor explaining overall variance.

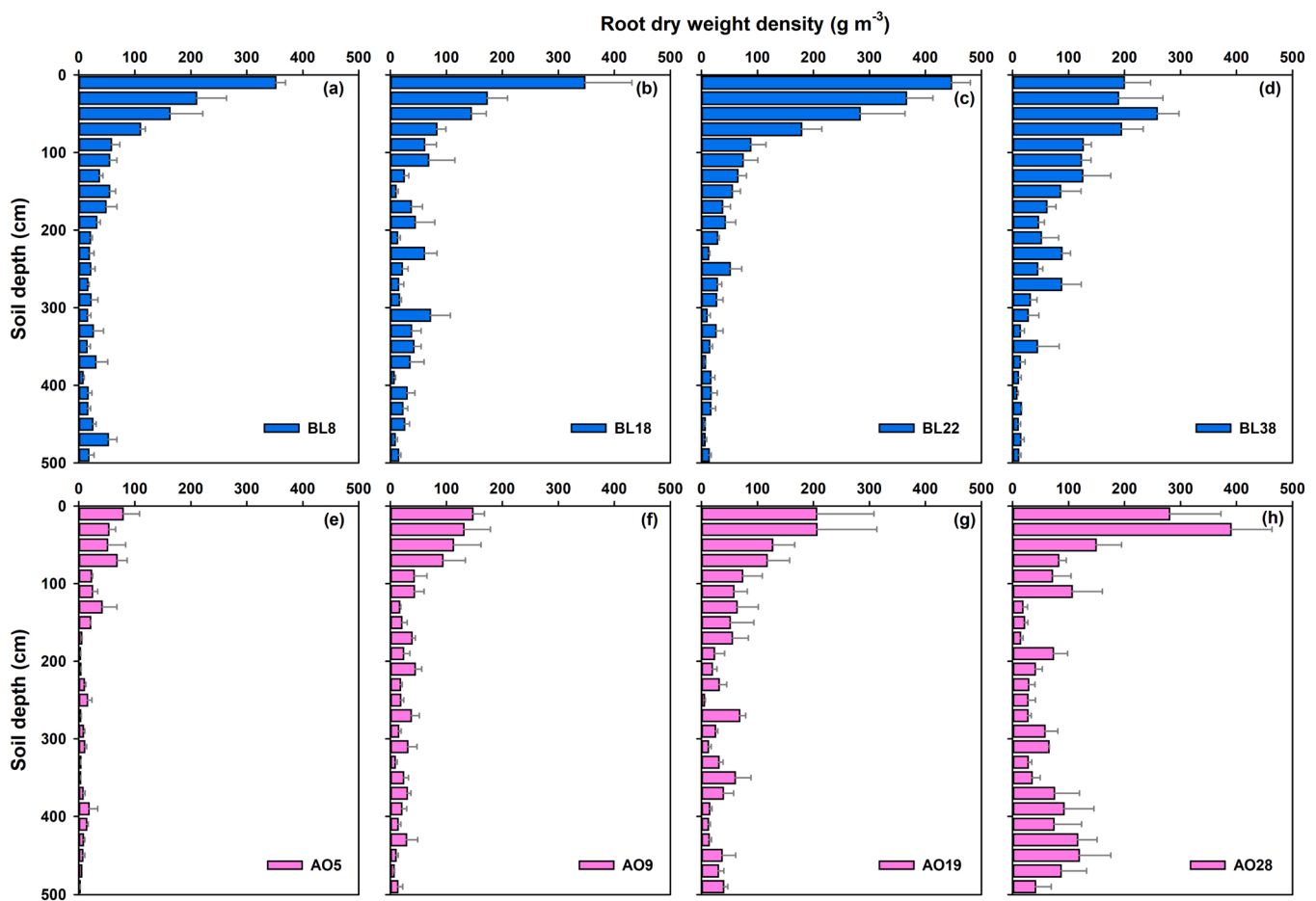


Fig. 2. Vertical distribution of root dry weight density (RDWD) in the 0–500 cm soil profile in black locust plantations (BL, a-d) and apple orchards (AO, e-h) of different stand ages. Error bars represent the standard error of the mean ($n = 3$).

200 cm soil layer under both species, but the deep soils (200–500 cm) still contained 14.5–29.0% and 23.6–41.7% of the total RDWD under black locust plantations and apple orchards, respectively (Fig. 2).

In black locust plantations, the fine roots in the upper 200 cm were more abundant at BL22 and BL38 compared to BL8 and BL18 ($p < 0.05$; Fig. 2). The RDWD at BL38 was 14.1% lower than at BL22 in the 0–200 cm layer, but this difference was not statistically significant. The RDWD exhibited few changes ($p > 0.05$) with increasing stand age across black locust plantations in the 200–500 cm soil layer. In contrast, an increasing trend in RDWD was detected in both the 0–200 cm and

200–500 cm soil layers with the increasing stand age in apple orchards; the RDWD at AO28 was significantly higher than that for younger apple orchards.

3.2. Profile SMC distribution and variation with stand age

The SMC profile was strongly affected by stand age and varied with soil depth for both black locust plantations and apple orchards ($p < 0.01$; Table 2, Fig. 3). For black locust plantations, the depth-averaged SMC exhibited a trend that declined initially and then

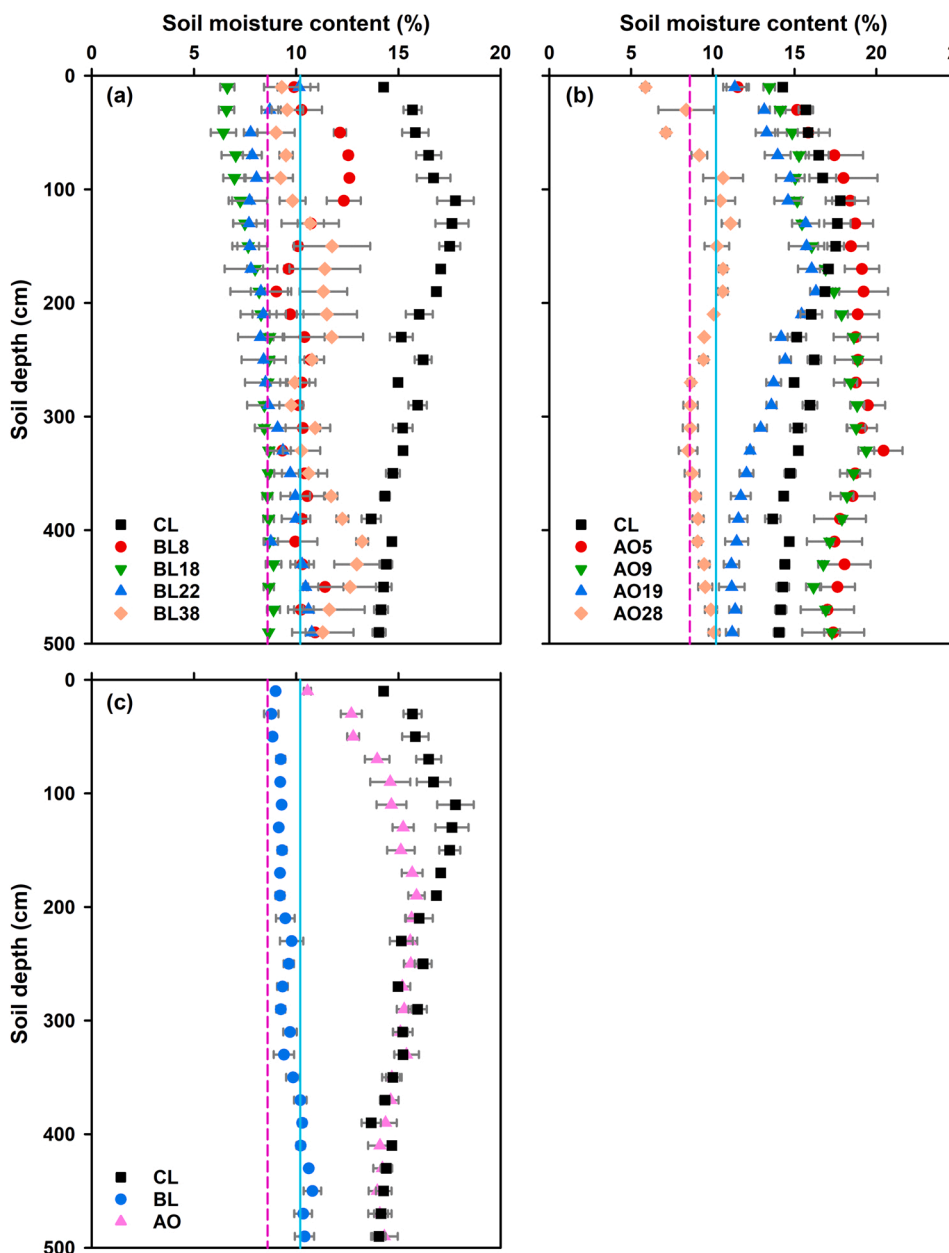


Fig. 3. Comparison of soil moisture content (SMC) between cropland (CL) and black locust plantations (BL) (a) and apple orchards (AO) (b) of different stand ages and the average SMC in BL and AO (c) within the 0–500 cm soil profile. Cyan (solid) and pink (dashed) lines denote the average stable field capacity (ASFC) and average permanent wilting point (APWP), respectively. Error bars represent the standard error of the mean ($n = 3$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

increased marginally with increasing stand age within the 0–500 cm soil profile. Specifically, the average SMC was lower (by 29.9–48.1%) under all black locust plantations than under long-term cultivated cropland within the 0–500 cm soil profile ($p < 0.05$; Fig. 3). The average SMC was the lowest (8.07%, less than average permanent wilting point) for BL18 compared to BL8 and BL38 ($p < 0.05$) and BL22 ($p > 0.05$) (Fig. 3). The coefficients of variation (CVs) varied within the range of 2.19–18.9%, 0.94–16.9%, 1.30–31.3%, and 3.83–27.5% for sites BL8, BL18, BL22, and BL38, respectively, in each 20 cm layer down to a depth of 500 cm (Fig. 3).

Compared to the black locust plantations, the depth-averaged SMC under apple orchards was typically much higher within the 0–500 cm soil profile ($p < 0.05$; Fig. 3). The average SMC at AO19 (14.0%) and AO28 (9.30%) was lower than at AO5 (17.9%) and AO9 (16.9%) ($p < 0.05$), with the lowest average SMC at AO28 approaching the average permanent wilting point (Fig. 3). Relative to the initial status (long-term cultivated cropland), the average SMC (0–500 cm) was 15.4% higher in the early growth stage (5 years old) of apple orchards, and 40.2% lower in the later growth stage (28 years old) ($p < 0.05$;

Fig. 3). The CVs of SMC varied within the range of 8.38–20.0%, 0.85–12.2%, 3.51–11.9%, and 2.40–35.3% for sites AO5, AO9, AO19, and AO28, respectively, in each 20 cm layer down to a depth of 500 cm (Fig. 3).

3.3. Vertical patterns of SOC content and density with stand age

The SOC content and density differed with stand age and soil depth, being highest in the top soil layer (0–20 cm) and then generally decreasing with increasing soil depth despite some fluctuations in black locust plantations and apple orchards (Table 2, Fig. 4). Furthermore, the variability of both SOC content and density were larger in the 0–100 cm layer than in the 100–400 cm layer (Fig. 4).

In the 0–20 cm soil layer of black locust plantations, the SOC content first showed a declining trend (not statistically significant) during the early stage (< 8 years), and then increased with increasing stand age; the SOC content at BL38 (13.9 g kg^{-1}) was significantly higher than for younger black locust plantations (BL8, BL18, and BL22) and cropland (Fig. 4). In terms of depth-averaged SOC content over the whole

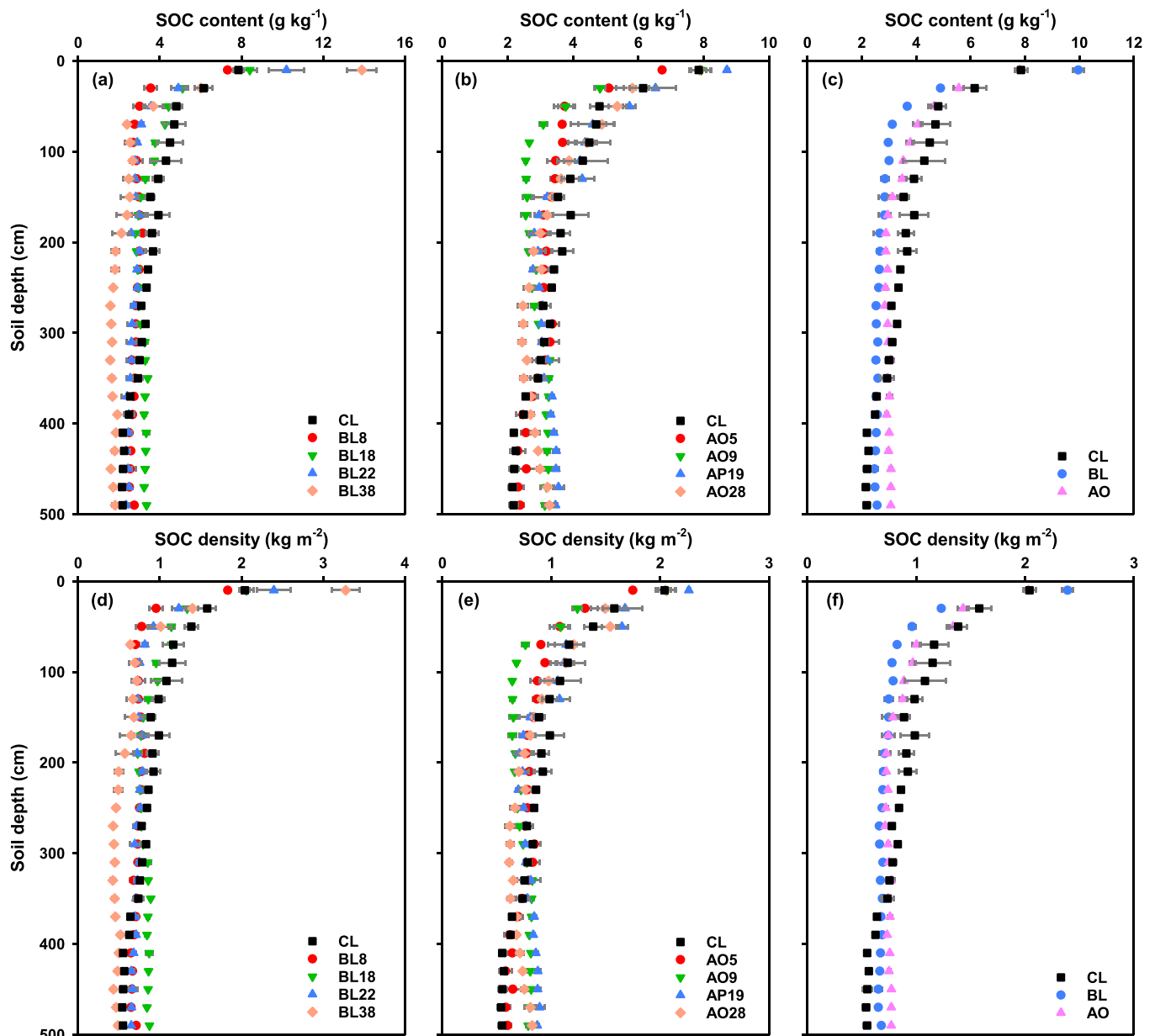


Fig. 4. Comparison of soil organic carbon (SOC) content between cropland (CL) and black locust plantations (BL) (a) and apple orchards (AO) (b) of different stand ages; average SOC content in BL and AO (c) within the 0–500 cm soil profile; comparison of SOC density between CL and BL (d) and AO (e) of different stand ages; and average SOC density in BL and AO (f) within the 0–500 cm soil profile. Error bars represent the standard error of the mean ($n = 3$).

0–500 cm soil profile, no obvious variation was noted at BL18 (3.58 g kg^{-1}) but a 13.0–25.5% decrease was detected at BL8, BL22, and BL38 ($p < 0.05$) compared to corresponding values under cropland (3.57 g kg^{-1}) (Fig. 4). Among the apple orchards, the SOC content in the 0–20 cm layer was the highest at AO19 and lowest at AO5, with both significantly different from cropland ($p < 0.05$; Fig. 4). Over the entire 0–500 cm profile, no significant differences in depth-averaged SOC content were identified among apple orchards and cropland (Fig. 4).

The SOC density showed a variation trend similar to that noted for SOC content (Fig. 4). The SOC density was the highest at BL38 (3.28 kg m^{-2}) among black locust plantations and in cropland in the 0–20 cm layer ($p < 0.05$; Fig. 4). Within the overall 0–500 cm profile, black locust plantations had a lower SOC density ($10.1\text{--}23.9\%$) than cropland (22.7 kg m^{-2}) ($p < 0.05$; Fig. 4), with the exception of BL18. The highest SOC density among black locust plantations was detected at BL18 ($p < 0.05$; Fig. 4). The corresponding value at AO19 (2.27 kg m^{-2}) was the highest compared to other apple orchards ($1.75\text{--}2.06 \text{ kg m}^{-2}$)

and cropland (2.04 kg m^{-2}) for the top 20 cm layer ($p < 0.05$; Fig. 4). The SOC density was not obviously different among apple orchards and cropland despite the high value at AO19 for the 0–500 cm profile.

The SOC density ranged from $4.98\text{--}7.02 \text{ kg m}^{-2}$ and $5.83\text{--}7.85 \text{ kg m}^{-2}$ in the 0–100 cm layer for black locust plantations and apple orchards, respectively; corresponding values in the 100–500 cm layer were 1.46–2.90 times and 1.99–2.55 times higher. Thus, the 0–100 soil layer contained large amounts of SOC, but the deep soil layers (below 100 cm) still contained 59.3–74.4% and 66.5–71.8% of total SOC density of the whole 500 cm profile under black locust plantations and apple orchards, respectively (Fig. 4).

3.4. Soil moisture deficit and SOC sequestration effect relative to cropland

SMD occurred at each 20 cm layer within the 0–500 cm profile under black locust plantations (Fig. 5). Generally, more severe SMD was detected at BL18 (-0.48) and BL22 (-0.42) compared to younger

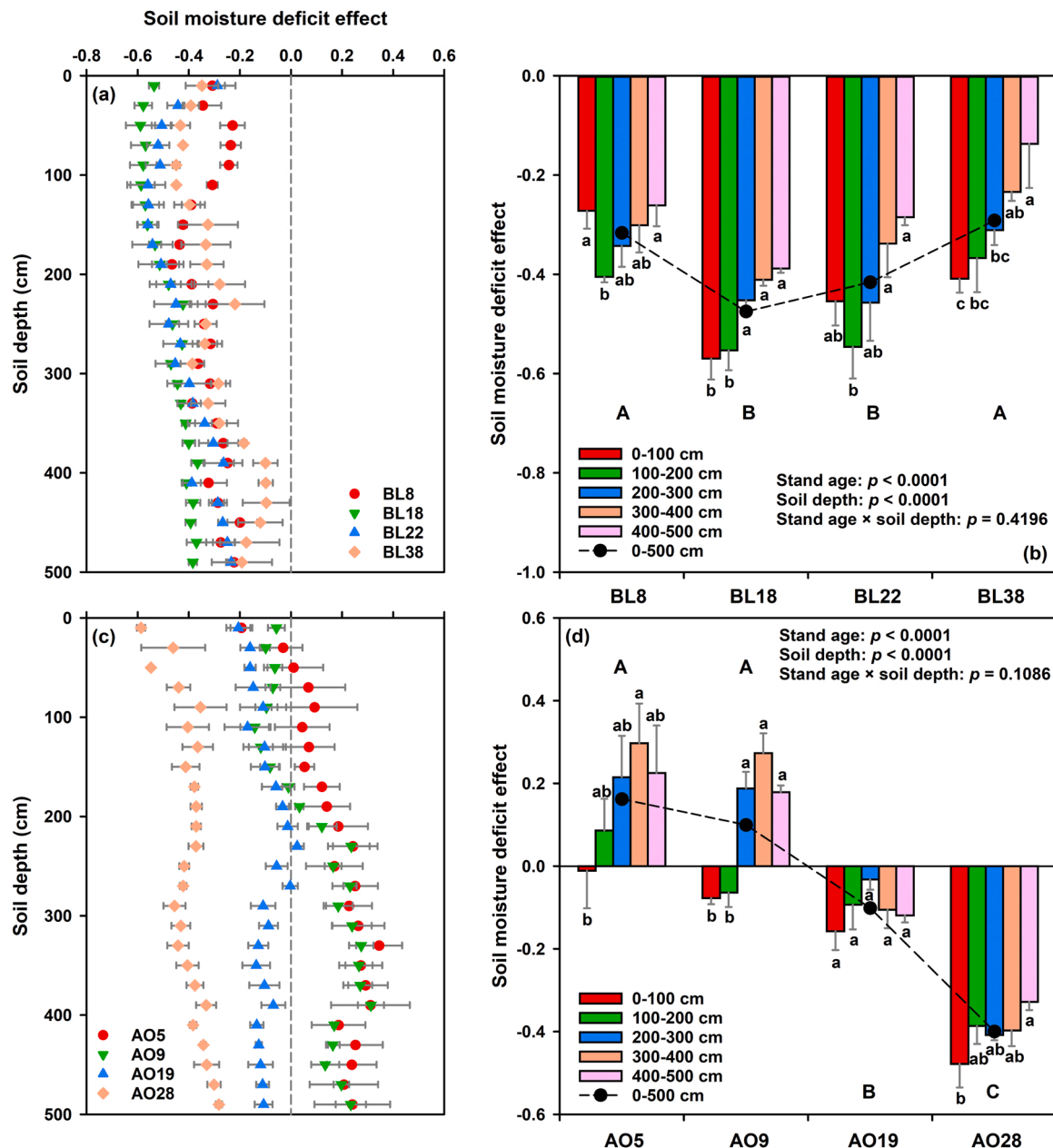


Fig. 5. Soil moisture deficit (SMD) in black locust plantations (BL) (upper) and apple orchards (AO) (lower) of different stand ages. (a) and (c) show the vertical distribution of SMD within the 0–500 cm soil profile and (b) and (d) show the average SMD for 100 cm intervals in soil depth under black locust plantations and apple orchards of different stand ages. Different upper-case letters indicate significant differences ($p < 0.05$) among stand ages within each site and lower-case letters indicate significant differences ($p < 0.05$) among each 100 cm soil layer at $p < 0.05$. Error bars represent the standard error of the mean ($n = 3$).

plantations (BL8, -0.32) over whole 0–500 cm profile ($p < 0.05$), but this severity was less for the oldest plantation (BL38, -0.29) (Fig. 5). In contrast, no SMD occurred in the initial growth stage (AO5 and AO9) of apple orchards over the whole 0–500 cm profile, whereas SMD became increasingly severe in the later growth stages (AO19 and AO28), especially for AO28 ($p < 0.05$) (Fig. 5).

The SOCSE varied with stand age and soil depth ($p < 0.01$; Fig. 6). Over the whole 0–500 cm profile of black locust plantations, the average SOCSE values ranked in the following order: BL18 (0.10) > BL22 (-0.06) > BL8 (-0.09) > BL38 (-0.27) (Fig. 6). For the top 20 cm layer, the SOCSE value was positive for black locust plantations, with the exception of BL8. The positive SOC sequestration primarily occurred in soils below 300 cm for black locust plantations (except for BL38). In apple orchards, AO19 had the highest SOCSE value (positive) over the whole 0–500 cm profile ($p < 0.05$; Fig. 6), whereas no obvious differences

were observed among AO5, AO9, and AO28 (Fig. 6). In addition, the majority of SOC sequestration in soils occurred below 300 cm.

3.5. Linking SMC, SOC density, and root parameters

The correlations among SMC, SOC density, and root parameters varied with different soil layers and deep-rooted species (Tables 3 and 4). The SOC density exhibited negative correlations with SMC at depths below 200 cm, with stronger correlations in the 300–400 and 400–500 cm layers ($p < 0.05$; Table 3). Obvious correlations were also noted between SMC and SOC density in all layers under apple orchards (Table 3).

The SMC was negatively correlated with RDWD in all layers under apple orchards but only obvious correlation was noted between SMC and RDWD when integrating all layers (0–500 cm) under black locust

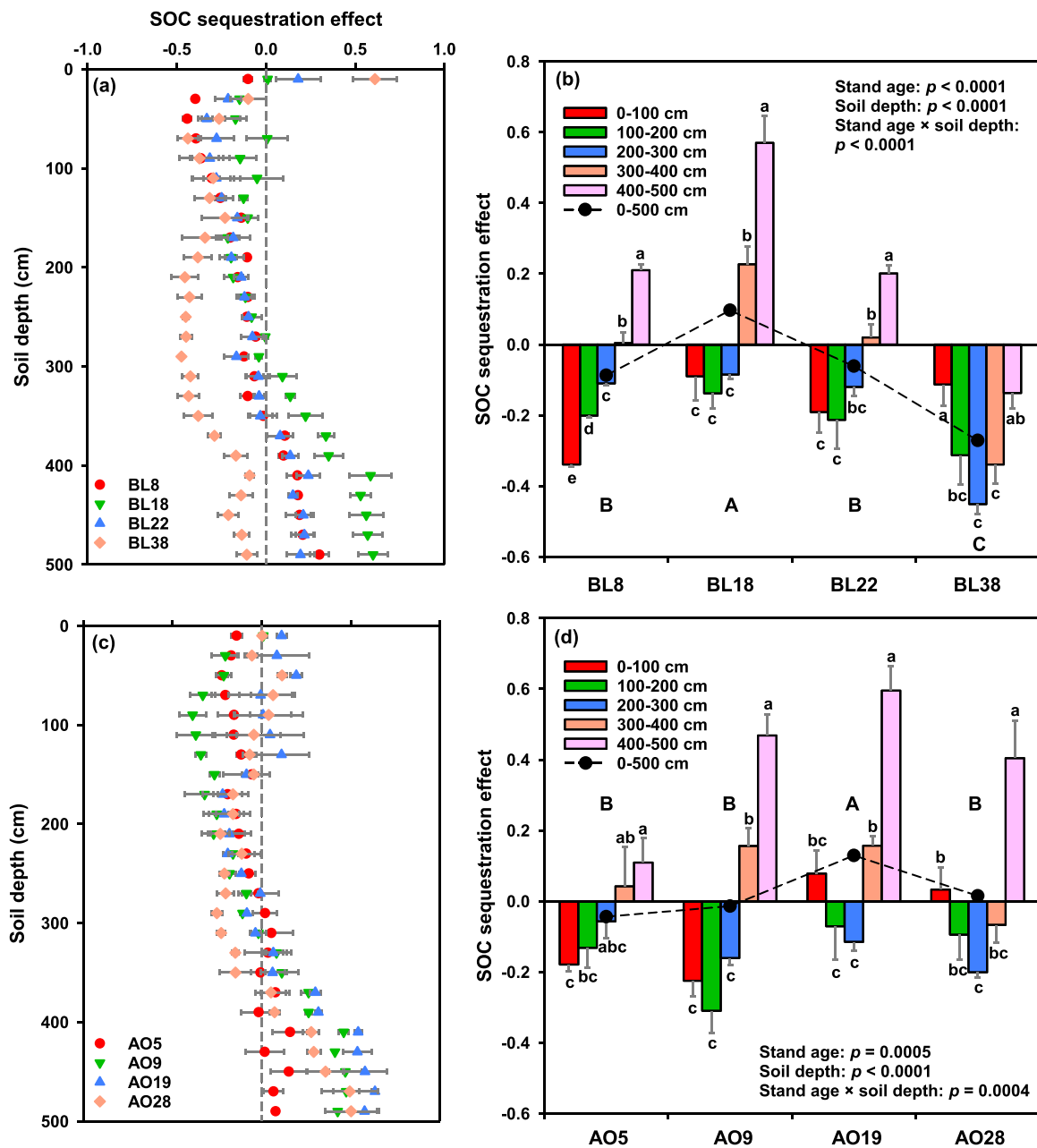


Fig. 6. Soil organic carbon sequestration effect (SOCSE) in black locust plantations (BL) (upper) and apple orchards (AO) (lower) of different stand ages. (a) and (c) show the vertical distribution of SOCSE within the 0–500 cm soil profile and (b) and (d) show the average SOCSE for 100 cm intervals in soil depth in black locust plantations and apple orchards of different stand ages. Different upper-case letters indicate significant differences ($p < 0.05$) among stand ages within each site and lower-case letters indicate significant differences ($p < 0.05$) among each 100 cm soil layer at $p < 0.05$. Error bars represent the standard error of the mean ($n = 3$).

Table 3

Spearman’s rank correlation coefficients between soil moisture and organic carbon (SOC) density for different soil layers under black locust plantations and apple orchards.

Soil layer (cm)	Black locust plantation	Apple orchard
0–100	-0.242	-0.648 **
100–200	-0.239	-0.282 *
200–300	-0.515 **	0.260 *
300–400	-0.729 **	0.394 **
400–500	-0.629 **	-0.341 **
0–500	-0.511 **	-0.167 **

Asterisks represent significant correlations (*, $p < 0.05$; **, $p < 0.01$).

Table 4

Spearman’s rank correlation coefficients between the root dry weight density (RDWD) and soil moisture content (SMC) and organic carbon (SOC) density for different soil layers in black locust plantations and apple orchards.

Soil layer (cm)	Black locust plantation		Apple orchard	
	SMC	SOC density	SMC	SOC density
0–100	-0.081	0.498 **	-0.535 **	0.480 **
100–200	0.173	-0.267 *	-0.390 **	0.173
200–300	0.240	-0.359 **	-0.460 **	-0.276 *
300–400	-0.109	0.241	-0.615 **	-0.115
400–500	-0.181	0.111	-0.589 **	0.323 *
0–500	-0.161 **	0.337 **	-0.518 **	0.324 **

Asterisks represent significant correlations (*, $p < 0.05$; **, $p < 0.01$).

plantations (Table 4). The SOC density was typically positively correlated with the RDWD when considering all layers (0–500 cm) together under black locust plantations and apple orchards ($p < 0.01$; Table 4). And the SOC density showed a strongest correlation with the RDWD in the 0–100 cm layer under both deep-rooted plants systems ($p < 0.01$; Table 4).

4. Discussion

4.1. Response of soil moisture to deep-rooted plants established after cropland abandonment

The deep-rooted trees planted on the CLP significantly affected the soil moisture dynamics depending on the stand age and soil layer (Table 2, Figs. 3 and 5). The SMC under all black locust plantations was significantly lower than for the former cropland throughout all layers (Fig. 3a and c), therefore confirming severe moisture deficit within the 0–500 cm profile (Fig. 5a and b) and aligning with previous results from the CLP (Gao et al., 2018; Jia et al., 2017; Yang et al., 2012, 2020). In water-limited regions, deep root uptake predominantly regulates the deep soil moisture status (Li et al., 2019; Yang et al., 2020). Black locust consumes large amounts of soil water from the deep layers to maintain its rapid growth rate in early stand ages (Gao et al., 2018). Black locust plantations also generally have higher evapotranspiration than conventional croplands. Moreover, the limited precipitation on the CLP (the sole source of soil moisture owing to very deep groundwater table) typically recharges shallow soil layers (0–200 cm) (Chen et al., 2008; Suo et al., 2018). For all of these reasons, black locust plantations in our study exhibited severe moisture deficit relative to long-term cultivated cropland. Notably, the SMC at BL18 and BL22 was lower or approaching the average permanent wilting point in most layers within the 0–500 cm profile (Fig. 3), suggesting black locust trees face severe drought stress and a high risk of drought-induced mortality, which in turn results in the unsustainability of growth and further influences soil hydrological processes (Zhang et al., 2020).

In terms of the temporal variations of SMC under black locust plantations, the depth-averaged SMC (0–500 cm) first decreased with increasing stand age and reached the lowest level at BL18, then increased with stand age; this value at BL38 was slightly higher (not significant) than at BL8 (Fig. 3), suggesting soil moisture recovers over a long time period after planting black locust. This supports the findings of Jia et al. (2017), who report soil moisture recovered under black locust plantations with increasing stand age over a 25-year period. This finding is also confirmed by observations of the most severe moisture deficit within the 0–500 cm profile at BL18 and the least severe at BL38 (Fig. 5). In the initial tree growth stage, the rapid SMC decline and moisture deficit are mainly attributed to the high moisture demand of trees (Jin et al., 2011). With the exhaustion of available soil moisture supporting for trees growth, the deep soils are severe depleted and may fail to support the normal growth of black locust trees. With increasing stand age, the stand density of black locust plantations decreased (Table 1), indicating a density-dependent mortality (natural thinning), as also reported by Jin et al. (2011). The strong competition for limited soil water resources in stand populations and increasing soil desiccation arising from moisture consumption by trees could stimulate tree mortality and in turn reduce the stand density of black locust plantations. The corresponding physiological activities (e.g., transpiration, photosynthesis, root uptake) decline as tree senescence (Jia et al., 2017; Li et al., 2021). Indeed, our study found no obvious differences in the proportion of deep fine roots (200–500 cm) among black locust plantations (Fig. 2), indirectly indicating the density-dependent mortality of trees. In addition, the aging black locust plantations generally had low canopy interception and a high soil water-holding capacity (Jia et al., 2017). For these reasons, the soil moisture within the deep profile recovered after maturation of black locust stands in our study.

The depth-averaged SMC (0–500 cm) was significantly higher under

early growth stages of apple orchards (AO5) than under cropland (Fig. 3), consistent with a previous study (Wang et al., 2015b) and perhaps the result of relatively higher evapotranspiration in cropland than young apple trees. On the contrary, the depth-averaged SMC (0–500 cm) was significantly lower for later apple orchard growth stages (AO28) than for cropland (Fig. 3). The imbalance between excessive depletion by roots and soil water availability might be responsible for this finding. Lower soil moisture and soil water potential motivate the roots of apple trees to penetrate deeper to extract moisture to sustain growth (Li et al., 2019; Pierret et al., 2016). Indeed, apple tree roots were found to reach to a depth of 23.2 (± 0.40) m in a 22-year-old orchard (Li et al., 2019). Despite the roots mostly being distributed in shallow layers, deep roots represent high water uptake efficiency and potential (Jackson et al., 1997). Unlike black locust plantations, the proportion of fine roots below 200 cm increased with increasing stand age in apple orchards in our study (Fig. 2) and the soil moisture significantly decreased with increasing RDWD (Table 4), implying the critical role of deep roots with respect to influencing soil moisture. SMD was evident at later growth stages (AO19 and AO28) but less so at initial growth stages (AO5 and AO9) of apple orchards across layers within the 0–500 cm soil profile (Fig. 3). One possible explanation is that, in the initial growth stage of apple trees after cropland abandonment, the soil water storage in deep soils can satisfy the moisture demand of trees because young apple orchards have low evapotranspiration. As the trees grow, they need to consume more moisture from deeper soils to sustain the increased above- and below-ground biomass (e.g., increasing fruit yield, canopy, and deep root penetration), which in turn desiccates the soil, especially in older apple orchards in our study.

The SMC at AO28 was lower or approaching the average permanent wilting point in some layers within the 0–500 cm profile (Fig. 3), but the density-dependent mortality arising from the strong drought stress was not apparent. This is because the apple orchards were generally well managed by their owners each year to achieve a better fruit yield. However, the older apple trees limited by ongoing soil moisture deficit still demonstrated reduced health, i.e., in terms of low production. Notably, the average profile SMC (0–500 cm) was generally higher under apple orchards (except AO28) than under black locust plantations (Fig. 3), indicating the different root uptake strategies and distinct distribution of fine roots of these two deep-rooted species (Fig. 2) could also be responsible. Moreover, the inconsistent results regarding SMC recovery of older black locust plantations but not older apple orchards indicate the temporal patterns of SMC with stand age following cropland abandonment are complicated. Therefore, further analysis of the temporal patterns of SMC under different plant types and climatic zones is necessary.

4.2. Effects of deep-rooted plantations on SOC

The SOC dynamics varied with the expansion of deep-rooted trees after cropland abandonment and differed with stand age and soil layer (Table 2, Figs. 4 and 6). Vegetation planting affects the SOC distribution by changing the balance between inputs from vegetation production and outputs via complicated physical, chemical, and biological decomposition processes (Jobbágy and Jackson, 2000). A large amount of SOC was buried in deep (> 100 cm) soils of black locust plantations and apple orchards (Fig. 4), similar to results reported in other regions worldwide (Han et al., 2018; Harper and Tibbett, 2013; Sommer et al., 2000; Wade et al., 2019). All of these results highlight the great potential of deep soils for carbon sequestration.

In the surface layers (0–20 cm), the SOC content and density first decreased (not significantly) during the early growth stage (< 8 years) of the black locust plantation, then increased with stand age (Fig. 4). The increasing trend of SOC content and density in surface soils from black locust plantations after 8-year growth period was probably the result of continuously increasing organic matter input from the litter (decayed leaves and branches) into soils (Gao et al., 2018). The stimulation of soil

aggregation following organic matter input can stabilize the physically protected SOC (Six et al., 2004). Moreover, the reduced soil erosion could decrease SOC loss following planting of deep-rooted trees after cropland abandonment. The lowest SOC content and density under the initial stage of black locust plantation (BL8) might be connected to a strong disturbance to soils due to afforestation and C input arising from lower above- or below-ground biomass was not enough to compensate for the continuous decomposition of residues derived from former cropland (Li et al., 2012). This temporal pattern of SOC in surface soils in our study supports previous work that shows an initial decrease in the early growth stage and then an increase with stand age in afforested areas (Ritter, 2007; Yang et al., 2011). The increasing trend in SOC content and density after 8 years in black locust plantations in the 0–20 cm layer (Fig. 4) indicates afforestation following cropland abandonment results in carbon sequestration in surface soils.

However, the SOC in deep layers exhibited different trends from the surface layer (Figs. 4 and 6). The depth-averaged (0–500 cm) SOC sequestration effect was significantly higher at BL18, and the carbon sequestration primarily occurred below a depth of 300 cm under black locust plantations (except for BL38) (Figs. 4 and 6). The source of deep SOC is mainly derived from root rhizodeposition and dead root tissues (Davidson et al., 2011; Rumpel and Kögel-Knabner, 2011). Therefore, the well-developed deep root system after black locust planting might stimulate SOC sequestration in deep (below 300 cm) soils in our study. However, limited carbon sequestration at depths of 20–300 cm (Fig. 6) demonstrates the different responses of SOC in various soil layers to planting of deep-rooted species. The limited soil moisture in these layers, characterized by the typically more severe moisture deficit in the 20–300 cm vs. 300–500 cm layers (Fig. 5), might constrain the stabilization of SOC (Li et al., 2020). The highest (positive) average sequestration effect of SOC under BL18 within the 0–500 cm profile might be due to the higher root-induced carbon input into deep soils because the 18-year black locust plantations is a vigorous growth period on the CLP (Wang et al., 2021), indirect evidence for which is the most severe moisture deficit under BL18 (Fig. 5) as the soils sequestered carbon at the cost of water.

Unexpectedly, a negative SOC sequestration effect was observed under BL38 throughout layers within the 20–500 cm profile (Fig. 6). This result is similar to a report that showed SOC stocks (200–400 cm) increased for up to 25 years and decreased thereafter when cropland was converted to woodland (Li et al., 2020). We presumed these carbon losses were related to the degradation of older black locust trees within the plantation. The aging trees generally have low biomass accumulation rates and many more dead branches, accompanied by unhealthy root growth conditions induced by long-term moisture deficit. The reduced carbon inputs derived from root residues and rhizodeposition could not completely compensate for the SOC losses induced by decomposition and mineralization processes. The extremely limited moisture condition could also constrain the SOC accumulation.

The highest (positive) average SOC sequestration was under AO19, whereas no obvious differences were apparent among AO5, AO9, and AO28 within the 0–500 cm profile (Fig. 6). The increase of SOC at AO19 was probably due to the higher fine root residues and rhizodeposition (Rumpel and Kögel-Knabner, 2011; Yang et al., 2020). The limited variations in average SOC sequestration (0–500 cm) in the initial growth stages (AO5 and AO9) might be the result of limited root biomass failing to alter the SOC (Li et al., 2019). The lower average SOC sequestration effect under the aging apple orchard (AO28) than under AO19 within the 0–500 cm depth can be attributed to several factors. First, the severe soil moisture deficit and formation of dry soil layers under the aging apple orchard might inhibit root uptake processes and growth, which in turn interferes with fine root turnover (Brunner et al., 2015). Second, the drying soils might facilitate the formation of suberin and lignin that could constrain the liberation of root exudates into soils (Brunner et al., 2015). Moreover, the physiological activity of aging apple trees decreases, which also influences root turnover. Notably, the positive SOC

sequestration effect was mostly present in deeper soil layers (below 300 cm) under apple orchards, similar to that under black locust plantations (Fig. 6), further confirming that deep soils in water-limited regions have great potential with respect to carbon sequestration.

4.3. Relationships among SMC, SOC density, and root parameters

The SMC was negatively correlated with SOC density at depths below 200 cm and for the whole 0–500 cm profile under black locust plantations (Table 3). This is similar to the results obtained from a long-term natural restoration succession (~150 a) that showed soil water storage is negatively related to SOC storage in the 0–200 cm layer (Zhang et al., 2016). Besides, the stronger negative correlation between SMC and SOC density in soil layers below 300 cm further confirmed that the SOC sequestration was more sensitive to the moisture condition in deeper layers under black locust plantations. For apple orchards, however, the correlation between SMC and SOC density was typically weaker than observed for black locust plantations at depths below 200 cm and the whole 0–500 cm profile (Table 3), suggesting the SOC sequestration capacity limited by soil moisture might be weaker under apple orchards than under black locust plantations. Contrary to our study, positive correlations between soil moisture and SOC have been reported. For example, Jin et al. (2011) found a significant positive relationship between SMC and organic matter (0–100 cm) after planting black locust trees in a watershed (MAP = 617 mm) located in the southern CLP. Tuo et al. (2018) reported SOC density was positively correlated with SMC in the 40–300 cm layer along a precipitation gradient on the CLP. These inconsistent relationships between soil moisture and SOC might be caused by the different spatial scales, soil depth, plant types, climatic conditions, and so on.

The SMC significantly declined with increasing RDWD in each layer and the whole 0–500 cm profile under apple orchards and this was the case only when considering all the layers (0–500 cm) together under the black locust plantations (Table 3). This again indicates the different water uptake patterns by roots within different deep-rooted plant systems. The weaker correlation between SMC and RDWD under black locust plantations than under apple orchards in our study might be related to the natural-thinning response to drought stress after maturation of black locust trees. Moreover, when linking the SOC density to the RDWD, positive correlations were typically noted for the whole 0–500 cm layer under black locust plantations and apple orchards (Table 4), illustrating the important contribution of roots to SOC accumulation exactly (Li et al., 2020). Previous studies have shown plant roots contribute substantially to SOC stabilization (Shahzad et al., 2018; Sommer et al., 2000). It should be noted that the significant negative correlation in the 100–200 and 200–300 cm layers under black locust plantations and in the 200–300 cm layer under apple orchards indicated the roots penetration might trigger the priming effect, which may result in the loss of SOC in these layers. Given the critical role of deep roots affecting the SMC and SOC, future studies are necessarily needed to explore the responses of soil moisture and organic carbon to the changes in physiochemical properties and microbial communities induced by the deep root inputs under the deep-rooted systems. In particular, the relative importance and contribution of functional traits of roots and the quantity and quality of root residues and rhizodeposition to the SOC sequestration in deep profiles should be explicitly evaluated.

4.4. Implications for future land management practices

The establishment of deep-rooted tree species on the CLP could result in the excessive exploitation of deep soil moisture and decreases in SOC sequestration (Fig. 7), inducing poor tree growth. This in turn endangers the health and services of the ecosystem (e.g., carbon sequestration, soil and water conservation). An important trade-off occurs between ecological conservation and the economic benefits of apple orchards, especially for fragile, water-limited ecosystems (Yang et al., 2020). In

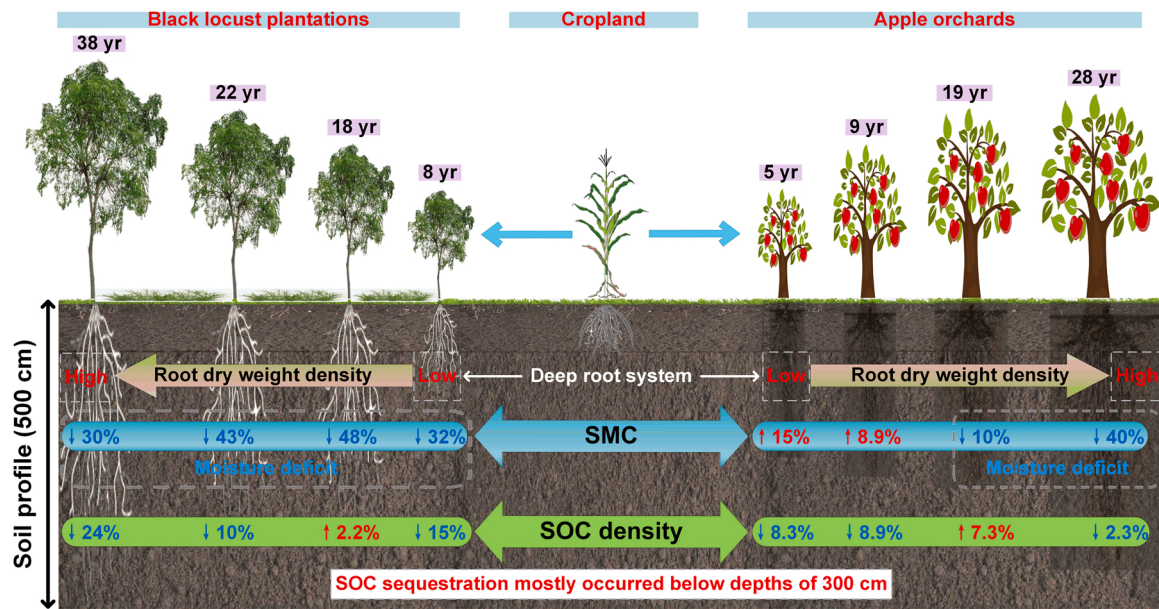


Fig. 7. Conceptual diagram illustrating the effects of deep-rooted plants established after cropland abandonment on soil moisture and organic carbon (SOC). The values show the changes of soil moisture content (SMC) and SOC density in percent to the long-term cultivated cropland. Up (in red) and down (in blue) arrows indicate increasing and decreasing trends, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

general, root-induced carbon sequestration is accompanied by notable soil moisture exhaustion. As a result, a major concern is that suitable management practices need to be seriously considered to increase carbon sequestration at the expense of low soil moisture exploitation (Li et al., 2020). For example, thinning of exotic plant species in high-density plantations is proposed to optimize the relationship between soil water availability and the demand from the plant, especially in water-limited regions on the CLP. An alternative recommendation is that the exotic plant species could be replaced with water-saving native species without threatening the local soil water storage. With respect to the management of apple orchards, increasing cover crops (e.g. grasses) has been confirmed to effectively enhance the soil quality by preventing soil and water losses and increasing soil water infiltration, water retention, and aggregate stability (Ling et al., 2017). In addition, sustainable practices, including no-tillage, returning pruning residues to the field, manure addition, etc., should be extensively applied to ensure sustainable production. The exploitation of rainwater (e.g., application of rainwater collection and infiltration systems) is a promising measure for providing more available water resources to cope with water scarcity on the CLP (Song et al., 2018).

5. Conclusions

This study investigated the deep SMC and SOC sequestration in two deep-rooted plant systems (black locust plantations and apple orchards) following cropland abandonment on the CLP. The following conclusions can be drawn from this study:

- (1) Severe SMD occurred throughout layers within the 0–500 cm profile under black locust plantations and under 19- and 28-year-old apple orchards, relative to cropland. Over time, the depth-averaged SMC (0–500 cm) first declined and then showed recovery under the 38-year-old black locust plantation but first increased (< 5 years) and then continuously declined under the apple orchards.
- (2) The temporal patterns of SOC in deep layers were different from those in surface layers. Furthermore, deep soils were important for carbon sequestration, with most occurring below depths of

300 cm under deep-rooted systems. Nevertheless, carbon sequestration did not always occur and carbon losses were sometimes detected over time after planting deep-rooted species.

- (3) The SOC accumulation was more likely affected by the SMC conditions under black locust plantations than under apple orchards. The decrease in SMC with increasing roots was more notable under apple orchards than under black locust plantations.

Our study highlights the interactions among moisture, carbon, and roots in deep soils. These findings contribute to guidance for vegetation restoration and maintenance of sustainable ecosystems on the CLP.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agee.2022.107855](https://doi.org/10.1016/j.agee.2022.107855).

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