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Interactive Effects of Honeysuckle Planting and Biochar Amendment on Soil Structure and Hydraulic Properties of Hillslope Farmland

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Abstract: Plant roots and biochar amendment cause changes in soil structure and hydraulic properties; however, their interactive influences are still inadequately understood. A six-year field study was conducted on hillslope farmland in the Sichuan basin, China, to evaluate how honeysuckle planting and biochar application affect soil structure and hydraulic properties. Various parameters related to soil structure (soil organic matter (SOM), soil aggregate stability, bulk density were obtained in the laboratory) and hydraulic (hydraulic conductivity, and soil water retention characteristics by single porosity of van Genuchten 1980 and dual porosity bi-exponential model) properties were determined. The results showed that honeysuckle planting alone increased (SOM) content, honeysuckle planting following biochar amendment could not only enhance SOM content to a greater magnitude in top 20 cm soil but also markedly increase the SOM content in deeper soil layers (20–30 and 30–40 cm), while the application of biochar alone enhanced the SOM content in top 20 cm soil. The combination of honeysuckle planting and biochar amendment could increase soil aggregate stability. Furthermore, It was found that soil pores with size $r > 125$ µm were the dominant macropores in all treatments. Honeysuckle planting increased saturated soil hydraulic conductivity (K_s) significantly ($p < 0.05$). Biochar amendment also significantly increased K_s directly or indirectly through enhancement of SOM content. Results also showed that honeysuckle planting and biochar amendment could lead to a greater increase in saturated soil water content than saturated soil hydraulic conductivity. However, SOM showed lower value in bare land plots suggesting that both honeysuckle planting and biochar could increase SOM in soil, hence improving soil quality. Therefore, our field study demonstrated that the practice of honeysuckle planting and biochar amendment jointly in sloping farmland of purple soil could effectively strengthen soil structure and improve soil water retention.

Keywords: soil aggregate; macropores; saturated hydraulic conductivity; soil water retention curve; hillslope; purple soil

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1. Introduction

Soil hydraulic properties are crucial for determining soil quality and environment, as well as its ability to serve the ecosystem [1]. Soil hydraulic properties, including water retention and hydraulic conductivity, are key parameters in studies of hydrological processes and the functioning of watersheds [2]. Plant roots are important in soil structure development for the formation of biopores from root growth and stabilization of soil aggregates [3], providing access to belowground water and nutrients [4–6], and anchoring plants in soils [7,8]. The roots of living plants alter the soil structure and hydrology parameters of the soil matrix (such as soil aggregate stability, soil cohesion, infiltration rate, soil moisture, and SOM) and reduce soil erosion [9]. Plant roots affect soil's physical and hydraulic properties in different ways, such as soil structure and pore system. For instance, plant roots can change soil hydraulic conductivities through macropores structure. According to Lu et al. [2], mature trees are characterized by coarse roots or decayed roots, which generate macropores in soil and increase saturated hydraulic conductivities (K_s). Furthermore, Lu et al. [2] reported that grass roots at an early stage are characterized by a high density of fine roots, which generate additional micropores and increase the heterogeneity of pore size distribution (PSD), leading to a decrease in K_s as well as increased saturated water content. Germann et al. [10] reported that plant roots improve soil pore structure and form macropores that enhance infiltration, drainage, and aeration. Ni et al. [11] studied the effects of plant roots on the soil hydraulic properties under single species and mixed planting species, and their results showed that the planting of single species decreased K_s while planting mixed species increased K_s. The inconsistent findings reflect that the current understanding of the impacts of plant roots on soil structure and soil hydraulic properties and underlying mechanisms is limited and insufficient.

Biochar is mostly used as a soil amendment to improve soil's physical, chemical, and biological qualities and reduce soil erosion. Kammann et al. [12] found that co-composted biochars have a higher plant growth-promoting effect than biochar only in soil. Studies also found that adding biochar can increase hydraulic parameters and other soil physical properties such as water retention, plant available water capacity, bulk density, and porosity [13–15]. However, the influences of biochar may depend on soil type and region [16]. Generally, biochar amendment could improve soil water holding capacity due to two main reasons, biochar's porous structure, which holds more water in biochar pores, and interaction of biochar with soil, which increases soil aggregates and hence improves soil water holding capacity [17].

Purple soil is an entisol based on the USDA soil classification and is a shallow, poorly structured soil formed by mudrocks or sandrocks. The soil is a very important arable soil type in the upper reaches of the Yangtze River watershed. Sloped farmland is the most common land type in this area. Purple soil on slopes is readily erodible and contains a large number of macropores, which contribute over 80% of the flow [14].

Honeysuckle, a perennial medical herb, is often planted for the purpose of soil and water conservation. In history, forestland and grassland in hilly purple soil areas of the upper Yangtze River watershed had been used for intensive agricultural activities and thus degraded. Since the 1970s, afforestation was implemented, mainly with cypress (alnus cremastogyne and cypress funebris), and led to improved soil quality, including changes in soil physical and hydraulic properties. To our best of knowledge, there is a scarcity of literature about the interactive effects of plant roots and biochar amendment on the physical and hydraulic properties of purple soil, and no studies were carried out to explore interactive effects of honeysuckle plant roots and biochar addition on the poor structure of purple soil.

Therefore, in this study, we conducted an experimental field study of honeysuckle planting and biochar addition in sloping farmland of purple soil, which is widely distributed in central hilly Sichuan in China and suffers severe water erosion.

We hypothesized that the honeysuckle planting and biochar addition in purple soil could alter soil structure, including both soil pore system and soil aggregate stability, and thus affect soil hydraulic properties. This study provides a better understanding of how honeysuckle planting and biochar amendment improves soil structure and water infiltration in soil and hence optimizes soil water management of purple soil.

2. Materials and Methods

2.1. Study Area

The research was carried out at the Agro-ecological station of purple soil in Yanting, which is located at 31°16′ N latitude and 105°27′ E longitude, in the hilly central Sichuan province of southwestern China (Figure 1a). The study area experiences a moderate subtropical monsoon climate, with an annual average temperature of 16.6 °C and annual average precipitation of 846.4 mm [18], with 70% of rainfall mainly occurring during the rainy season (May to September) [19]. Sloping farmland is the most common land type in the catchment (44%), with an average slope of approximately 6^0, and the typical soil in the catchment is readily erodible purple soil. The soil thickness on the slopes varies from 25 cm to 60 cm, and mudrock with visible fine fractures lies beneath the shallow purple soil and overlies impermeable sandstone [14]. The purple soil investigated in this research study is a loamy soil with a soil pH of 8.3, a bulk density of 1.33 g cm^{-3}, SOM content of 8.75 g kg^{-1}, and K_s of 16.8 mm h^{-1} [20].

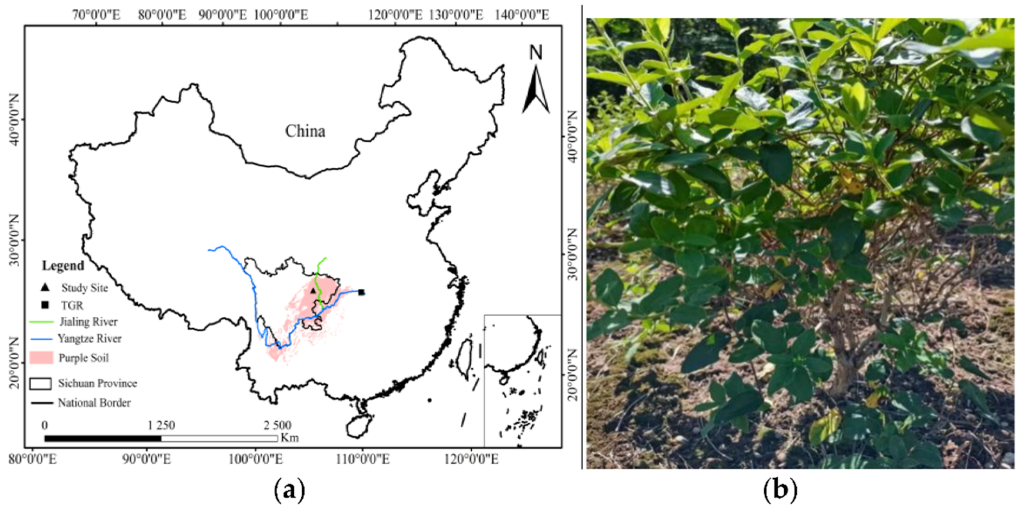


Figure 1. (**a**) Location of the study area and (**b**) actual view of honeysuckle planting.

2.2. Soil Sampling

Soil samples were collected from long-term experimental plots (5 m in width and 20 m in length) with a slope of 6°. Four plots including (1) bare land plot (BL), (2) honeysuckle planting plot (HP), (3) bare land with 1% biochar applied to top 20 cm soil (BLBC), and (4) honeysuckle planting with 1% biochar applied to top 20 cm soil (HPBC) were selected for sampling. In HP and HPBC plots, both rhizosphere soil and inter-row soil were collected. These experimental plots were constructed in 2015 in farmland consolidated in 2013. The biochar applied in BLBC and HPBC plots is a commercial biochar made in China, from the pyrorisis of mixed straws, with organic matter content of 833.8 g kg^{-1} and a pH of 10.22 [15]. A total of 1% (w/w, %) biochar was applied on the soil surface, followed by plowing to the depth of 20 cm. Honeysuckle (Figure 1b) was planted in the same year of 2015 after biochar application. Spacing in the rows of honeysuckle and spacing between rows was 80 cm, respectively. Since honeysuckle planting and biochar amendment in 2015, the plots have not been fertilized or tilled.

In BL and BLBC plots, undisturbed soil core samples (D = 5 cm, H = 5.05 cm) were collected from each plot at fourth depths of 0–10, 10–20, 20–30, and 30–40 cm with 3 replicates, and in HP and HPBC plots, soil core samples were collected from both rhizosphere soil and inter-row soil, respectively. Sampled soil cores were kept in a refrigerator at 4 °C before laboratory measurements of soil water retention curve, Ks and water content, bulk density, and porosity. Loose soil samples were also collected at each depth with the same sampling strategies as soil cores and were packed in plastic bags and transported to the laboratory for air drying. The air-dried loose soils were divided into two sub-samples. One sub-sample was kept in a plastic bag for soil aggregate size and stability analysis, another sub-sample was mashed and passed through a 2 mm mesh sieve for analysis of basic soil properties, including soil pH and SOM content.

2.3. Laboratory Analysis

2.3.1. Analysis of Soil Basic Properties

Soil pH was determined at a 1:5 soil-water ratio (w/v) by a pH meter [21]. Soil organic carbon (SOC) was measured by a CN analyzer. SOM content was obtained by multiplying 1.724 by the measured value of SOC [22]. Soil dry bulk density was measured by oven-drying at 105 °C for 24 h, and the porosity was obtained from bulk density (ρ_b) by considering a constant particle density of 2.65 g cm^{-3}.

2.3.2. Soil Aggregate Size Distribution and Its Stability

The measurement and details of dry soil aggregate size distribution were determined by following the method used by [23,24]. Six aggregate size classes were determined by vernier caliper [24]; moreover, the aggregate size classes smaller than 1 mm (0.5–1 mm, 0.25–0.5 mm, and < 0.25 mm) and the mean particle size was obtained as the arithmetic mean of the upper and lower sieve sizes.

The mean weight diameter (MWD) was calculated as:

$$\text{MWD} = \sum_{\text{i}=0}^{\text{n}} \overline{x_i} \times W_i \tag{1}$$

where, $\overline{x_i}$ is the mean diameter (mm) of aggregate at size i; and W_i is the weight percentage (%) at size i. The bigger the MWD value represents better soil aggregation and higher soil aggregate stability. A fractal dimension of mass, D_m, quantifies space-filling characteristics of the solid in a space of radius r. For a mass fractal, the scaling of mass, M, follows a relationship of the form [25].

$$M,\ r^{D_m},\ D_m\ \leq\ d \tag{2}$$

where, d is the embedding dimension, defined as the minimum number of coordinates needed to enclose an object (i.e., d = 2 and 3 correspond to a two- and three-dimensional space, respectively). D_m can be obtained from measurements of mass on aggregates of different sizes. It can be estimated based on the Tyler and Wheatcraft (1992) model [26], which can be expressed as Equation (3):

$$D_m = 3 - \frac{\log\left({}^{W_i}/{}_{W_0}\right)}{\log\left({}^{\overline{d_i}}/{}_{\overline{d_{max}}}\right)} \tag{3}$$

where, W_i is the mass of aggregates with size < d_i; W_0 was the total mass of aggregates; $\overline{d_i}$ was the mean aggregate diameter at a size class between d_i and d_{i+1}, and, in this study, $\overline{d_i}$ shared the same data with $\overline{x_i}$ in Equation (1); $\overline{d_{max}}$ was the mean diameter of aggregate at the top sieve (>10 mm class in this study).

2.3.3. Soil Hydraulic Properties

In the laboratory, soil core samples were saturated with distilled water from the bottom for 18 h, the saturated hydraulic conductivity (K_s) was measured using the constant head method [27]. After measurement of K_s, the soil water retention curve (SWRC) was measured on the same soil cores samples at 12 suctions of −1, −2.5, −10, −31.6, −63.1, 100, −337, −510, −1020, −2040, −5100, and −15300 cm H_2O. A sandbox-pressure plate was used for suctions of −1 to −100 cm H_2O, while the pressure plate was used at the suctions of −337 to −15,300 cm H_2O (Soil Moisture Equipment Corp., Santa Barbara, CA, USA). At the end of the experiment, the soil cores were oven-dried at 105 °C for 24 h to determine soil water content.

The single porosity of van Genuchten (1980) model (vG) [28] and the dual porosity biexponential (BE) model [29] by the RETC fitting program (RECT Version 6.02, University of California) and the Origin software program (Origin Lab Corporation), respectively, were used to fit data of SWRC obtained.

The van Genuchten 1980 model equation can be described as:

$$S^*(h) = \frac{\theta(h) - \theta_{r-vG}}{\theta_{s-vG} - \theta_{r-vG}} = \frac{1}{(1 + |\alpha_{vG}\, h|^n)^m} \quad (4)$$

where, S^* is the relative water saturation of the soil, h is the pressure head (cm), θ_{s-vG} and θ_{r-vG} are the saturated water content and residual water content, respectively ($m^3\ m^{-3}$), and α_{vG} (cm^{-1}), n, and m (=$1 - 1/n$) are empirical parameters, n is related to slope of the SWRC at the inflection point [30].

The SWRC fitted using the vG model [28] has a unique inflection point where the curvature is zero or it changes from convex to concave. The water content at the inflection point (θ_{inf}) of the fitted vG model [28] and the inflection slope (S_{inf}) were calculated from these model parameters using the equations from Dexter [31], as described as follow:

$$\theta_{inf} = \theta_{r-VG} + (\theta_{s-vG} - \theta_{r-VG})\left(1 + \frac{1}{m}\right)^{-m} \quad (5)$$

$$S_{inf} = -n(\theta_{s-vG} - \theta_{r-VG})\left(1 + \frac{1}{m}\right)^{-(1+m)} \quad (6)$$

The single porosity vG model [28] incorporates over the whole soil water retention curve to allow the determination of inflection slope (S_{inf}), which reflects the general soil physical quality.

The BE model can be described as:

$$\theta = \theta_{r-BE} + \theta_{txt-BE}\ exp\left(1 + \frac{h}{h_{a-txt}}\right) + \theta_{str-BE}\ exp\left(1 + \frac{h}{h_{a-str}}\right) \quad (7)$$

where, θ_{txt-BE} represents the difference between saturated water content (θ_{s-txt}) and the residual water content (θ_{r-txt}) in the textural pore space; θ_{str-BE} represents the difference between saturated water content (θ_{s-str}) and residual water content (θ_{r-str}) in the structural pore space; h_{a-txt} and h_{a-str} represent the air entry potentials in the textural and structural pore space, respectively; θ_{r-BE} is the sum of residual soil water contents in the textural and structural pore space (=θ_{r-txt} + θ_{r-str}).

2.3.4. Characterization of Soil Pore System

The pore size distribution was determined as the derivative of the $\theta(r)$ curve converted from the fitted vG and BE $\theta(h)$ equations by calculating r (µm) (the radius of pores that remain full of water at a given pressure head (h) (cm)) using the Young-Laplace equation [32]:

$$r = \frac{1490}{|h|} \quad (8)$$

According to the drainage capacity of the pore [14], the soil pore systems were categorized into 3 main classes (1) non-drainage micropores (<0.1 µm or $|h|$ > 14900 cm, residual water), (2) drainable pores (0.1 < r < 125 µm or 12 cm < $|h|$ < 14900 cm), and (3) gravitationally drainable macropores (r >125 µm or $|h|$ < 12 cm).

2.4. Statistical Analysis

SPSS software (version 22, IBM SPSS Statistics) was used to analyze the data. Effects of honeysuckle plant roots and biochar on soil structure and hydraulic properties were examined by analysis of variance (ANOVA), while the interactive effect of honeysuckle planting and biochar amendment on soil was evaluated by multivariate analysis. Furthermore, using a generalized least squares estimator, a structural equation model (SEM) was used to analyze the impacts of the honeysuckle plant and biochar presence on SOM, soil structure (a latent variable including S_{inf}, MWD, and D_m), and soil hydraulic properties (saturated hydraulic conductivity, saturated soil water content, and soil residual water content), the relationships among SOM, soil structure, and soil hydraulic properties. The SEM was conducted using the *lavanne* package in R (R Core Team, 2020). All statistical tests were considered significant at $p < 0.05$. Origin Pro 9.1 (OriginLab, Northampton, MA, USA) was used for the generation of other plots.

3. Results

3.1. Soil Basic Properties

Soil basic properties are shown in Tables 1 and 2. For all plots, soil pH showed a sharp increase from 0–10 cm to 10–20 cm (from 8.26 to 8.36 in BL, from 8.17 to 8.35 in HP_{rhi}, from 8.31 to 8.36 in HP_{int}, and from 8.30 to 8.36 in BLBC, from 8.10 to 8.34 in $HPBC_{rhi}$, from 8.16 to 8.33 in $HPBC_{int}$). The 0–40 cm soil in plot BL showed a significantly higher average value of pH than that in plot HP ($p < 0.05$). The soil in plot HPBC showed a significantly lower soil pH than soil in plot BLBC. Soil organic matter (SOM) showed a significant difference with depth in BL and HP plots. Furthermore, planted location in plot HP (HP_{rhi}) showed a much higher SOM content compared to that at inter-row location (HP_{int}). Biochar amendment in soil caused a significantly higher SOM content in the top 20 cm compared to 20–40 cm. Moreover, $HPBC_{rhi}$ and $HPBC_{int}$ soil showed significantly higher SOM ($p < 0.05$) than soil in BLBC, indicating a strong accumulation of SOM by honeysuckle planting in purple soil.

Table 1. Soil pH, bulk density, total porosity, and SOM content in BL and HP plots.

Plot	Depth (cm)	pH	Bulk Density (g cm^{-3})	Porosity (m^3 m^{-3})	SOM (g kg^{-1})
BL	0–10	8.26 ± 0.02a	1.60 ± 0.08	0.39 ± 0.03	7.56 ± 0.65
	10–20	8.36 ± 0.03ab	1.59 ± 0.04	0.40 ± 0.02	4.75 ± 0.03
	20–30	8.60 ± 0.18bc	1.58 ± 0.08	0.40 ± 0.03	3.86 ± 0.31
	30–40	8.68 ± 0.03c	1.60 ± 0.06	0.39 ± 0.02	3.60 ± 0.18
	Mean	8.48 ± 0.19 *	1.59 ± 0.06	0.40 ± 0.02	4.94 ± 1.67 *
HP_{rhi}	0–10	8.17 ± 0.11a	1.49 ± 0.02	0.43 ± 0.01	83.12 ± 6.91
	10–20	8.35 ± 0.06ab	1.58 ± 0.07	0.40 ± 0.03	89.28 ± 74.12
	20–30	8.42 ± 0.07b	1.54 ± 0.01	0.42 ± 0.00	79.24 ± 78.41
	30–40	8.44 ± 0.01b	1.65 ± 0.13	0.38 ± 0.05	67.28 ± 17.02
	Mean	8.35 ± 0.13 *	1.56 ± 0.09	0.41 ± 0.03	80.07 ± 55.69 *
HP_{int}	0–10	8.31 ± 0.02	1.55 ± 0.04	0.41 ± 0.02	55.26 ± 43.37
	10–20	8.36 ± 0.04	1.61 ± 0.08	0.39 ± 0.03	39.35 ± 92.16
	20–30	8.38 ± 0.09	1.44 ± 0.14	0.45 ± 0.05	23.27 ± 30.29
	30–40	8.40 ± 0.03	1.59 ± 0.09	0.40 ± 0.03	74.27 ± 62.32
	Mean	8.36 ± 0.06 *	1.55 ± 0.10	0.42 ± 0.04	31.56 ± 50.14 *

Note: SOM—soil organic matter content; BL—bare land treatment; HP_{rhi}—planted location in honeysuckle planting treatment; HP_{int}—inter-row location in honeysuckle planting treatment; different lower case letters represent significant differences at the 0.05 level among soil depths in each plot; * means significant differences ($p < 0.05$) in mean value among treatments at 0–40 cm depth.

Table 2. Soil pH, bulk density, total porosity, and SOM content in plots BLBC and HPBC.

Soil	Depth (cm)	pH	Bulk Density (g cm^{-3})	Porosity (m^3 m^{-3})	SOM (g kg^{-1})
BLBC	0–10	8.30 ± 0.02a	1.55 ± 0.04	0.41 ± 0.02	62.81 ± 13.68
	10–20	8.36 ± 0.04c	1.60 ± 0.08	0.39 ± 0.03	14.19 ± 1.04
	20–30	8.38 ± 0.09b	1.44 ± 0.14	0.45 ± 0.05	6.20 ± 0.36
	30–40	8.40 ± 0.03c	1.59 ± 0.09	0.40 ± 0.03	5.96 ± 0.96
	Mean	8.36 ± 0.06 *	1.55 ± 0.10 *	0.41 ± 0.04 *	22.29 ± 25.37 *
$HPBC_{rhi}$	0–10	8.10 ± 0.12a	1.39 ± 0.15	0.47 ± 0.05	111.56 ± 111.5
	10–20	8.34 ± 0.06b	1.58 ± 0.07	0.40 ± 0.03	111.8 ± 93.25
	20–30	8.34 ± 0.02b	1.65 ± 0.04	0.37 ± 0.02	75.50 ± 27.03
	30–40	8.31 ± 0.09ab	1.58 ± 0.14	0.40 ± 0.05	70.42 ± 54.53
	Mean	8.27 ± 0.13 *	1.55 ± 0.14 *	0.41 ± 0.05 *	94.27 ± 70.79 *
$HPBC_{int}$	0–10	8.16 ± 0.09	1.31 ± 0.02a	0.51 ± 0.01b	79.77 ± 27.25
	10–20	8.33 ± 0.09	1.48 ± 0.06b	0.44 ± 0.02a	55.11 ± 15.66
	20–30	8.35 ± 0.10	1.53 ± 0.07b	0.42 ± 0.03a	42.34 ± 55.26
	30–40	8.35 ± 0.06	1.52 ± 0.03b	0.42 ± 0.01a	33.1 ± 7.35
	Mean	8.30 ± 0.11 *	1.46 ± 0.10 *	0.45 ± 0.04 *	52.56 ± 31.12 *

Note: SOM—soil organic matter; $HPBC_{rhi}$–planted location in honeysuckle planting plus biochar addition plot; $HPBC_{int}$—inter-row location in honeysuckle planting plus biochar addition plot; different lower case letters represent significant differences at the 0.05 level among soil depths in each plot; * means significant differences of mean value among plots at 0–40 cm depth.

3.2. Soil Aggregate Size Distribution and Its Stability

Measurements of soil dry aggregate size distribution (represented by MWD) and aggregate stability (represented by D_m) are presented in Figure 2. It was found that MWD exhibited no changes with depth in all plots except plot BLBC. Compared to the other treatments, plot BLBC showed significantly higher MWD at 0–10 cm and 10–20 cm but lower MWD at depths of 20–30 cm and 30–40 cm.

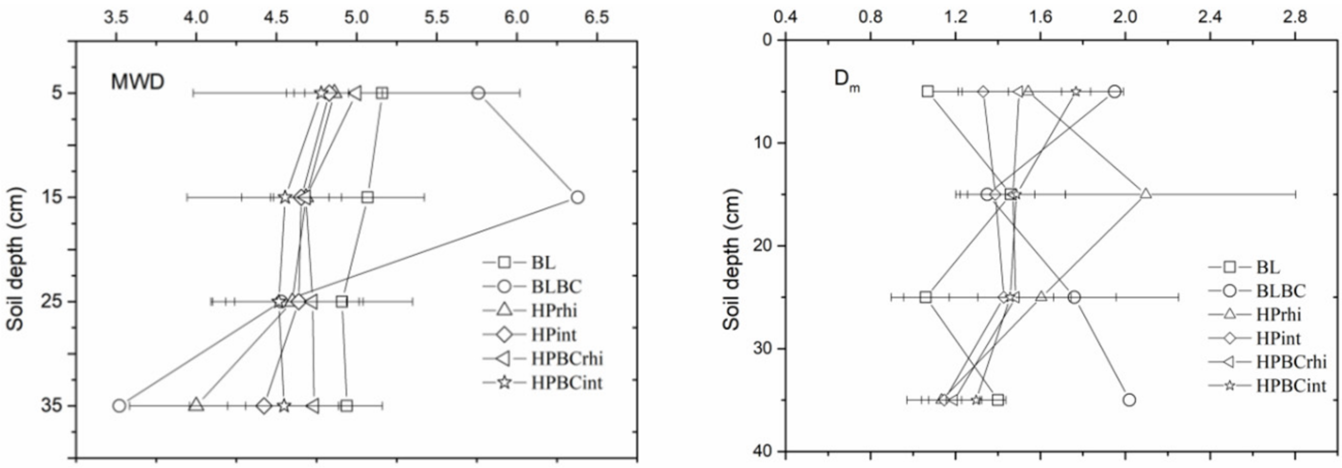


Figure 2. MWD and D_m (Mean ± standard deviation) at each depth in experimental plots. Note: MWD—mean weight diameter; D_m—fractal dimension of mass; BL—bare land treatment; BLBC—bare land with biochar; HP_{rhi}- planted location in honeysuckle planting treatment; HP_{int}-inter-row location in honeysuckle planting treatment; $HPBC_{rhi}$- planted location in honeysuckle planting plus biochar addition plot; $HPBC_{int}$- inter-row location in honeysuckle planting plus biochar addition plot.

At a depth of 0–10 cm, the soil in plot BLBC showed the highest D_m, indicating better aggregate stability. There were no significant differences in D_m among different soil layers ($p > 0.05$) for all plots. Two-way ANOVA analysis found that honeysuckle roots or biochar amendment individually had no significant influence on D_m ($p > 0.05$); however, the interaction of honeysuckle root with biochar amendment caused a significant increase of D_m ($p = 0.04$).

3.3. Soil Water Retention Curve (SWRC) Estimated by vG and BE Models

Soil water retention curves of studied plots were shown in Figures 3 and 4.The residual water content (θ_r) ranged from 0.18 m^3 m^{-3} to 0.30 m^3 m^{-3} with an averaged value of 0.24 m^3 m^{-3}, and saturated water content (θ_s) ranged from 0.35 m^3 m^{-3} to 0.58 m^3 m^{-3} with an averaged value of 0.43 m^3 m^{-3} (Tables 3 and 4). Plot BLBC showed significantly higher θ_r compared to plot BL. Rhizospheric soil at 0–10 cm and 10–20 cm in plot HP (HP_{rhi}) showed higher θ_s than the soil at plot HP's inter-row location (HP_{int}) and the soil in plot BL, and rhizospheric soil in plot HPBC ($HPBC_{rhi}$) also had higher θ_s than the soil at plot HPBC's inter-row location ($HPBC_{int}$) and the soil in plot BLBC, indicating an increase of soil water capacity by honeysuckle planting.

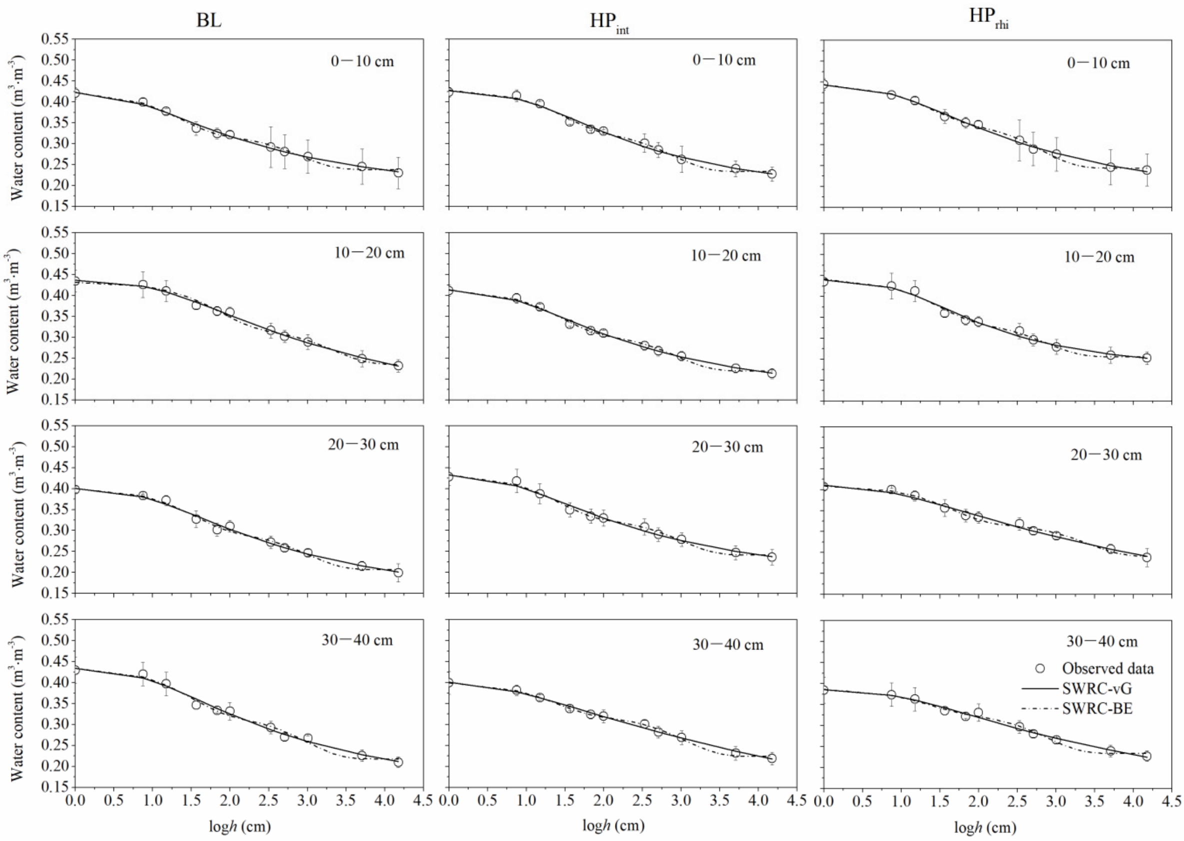


Figure 3. Comparison of soil water retention curves obtained by fitting the single porosity van Genuchten (1980) model (SWRCvG) and biexponential model (SWRCBE) to water content data measured on soil core samples collected from plot BL, inter-row location (HP_{int}), and honeysuckle planted location (HP_{rhi}) of plot HP.

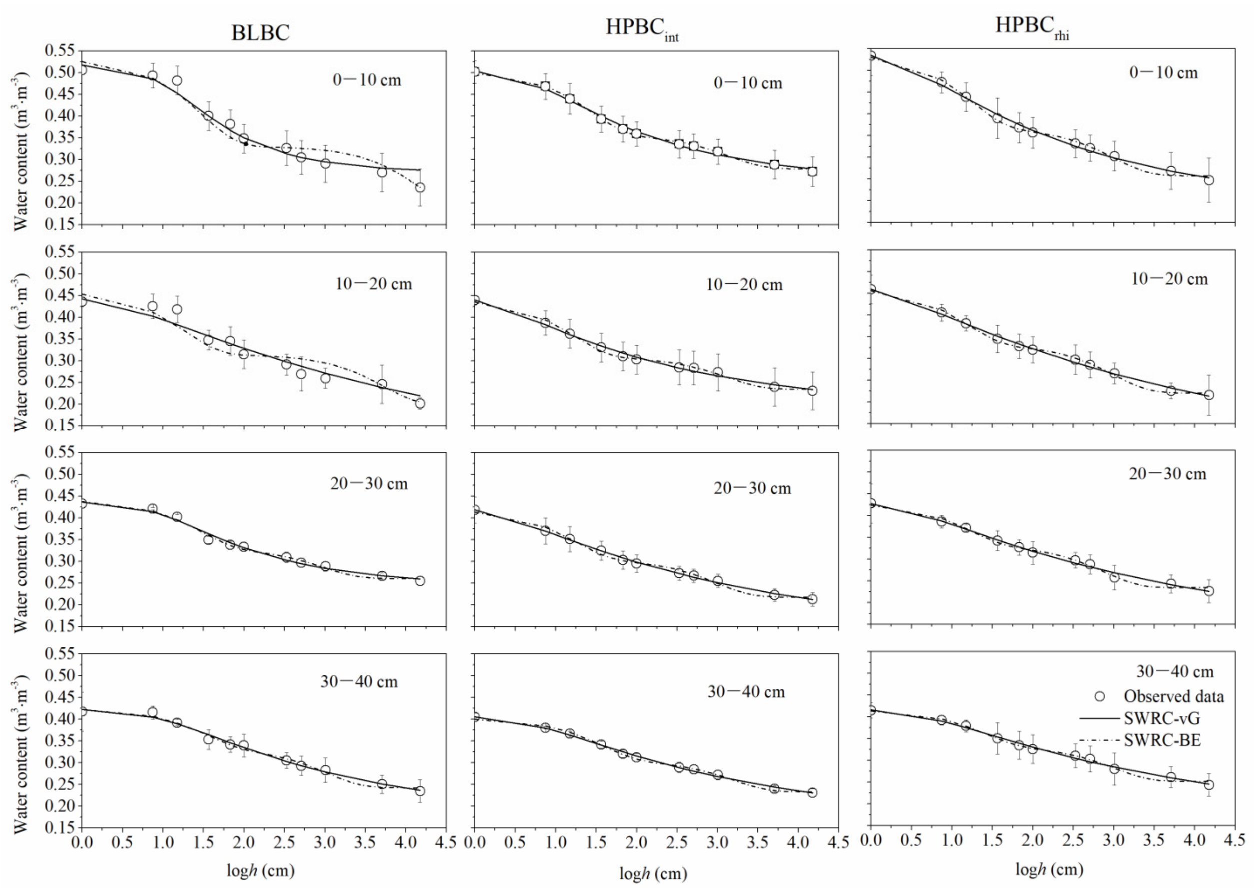


Figure 4. Comparison of the soil water retention curves obtained by fitting the single porosity van Genuchten (1980) model (SWRC-vG) and biexponential model (SWRC-BE) to water retention data measured on soil core samples collected from plot BLBC, inter-row location ($HPBC_{int}$), and honeysuckle planted location ($HPBC_{rhi}$) of plot HPBC.

Table 3. Fitted soil water retention parameters (mean ± std.) using vG and BE model in plots BL and HP.

Soil	Depth (cm)	vG Model				BE Model		
		θ_r ($m^3 \cdot m^{-3}$)	θ_s ($m^3 \cdot m^{-3}$)	n	S_{inf}	$\theta_{r\text{-}BE}$ ($m^3 \cdot m^{-3}$)	$\theta_{txt\text{-}BE}$ ($m^3 \cdot m^{-3}$)	$\theta_{str\text{-}BE}$ ($m^3 \cdot m^{-3}$)
BL	0–10	0.230 ± 0.025	0.421 ± 0.034	1.21 ± 0.08	0.035 ± 0.002	0.238 ± 0.034	0.102 ± 0.041	0.147 ± 0.015
	10–20	0.232 ± 0.016	0.435 ± 0.019	1.14 ± 0.04	0.034 ± 0.002	0.235 ± 0.028	0.108 ± 0.029	0.117 ± 0.014
	20–30	0.199 ± 0.009	0.398 ± 0.028	1.20 ± 0.03	0.026 ± 0.005	0.207 ± 0.038	0.102 ± 0.008	0.070 ± 0.007
	30–40	0.210 ± 0.012	0.430 ± 0.015	1.19 ± 0.09	0.022 ± 0.008	0.218 ± 0.029	0.112 ± 0.039	0.091 ± 0.008
HP_{rhi}	0–10	0.240 ± 0.038	0.445 ± 0.014	1.26 ± 0.08	0.046 ± 0.004	0.245 ± 0.037	0.086 ± 0.006	0.117 ± 0.037
	10–20	0.253 ± 0.015	0.436 ± 0.026	1.26 ± 0.06	0.034 ± 0.006	0.256 ± 0.016	0.103 ± 0.034	0.086 ± 0.012
	20–30	0.238 ± 0.022	0.407 ± 0.007	1.12 ± 0.05	0.023 ± 0.005	0.239 ± 0.025	0.090 ± 0.018	0.082 ± 0.013
	30–40	0.227 ± 0.013	0.385 ± 0.032	1.16 ± 0.08	0.024 ± 0.010	0.230 ± 0.014	0.067 ± 0.026	0.088 ± 0.017
HP_{int}	0–10	0.227 ± 0.017	0.423 ± 0.012	1.23 ± 0.11	0.037 ± 0.012	0.232 ± 0.015	0.097 ± 0.019	0.103 ± 0.026
	10–20	0.213 ± 0.012	0.412 ± 0.014	1.22 ± 0.07	0.034 ± 0.005	0.222 ± 0.011	0.105 ± 0.015	0.093 ± 0.011
	20–30	0.236 ± 0.018	0.429 ± 0.021	1.20 ± 0.04	0.027 ± 0.001	0.241 ± 0.017	0.105 ± 0.009	0.091 ± 0.011
	30–40	0.218 ± 0.015	0.400 ± 0.027	1.09 ± 0.02	0.021 ± 0.005	0.222 ± 0.013	0.084 ± 0.026	0.095 ± 0.016

Table 4. Fitted soil water retention parameters (mean ± std.) by using vG and BE model in plots BLBC and HPBC.

Soil	Depth (cm)	vG Model				BE Model		
		θ_r ($m^3 \cdot m^{-3}$)	θ_s ($m^3 \cdot m^{-3}$)	n	S_{inf}	$\theta_{r\text{-}BE}$ ($m^3 \cdot m^{-3}$)	$\theta_{txt\text{-}BE}$ ($m^3 \cdot m^{-3}$)	$\theta_{str\text{-}BE}$ ($m^3 \cdot m^{-3}$)
BLBC	0–10	0.290 ± 0.025	0.506 ± 0.035	1.51 ± 0.05	0.060 ± 0.015	0.183 ± 0.034	0.201 ± 0.071	0.148 ± 0.012
	10–20	0.256 ± 0.019	0.436 ± 0.044	1.09 ± 0.09	0.027 ± 0.004	0.198 ± 0.039	0.146 ± 0.051	0.117 ± 0.014
	20–30	0.255 ± 0.011	0.432 ± 0.021	1.33 ± 0.11	0.034 ± 0.008	0.261 ± 0.025	0.110 ± 0.049	0.070 ± 0.004
	30–40	0.235 ± 0.009	0.418 ± 0.051	1.18 ± 0.08	0.029 ± 0.005	0.243 ± 0.021	0.091 ± 0.012	0.092 ± 0.005
$HPBC_{rhi}$	0–10	0.288 ± 0.018	0.534 ± 0.045	1.26 ± 0.07	0.056 ± 0.012	0.256 ± 0.049	0.177 ± 0.088	0.107 ± 0.020
	10–20	0.233 ± 0.046	0.459 ± 0.033	1.19 ± 0.01	0.040 ± 0.004	0.220 ± 0.018	0.136 ± 0.069	0.110 ± 0.015
	20–30	0.232 ± 0.024	0.428 ± 0.045	1.20 ± 0.06	0.038 ± 0.007	0.234 ± 0.024	0.100 ± 0.072	0.096 ± 0.027
	30–40	0.257 ± 0.016	0.415 ± 0.018	1.23 ± 0.11	0.044 ± 0.015	0.250 ± 0.022	0.088 ± 0.050	0.079 ± 0.014
$HPBC_{int}$	0–10	0.272 ± 0.034	0.502 ± 0.026	1.28 ± 0.07	0.047 ± 0.012	0.279 ± 0.034	0.148 ± 0.016	0.079 ± 0.007
	10–20	0.232 ± 0.043	0.440 ± 0.011	1.23 ± 0.06	0.039 ± 0.002	0.233 ± 0.039	0.137 ± 0.031	0.075 ± 0.018
	20–30	0.213 ± 0.016	0.418 ± 0.030	1.18 ± 0.03	0.036 ± 0.007	0.218 ± 0.016	0.117 ± 0.015	0.087 ± 0.003
	30–40	0.231 ± 0.010	0.405 ± 0.010	1.16 ± 0.04	0.026 ± 0.005	0.233 ± 0.008	0.097 ± 0.015	0.073 ± 0.002

Rhizospheric soil (HP_{rhi}) at the top 20 cm showed the highest $\theta_{r\text{-}BE}$ compared to the inter-row soil and the soil in bare land (Table 3). $HPBC_{int}$ and $HPBC_{rhi}$ soil showed higher $\theta_{r\text{-}BE}$ at depths of 0–10 cm and 10–20 cm than that in the BLBC plot (Table 4). However, drainable soil textural porosity ($\theta_{txt\text{-}BE}$) showed the opposite pattern: bare land soil at the top 20 cm had the highest value while rhizospheric soil at the top 20 cm had the lowest value. The drainable structural porosity ($\theta_{str\text{-}BE}$) of the top 20 cm soil showed the same pattern as $\theta_{txt\text{-}BE}$, indicating a decrease of drainable soil porosity by honeysuckle planting.

The parameter n of vG model [28] is mostly related to soil texture rather than soil structure, and n is positively related to S_{inf}, which is an indicator of the soil physical quality. Dexter [33] proposed that the S_{inf} of soil water retention curve can be used as an index of soil quality because it reflects microstructural porosity. The values of inflection slope (S_{inf}) at a depth of 0–10 cm for different plots were relatively higher than other soil layers and followed the order, HP_{rhi} (0.046) > HP_{int} (0.037) > BL (0.035), which could reflect the marked impacts of plant roots on soil physical quality. Across soil profiles, lower S_{inf} values were observed at depths of 20–30 cm and 30–40 cm in both plot BL and plot HP. Higher S_{inf} values of shallow soil layers in plot HPBC than plot HP were found, which could be attributed to biochar amendment in soil. Comparison of plots BL and BLBC revealed that the treatment of biochar addition alone could have a significant positive influence on S_{inf} of unplanted soil ($p = 0.005$).

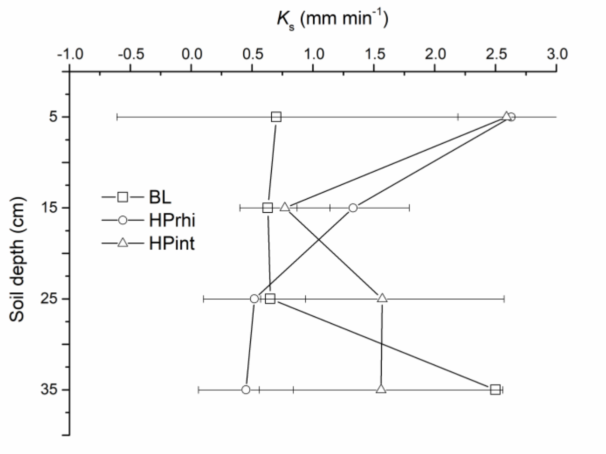
Different values of S_{inf} were proposed as an indication of good and poor soil pore systems. For example, Dexter and Czyz [34] proposed a S_{inf} value of 0.035 as the dividing line between soils with good and poor structural quality. However, Andrade and Stone [35] suggested that the S_{inf} value of 0.045 can be used to measure the soils with good structure conditions from degraded soils, while values of $S_{inf} \leq 0.025$ represent degrading soil physical state. As shown in Tables 3 and 4, the observed higher S_{inf} values of HP compared to bare land indicate a better soil structure developed by honeysuckle planting, and the higher S_{inf} values in plot HPBC (with an average value of 0.041) than plot HP (with an average value of 0.031) reflect a further positive contribution of biochar amendment on soil physical quality.

3.4. Soil Pore Distribution Estimated by SWRC

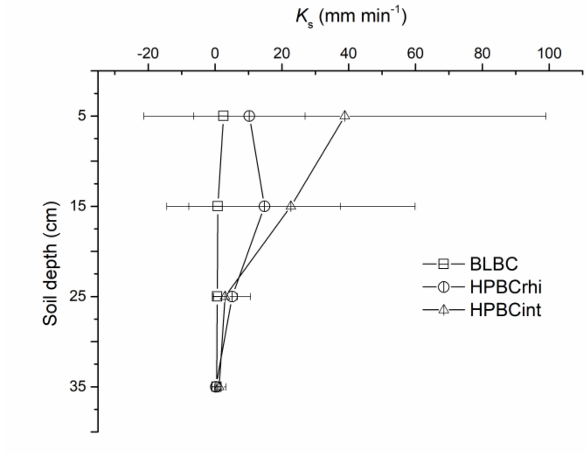
Analysis of characteristics of 3 pore size classes (i.e., $r > 125$ μm, $0.1 < r < 125$ μm and $r < 0.1$ μm) showed that pores with size $r > 125$ μm were dominant in the studied soil, At depth of 0–10 cm, relative percentage of pores with size $r > 125$μm was higher in plots with biochar amendment (plots BLBC and HPBC) ($p < 0.05$). At a depth of 10–20 cm, the highest relative percentage of pores with size $r > 125$ μm were observed in plot BLBC. Furthermore, at a depth of 10–20 cm, the difference in relative percentage of pores with $r > 125$ μm between HPBC and HP plot was smaller than their differences at a depth of 0–10 cm. At a depth of 20–30 cm, the gap is further narrowed for the relative percentage of pores with size $r > 125$ μm. However, when it comes to soil at a depth of 30–40 cm, all of the 3 pore size groups showed significant differences among plots ($p < 0.05$). HP_{rhi} and HP_{int} showed lower relative percentages of soil pores with size $r > 125$ μm, compared to BL. Contrastingly, $HPBC_{rhi}$ and $HPBC_{int}$ showed a higher relative percentage of pores with size $r > 125$ μm, compared to BLBC.

3.5. Saturated Soil Hydraulic Conductivity

Statistical analysis revealed that there are significant differences in K_s among all plots ($p = 0.005$). HP_{rhi} and HP_{int} topsoil showed higher K_s compared to BL, indicating an improvement of saturated water conductivity by honeysuckle planting (Figure 5a). Comparing K_s values between the topsoils of plots BLBC and HPBC (Figure 5b), it was found that honeysuckle planting could lead to a greater increase of saturated water conductivity in biochar amended soil ($p = 0.000$).



(**a**)



(**b**)

Figure 5. (**a**) Mean values and standard deviations of saturated soil hydraulic conductivity (K_s) for BL, HPrhi and HPint; (**b**) Mean values and standard deviations of saturated soil hydraulic conductivity (K_s) for BLBC, HPBCrhi and HPBCint. Note: BL—bare land treatment; HPrhi—planted location in honeysuckle planting treatment; HPint—inter-row location in honeysuckle planting treatment; BLBC—bare land with biochar; HPBCrhi—planted location in honeysuckle planting plus biochar addition plot; HPBCint—inter-row location in honeysuckle planting plus biochar addition plot.

3.6. Linking Treatment with Soil Properties

Soil bulk density was negatively correlated with relative percentages of pores with size $r > 125$ μm, $\theta_{r\text{-BE}}$ and $\theta_{txt\text{-BE}}$. Soil pH was negatively correlated with relative percentages of pores with size $r > 125$ μm and $\theta_{r\text{-BE}}$, and positively correlated with relative percentages of pores with size $r < 0.1$ μm. No relationships of soil organic matter content with soil pore characteristics were observed (Table 5).

Table 5. Correlations of basic soil properties with soil pore characteristics at 0–40 cm soil for all studied plots.

Soil Basic Properties	Soil Pore Characteristics						
	$r > 125$ (μm)	$0.1 < r < 125$ (μm)	$r < 0.1$ (μm)	$\theta_{r\text{-BE}}$ ($m^3.m^{-3}$)	$\theta_{txt\text{-BE}}$ ($m^3.m^{-3}$)	$\theta_{str\text{-BE}}$ ($m^3.m^{-3}$)	Total Porosity %
Bulk density	−0.461 **	−0.068	0.224	−0.299 *	−0.402 **	0.092	−1.000 **
pH	−0.301 *	−0.246	0.324 *	−0.273 *	−0.239	0.027	−0.275 *
SOM	0.053	0.119	−0.123	−0.085	−0.074	0.209	−0.017

* means significance at 0.05 level, and ** means significance at 0.01 level.

Results of two-way ANOVA analysis of the interaction between honeysuckle plant roots and biochar amendment on soil pore characteristics are presented in Table 6. Honeysuckle planting only caused a significant influence on pores with size $r < 0.1$ μm, while biochar amendment caused significant influences on pores with size $r > 125$ μm and $r < 0.1$ μm. Interaction of honeysuckle planting and biochar addition caused significant changes in relative percentages of pores with size $r < 0.1$ μm and 0.1 μm $< r < 125$ μm.

Table 6. P values of the interaction between honeysuckle planting and biochar amendment on soil pores estimated by SWRC.

Treatment	$r < 0.1$ μm	0.1 μm $< r < 125$ μm.	$r > 125$ μm
Honeysuckle planting	0.049	0.177	0.168
Biochar amendment	0.001	0.053	0.000
Honeysuckle planting × Biochar	0.004	0.009	0.112

3.7. SEM

SEM ananlysis found honeysuckle planting was positively correlated to the latent variable "soil structure" (Figure 6, $R^2 = 0.35$, $p < 0.05$), but the relationships of honeysuckle planting with K_s, θ_r and θ_s were not significant ($p > 0.05$). Biochar amendment showed positive relationships with "soil structure" ($R^2 = 0.45$, $p < 0.05$), saturated soil water conductivity K_s ($R^2 = 0.48$, $p < 0.05$), and saturated water content ($R^2 = 0.31$, $p < 0.05$), while biochar amendment exhibited no significant relationships with soil residual water content ($p > 0.05$). A better "soil structure" could lead to a higher θ_s but a lower θ_r ($p < 0.05$). SOM content had a strong positive relationship with soil residual water content; however, there was no significant relationship between SOM content with K_s ($p > 0.05$) and θ_s ($p > 0.05$). A higher SOM content may be associated with a better "soil structure", but this positive bidirectional relationship was not statistically significant ($R^2 = 0.09$, $p > 0.05$).

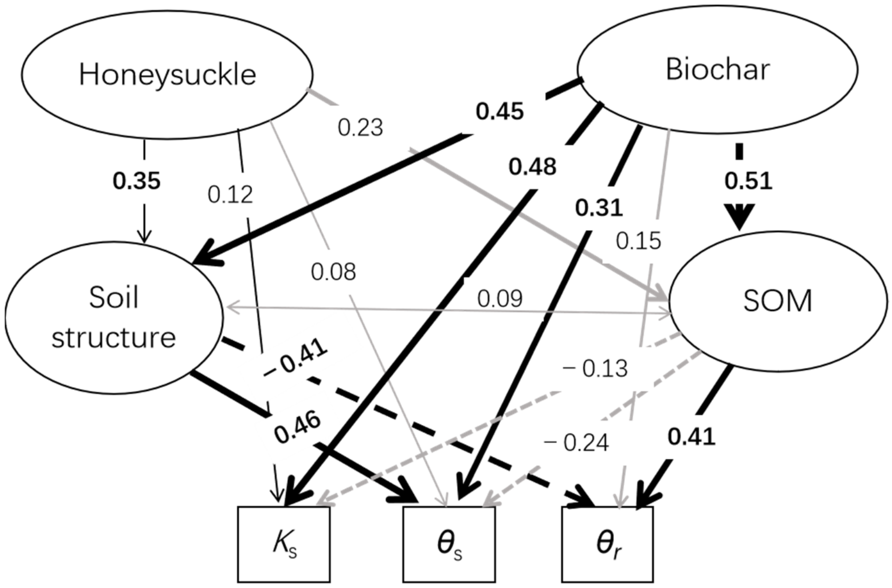


Figure 6. Results of SEM path analysis. Arrows represent the directionality of influence, with negative relationships represented by a dashed line. Black indicates a significant relationship ($p < 0.05$) and grey represents an insignificant relationship ($p > 0.05$). Thicker lines represent stronger correlations. Note: SOM—soil organic matter; K_s—saturated soil hydraulic conductivity; θ_s—saturated water content; θ_r—residual water content.

4. Discussion

4.1. Effects of Honeysuckle Planting

Honeysuckle planting decreased soil pH and showed higher SOM in plot HP, as compared to the soil in bare land (Table 1). This implied that honeysuckle plant roots affected the soil properties of the HP plot. The decrease in soil pH indicated the function of honeysuckle planting to neutralize the alkalinity of purple soil in this studied area. Previous studies in soils with similar genesis reported a decrease of soil pH by frequent cultivation in sloping low land [24]. The observed higher SOM in plot HP, which indicates the enrichment of SOM by planting through leaf litter return to soil, might be one mechanism of soil neutralization by planting [36]. With honeysuckle planting, root exudate and soil microbial activities inspired by soil organic matter would be another mechanism of soil neutralization [37,38].

Honeysuckle planting improved soil structure and water retention of the purple soil (Table 3). The observed higher value of S_{inf} in HP_{rhi} than bare land indicates a better soil physical quality as a result of the growth of honeysuckle roots. These results implied that honeysuckle roots altered the poor structure of purple soil in the studied area. Furthermore, honeysuckle planting improved the saturated soil hydraulic conductivity, as compared to bare land (Figure 7a). The root development of honeysuckle changed the pore system through the mechanical moving of soil particles and aggregates [37], which is crucial in macropore formation. The formation of soil macropores can change soil structure and hydraulic conductivity and thus lead to greater water infiltration in the soil. Our results are consistent with Luo et al. [39], who reported that plant roots increased the saturated hydraulic conductivity of soil covers in a four-year field experiment in South China. Meanwhile, the decreased soil organic matter by litter leaf and rhizospheric decomposition of the honeysuckle roots could improve soil water retention and water-stable aggregates, which is in agreement with the results of a previous study with other perennial plants [40]. Our results suggest that honeysuckle planting could be considered as a measure to improve soil hydraulic properties and optimize the water management in sloping farmland of this purple soil area, which is prone to drought stress [14,41].

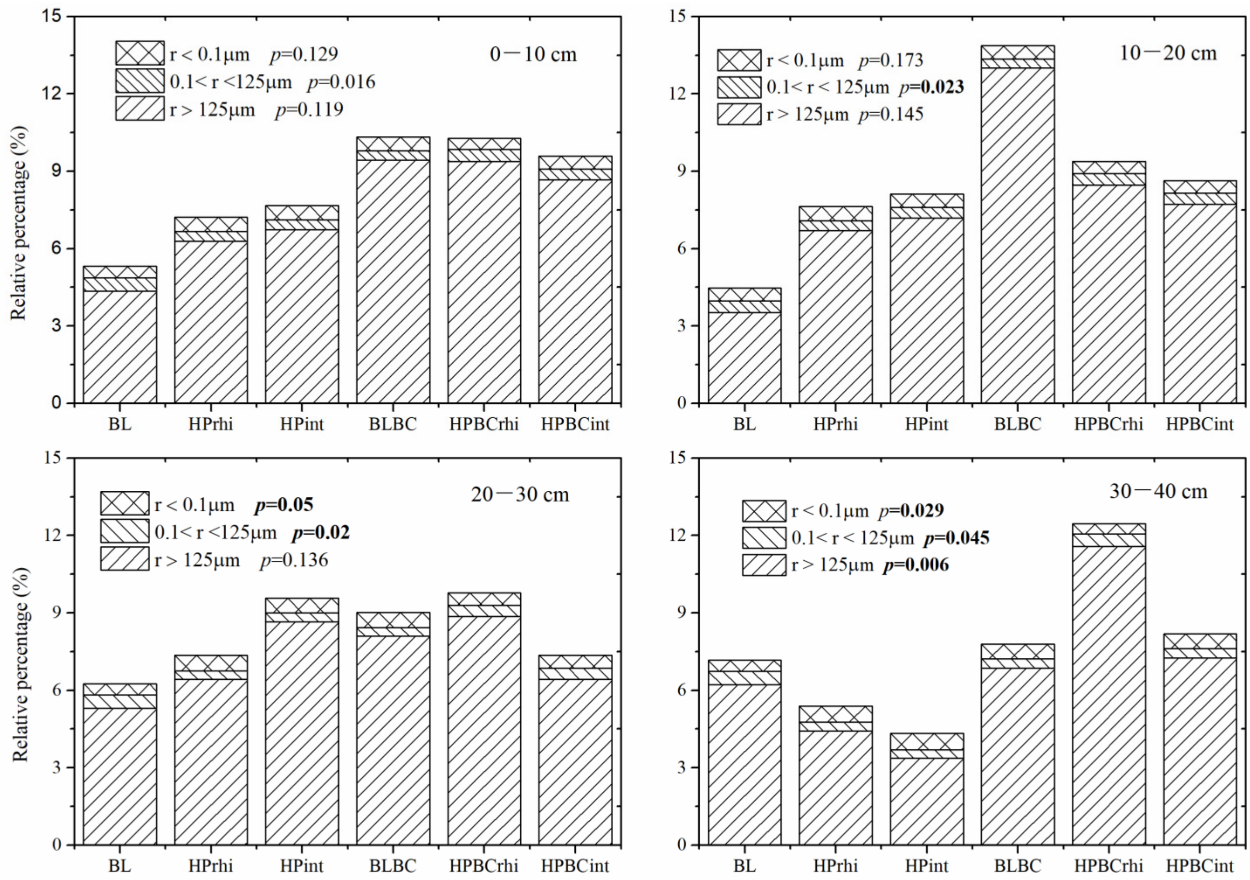


Figure 7. Relative percentages of three pore size groups calculated from SWRC for each soil layer in experimental plots. Note: BL—bare land treatment; HPrhi—planted location in honeysuckle planting treatment; HPint—inter-row location in honeysuckle planting treatment; BLBC—bare land with biochar; HPBCrhi—planted location in honeysuckle planting plus biochar addition plot; HPBCint—inter-row location in honeysuckle planting plus biochar addition plot.

4.2. Effects of Biochar Amendment

The application of biochar increased SOM content and reduced soil bulk density (Table 2). This implied that biochar improved the soil structure of purple soil with high organic matter and high soil porosity of the studied area. Biochar is a carbon-rich, porous material produced from different biomass products such as plants, animals, and sewage in a limited oxygen environment [42–44] and is widely known as a potential soil amendment to improve soil quality [45,46]. Thus, the addition of biochar in the soil directly increases soil porosity and reduces bulk density [47] due to the higher porosity and lower bulk density of biochar than soil [48]. Alternatively, the much higher carbon content of biochar than soil (about 83%) is responsible for the observed increases in SOM content upon biochar amendment. Our results conform to the previous study's findings of [46,48–52]. Moreover, biochar amendment improved soil structure. First, biochar increased the content of macropores in the purple soil, in particular, that of pores $r > 125$ μm (Figure 5). A previous study on shallow entisol [17] found that biochar increased mesoporosity and decreased macroporosity of soil. Secondly, biochar increased soil physical quality, as indicated by a higher value of S_{inf} (Table 4). The results are consistent with Liu et al. [15], who reported an increase in S_{inf} index of purple soil under cropping rotations of winter wheat and summer maize by biochar treatment. Generally, biochar has a highly porous structure with higher porosity and larger surface area than soil [53], and biochar application could increase soil porosity as well as soil structure. For example, Blanco-Canqui et al. [47] observed that biochar increased the percentage of porosity by 14 % to 64 %, implying that the addition of biochar in soil improved soil structure.

Biochar amendment could also enhance soil water retention (Figure 7) due to biochar's larger amount of pores and specific surface area, which might result in an increase in the content of available water in soil [46]. Our findings are similar to that of Wong et al. [54], who reported that biochar addition increased the saturated hydraulic conductivity of kaolin clay. On the contrary, Ni et al. [55] reported that biochar decreased saturated hydraulic conductivity in a two-year field study. Biochar effects are strongly dependent on soil type [46], and the differences in the type of feedstock and pyrolysis temperature could also partly explain the inconsistent results obtained in different studies.

4.3. Interactive Effects of Planting and Biochar

In our study, the neutralization effect of honeysuckle planting combined with biochar addition was observed in the alkaline purple soil. Honeysuckle plants improved the SOM of the studied area; these results implied the improvement of purple soil structure and hydraulic properties. The SOM increase was a result of inputs from aboveground litter, root decay, and rhizo-decomposition [56]. Biochar application in soil with organic matter from plants could catalyze the oxidization of biochar and may form acidic organic matter [57], further producing acidic matter [58,59]. The formation of acidic organic functional groups in the soil can neutralize the alkalinity of the soil. A mesoscomstudy by Ntacyabukura et al. [44] reported that biochar increased soil pH in Eutric regosols called purple soil, which is inconsistent with the results of our present study. Apparently, this difference is due to honeysuckle planting, which neutralized not only the alkaline purple soil but also the alkaline (pH 10.22) biochar amended in our study.

Honeysuckle planting after biochar application can facilitate the relocation of biochar to the deep soil layers depth through root growth (to a depth of 40 cm). Therefore, the presence of roots together with the relocated biochar in the deep layers may be responsible for the observed increases in SOM content. The increased SOM would accelerate soil microbial activity and further improve soil aggregate stability and soil physical quality [60,61]. A previous study by Wang et al. [62] reported that biochar alone could improve soil structure as well as soil aggregate stability in Yolo soil. Our findings suggest that implementation of both honeysuckle planting and biochar addition in purple soil can increase the SOM and moreover enhance the soil quality in hilly areas of the Sichuan basin.

A previous study by Wang et al. [14] reported that macropores contributed more than 87.9% to water flow in the shallow entisol. All changes of soil structure induced by planting and biochar amendment would functionally lead to an increase in soil hydraulic conductivity. The increased amount of macropores with size $r > 125$ μm in purple soil by honeysuckle planting and biochar application would lead to a more dominant role of the $r > 125$ μm pores in conducting water flow. Our findings suggest that the combination of honeysuckle planting and biochar may promote water infiltration and thus minimize the occurrence of surface runoff, which could help in water conservation and the reduction of soil erosion in farmland with purple soil.

5. Conclusions

A six-year field experiment was conducted to explore the interactive effects of honeysuckle planting and biochar addition on soil physical structure and hydraulic properties of farmland purple soil in hilly areas of the Sichuan basin, China. The results showed that honeysuckle planting alone could improve soil physical quality, and a greater improvement can be achieved by the implementation of both honeysuckle planting and biochar amendment. Soil aggregate stability can be enhanced by the combination of honeysuckle planting and biochar amendment. Biochar amendment significantly increased the saturated soil hydraulic conductivity directly or indirectly through increasing soil organic matter content. Both honeysuckle planting and biochar amendment can lead to a greater increase in saturated soil water content than saturated soil water conductivity. The findings of this study suggest that honeysuckle planting and biochar amendment can be considered as potential measures to improve soil quality and agricultural water management in sloping farmland of purple soil and other similar soils that are prone to seasonal drought and soil erosion.

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