

INFLUENCE OF SOIL HYDRODYNAMIC AND PHYSICOCHEMICAL PROPERTIES ON TEA GROWTH IN HILLY REGIONS: A CASE STUDY OF QINBA MOUNTAIN

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ABSTRACT

This study used the Van Genuchten model to estimate soil hydrological processes in four different tea growth zones in the main tea-growing region of Qinba Mountain and analyzed the physicochemical properties of soils to provide a scientific basis for selecting and planning tea cultivation in hilly regions of China. The retention capacity of soil water, water release properties, unsaturated hydraulic conductivity, diffusivity of soil water and porosity in the various regions were also assessed. The analysis results showed that the tea plantations in the Qinba Mountains consisted primarily of muddy clay, while when growth was poor, both the water content and the bulk density were significantly higher compared to other growing areas and the sand content, organic matter and porosity were the lowest. Conversely, luxuriant growth had the highest sand content and the lowest silt content. The characteristic curve for soil moisture was precisely adjusted using the V-G model with an R² value of over 0.99. In addition, the index $K(x) = a \cdot \exp(b \cdot x)$ effectively described water absorption and unsaturated hydraulic conductivity, resulting in an R² value of over 0.90. The moisture content of the soil and the diffusivity of the soil water were cleverly modelled using the exponential function $D(\theta) = aeb\theta$, with the R² value exceeding 0.99. In the entire suction sector, the water holding capacity was rated as weak growth > moderate growth > well growth = lush growth. Optimal water delivery capacity was observed in areas of weak growth, while areas with well growth had the least favorable performance. The order of unsaturated hydraulic conductivity in the four areas was as follows: lush growth, well growth, moderate growth, and poor growth. In addition, the diffusivity of soil water gradually increased as the moisture content of the soil volume increased and approached an infinite increase as the volume moisture content approached saturation. When choosing hilly areas for growing tea, the optimal soil texture should be loose and well-aerated clay soil with higher sand and lower silt content, high porosity, low bulk density and high organic matter content. In addition, the high water diffusing capacity and the moderate water holding capacity of the soils enable effective drainage and water storage under various conditions.

Keywords: Tea growth; Hydrodynamic properties; Soil structure; Soil water characteristic curve

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INTRODUCTION

Camellia sinensis, commonly referred to as the tea plant, is an evergreen shrub in the family Theaceae, prized for its young leaves and buds utilized in tea production (Ji *et al.*, 2017). In recent years, tea cultivation in hilly areas has emerged as a primary strategy for regions in China that are constrained by natural conditions and face challenges in economic development, aiming to cultivate economically valuable crops (Zhao *et al.*, 2022). However, during extensive development of hilly tea plantations, insufficient consideration of tea plant growth characteristics has led

to sub-optimal site selection, resulting in reduced tea survival rates and declining tea quality (Liu *et al.*, 2023). Tea plants require specific growth conditions, with optimal soil, water, and nutrient availability being essential for their health and high-quality leaf production (De Silva 2007; Hasan *et al.*, 2023). Neglecting these requirements can lead to poor plant growth, soil degradation, water wastage, and other ecological issues (Le *et al.*, 2021). Proper management of these factors is crucial for sustainable tea cultivation.

The study of hydrodynamic characteristics and physicochemical properties of soils in hilly tea plantations plays a crucial role in fostering tea plant

growth, optimizing tea yield and quality, and safeguarding ecological environments (Zhang *et al.*, 2020). In a study examining the influence of soil hydrodynamic characteristics and pore structure under varying plant growth conditions. Duwig *et al.*, (2019) observed significant alterations in total porosity and infiltration macroporosity. These changes subsequently impacted soil water characteristics, including saturated hydraulic conductivity and water retention. The hydrodynamic properties of soil govern its capacity to retain and release water. Key parameters such as the soil moisture characteristic curve, specific water capacity, unsaturated hydraulic conductivity, and soil moisture diffusion rate play pivotal roles in soil hydrodynamics, reflecting its hydraulic conductivity, water storage, and supply capacity (Assouline *et al.*, 1998). These parameters are influenced by factors including the organic matter content, soil texture, and soil structure, thereby impacting the movement and distribution of water within the soil (Balkhair, 2016).

The soil moisture characteristic curve serves as a cornerstone hydraulic parameter, revealing the relationship between soil matrix potential and water content. It intricately captures the interplay between energy and quantity indicators of soil water dynamics. This curve plays a pivotal role in analyzing water holding capacity, soil moisture availability, and examining the retention and supply of soil moisture within the soil-plant-atmosphere continuum (SPAC) (Rheingantz and Duckworth, 2021). Numerically akin to the slope of the soil moisture characteristic curve, specific water capacity diminishes as suction increases, playing a crucial role in comprehending soil moisture dynamics. It quantifies the volume of water that a specific mass of soil can either release or retain for plant utilization across varying unit suctions, thereby delineating the efficacy and extent of its water supply capability. Thus, it emerges as a pivotal metric for assessing drought resilience (Jabro *et al.*, 2020). The specific water capacity exhibits variation across different suction ranges due to the nonlinear nature of the soil moisture characteristic curve.

Unsaturated hydraulic conductivity refers to the ability of groundwater to permeate through soil or rock pores per unit area when saturation is not achieved. Soil water infiltration primarily transpires under unsaturated conditions, thereby establishing a close association between unsaturated hydraulic conductivity and soil texture, porosity, and compaction (Köhne *et al.*, 2009). Malama and Kuhlman (2015), study delves into the influence of soil hydrodynamic characteristics on infiltration using the closed-form three-parameter model. The findings indicate a negative correlation between unsaturated hydraulic conductivity and soil bulk density, while a positive correlation is observed with total porosity. Soil water diffusivity, a vital parameter in soil water movement, quantifies the distance of soil water

diffusion over a given unit of time and is intricately linked with water content. This parameter serves as a reflection of soil porosity, pore size, and spatial distribution (Shi *et al.*, 2020).

In terms of modeling of soil moisture characteristic curves, commonly employed empirical formulas include the Brooks-Corey model, Van-Genuchten model, and Gardner model (Du 2020; Haghverdi *et al.*, 2020). Among these, the Van-Genuchten (V-G) model stands out as the most prevalent. Pan *et al.*, (2019) conducted a comparative analysis of the curve-fitting coefficients of each model and concluded that the V-G model exhibits high accuracy. Furthermore, Mishra *et al.*, (2020), through an analysis of simulation performance using different optimization algorithms, observed that the V-G model effectively fits measured values on the "S" curve. Additionally, some studies have noted that besides its fitting prowess, the V-G model can also establish correlations with fundamental physical soil properties such as particle gradation and bulk density (Wang and Ni, 2023).

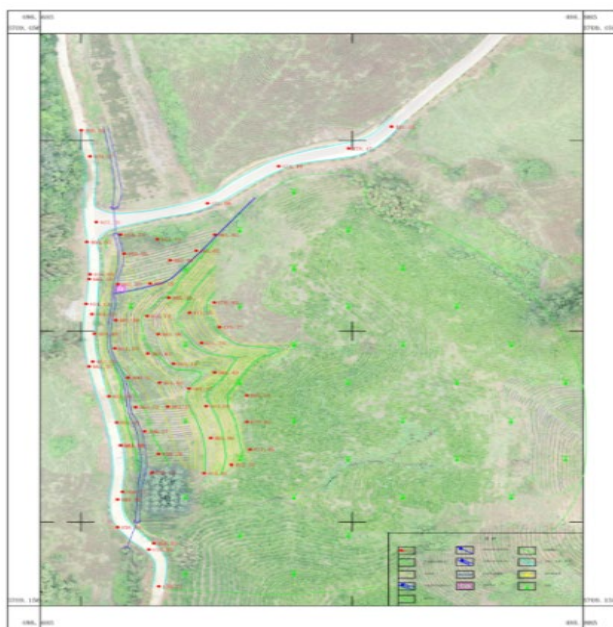
Currently, research on the physicochemical and hydrodynamic properties of soils in hilly tea-growing areas is primarily focused on arable land, with relatively limited studies relating to the cultivation of tea plants. As a result, the hydrological mechanisms of soil during the transition from ecological to economic land remain unclear. Investigating the hydrological properties of tea plantations under different growth conditions is promising to reduce soil erosion, protect water resources increase tea yield. Likewise; Van-Genuchten model to estimated soil hydrological processes under four distinct tea growth areas in the primary tea-producing region of the Qinba Mountain, China. And the analysis the comparison among soil water holding capacity, water release characteristics, unsaturated hydraulic conductivity, soil water diffusivity, and porosity across different growth areas of tea plantations. With this study, we want to create a scientific basis for the rational selection and planning of tea-growing areas. This will facilitate the coordinated ecological and economic development of the hill regions and ultimately contribute to the sustainable development of the tea industry.

MATERIALS AND METHODS

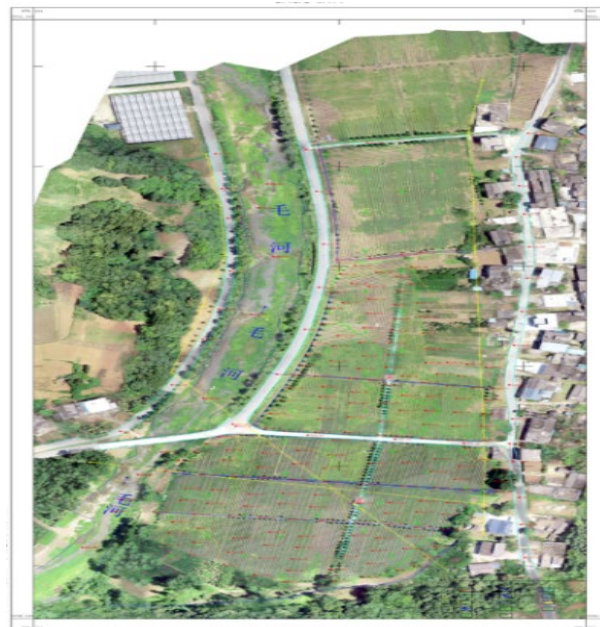
Study Area Profile: The Qinba mountain region represents the northernmost extension of the natural distribution of tea trees in China. It is located in the Qinling and Dabashan Mountains and covers the headwaters of the Han River. It is a confluence area that includes Shaanxi, Chongqing, Sichuan, and Hubei provinces. This region is characterized by a favorable natural environment, fertile soil, abundant sunlight and suitable temperatures, and essentially meets the growing requirements of tea trees (Long *et al.*, 2022). Shangnan

County is situated in the southeastern region of Shangluo, within the Qinba Mountain region. It falls within the middle reaches of the Dan River. Shangnan County boasts abundant water and heat resources, albeit with uneven spatiotemporal distribution characterized by notable variations in temperature and precipitation. The northern and northwestern regions fall within the warm temperate climate zone, constituting 49.3% of the area, while the central and southern regions belong to the northern subtropical climate zone, comprising 50.7%. The study area encompasses Shima Town and Chengguan Town in Shangnan County. The Qinyuan Spring Tea Factory in Shima Town (33 °31.345 °N 110

°46.961 E) is situated in the western part of Shangnan County, formerly a river beach that was subsequently transformed into a tea cultivation base after soil amelioration. The terrain of the experimental area is predominantly flat, with higher elevation in the south and lower in the north. Conversely, the Guashan Tea Factory in Chengguan Town (33 °30.473 °N 110 °51.807 °E) lies in the southwest of Shangnan County, previously a shrubland that underwent reclamation and conversion into a tea cultivation base. The topography of this experimental area features a combination of river valleys, hills, and middle to low mountain areas (Figure 1).



(a)



(b)

Figure 1. Image map of the study area.; Image map of the study area: (a) Qinyuan Spring Tea Factory (b) Guashan Tea Factory.

Soil sample collection: After the survey of study areas, four types of land were selected as typical sample areas under conditions of poor growth, moderate growth, well

growth and luxuriant growth (Defined by biomass, 100-grain weight and growth density) (Prematilake *et al.*, 2004; Zhang *et al.*, 2020; Long *et al.*, 2022), (Table 1).

Table 1. Conditions for Defining the Study Area.

Growth categories	Biomass(t·hm-2)	Hundred-grain Weight(gram)	Growth Density(plants·hm-2)
poor growth	10	≤100	50000
moderate growth	15	100~110	60000
well growth	20	110~120	67500
luxuriant growth	25	>130	75000

Three standard plots were randomly arranged according to the cultivated land of 5 m ×5 m in each growth category region (Figure 2). A total of 252

disturbed and undisturbed soil samples in triplicates from each allocated study areas at 0-20 cm soil depth were collected using a cutting ring with a volume of 100 cm³

per sample. Moreover, disturbed soil samples weighing approximately 1.0 kg were collected via dichotomy. The collected soil samples were promptly sealed and

cryopreserved for transportation back to the laboratory. Subsequently, the relevant parameters were determined.

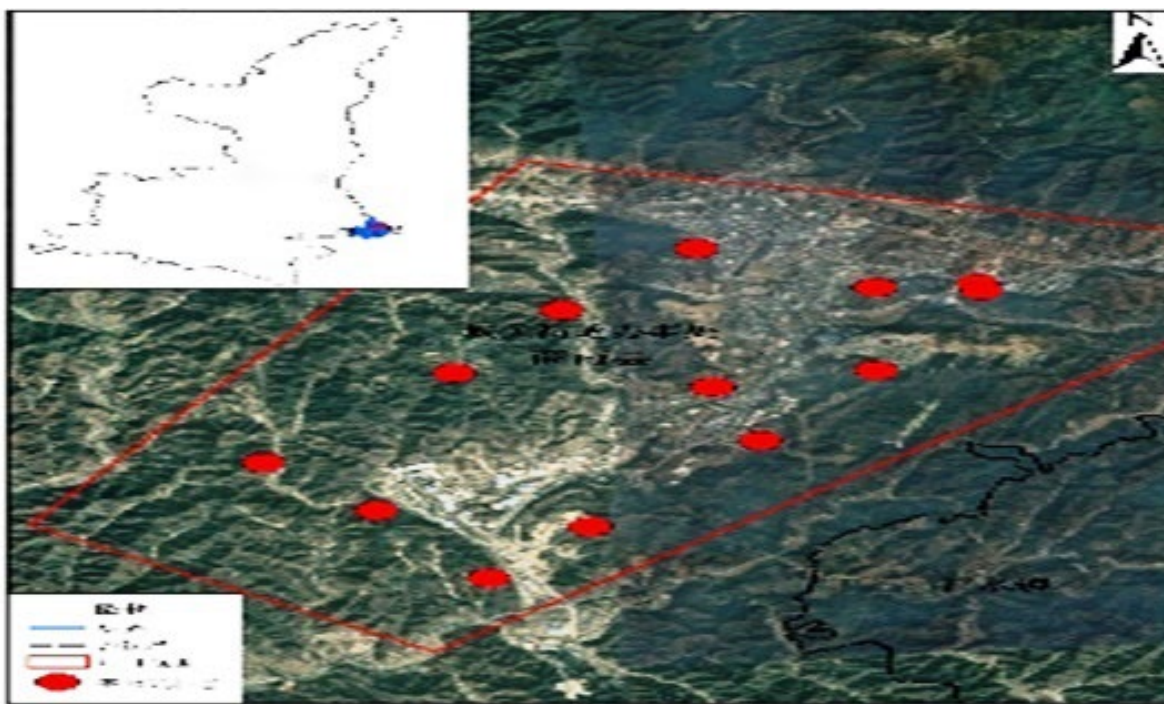


Figure 2. Study area and sampling site in Shangnan city.

Methods: The total soil porosity was determined using the pycnometer method (Hao *et al.*, 2008), soil organic matter content was assessed via the potassium dichromate external heating method in soil agrochemical analysis (Nelson and Sommers, 1982), and soil Bulk density by using the ring knife method (Grossman and Reinsch, 2002). Soil samples underwent treatment with 10% hydrogen peroxide and 10% hydrochloric acid to eliminate organic matter and carbonate. Subsequently, ultrasonic dispersion with sodium hexametaphosphate as a dispersant was employed prior to determining soil particle size using the Mastersizer 3000 laser particle size analyzer (Bieganski *et al.*, 2018). Soil texture classification was determined using the USDA soil texture classification standard triangle map (Moreno-Maroto and Alonso-Azcarate, 2022). Unsaturated hydraulic conductivity was measured using the Ku-pf unsaturated hydraulic conductivity measuring system (Bormann and Klaassen, 2008). Soil moisture characteristic curves were established based on the measured data of soil particle composition, utilizing the soil conversion function method, the PTFs method, and the neural network method to establish the functional relationship between the parameters of the soil moisture characteristic curve and soil basic physical properties. Finally, the variation curve of soil water content with increasing soil water suction was obtained using V-G

model by using formula (1), while for specific water capacity formula (2) were used.

$$\theta = \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^m} - \theta_r, \quad (1)$$

While f soil can be obtained from formula (1),

$$C(h) = \frac{d\theta}{dh} = -(\theta_s - \theta_r) m n \alpha^n \frac{h^{n-1}}{[1 + (\alpha h)^n]^{m+1}}, \quad (2)$$

The θ is the soil volume water content (cm³/cm³). The θ_r is the soil residual water content (cm³/cm³). θ_s is the soil saturated water content (cm³/cm³). The α is approximately the reciprocal (cm⁻¹). The h is the soil water suction (kPa). The n and the m are the parameters that control the shape of the soil water characteristic curve, where m is the soil specific water capacity (cm³·kPa).

The diffusivity of soil water was determined using the horizontal soil column method. Firstly, the Mariotte bottle water supply valve was opened and the start time was recorded. Then the time required for the wetting peak to move forward 10 cm was recorded visually. In triplicates the water supply valve was closed when the wetting peak reaches 120 cm and the end time was recorded and soil from the wetting peak was quickly taken at every 10 cm. The weight and water content of soil samples were determined by drying method. Finally,

the bulk density is utilized to calculate the soil volume water content. Water diffusivity ($D(\theta)$, cm²/min) is obtained by formula $\lambda = xt^{-1/2}$ transformation to obtain Boltzmann transformation parameters (λ , cm²/min), that is following formula (3),

$$D(\theta) = \frac{-1}{2(\Delta\theta/\Delta\lambda)} \left(\sum_{\theta_t}^{\theta} \lambda(\theta) \Delta\theta \right), \quad (3)$$

Data analysis: The data is computed using Excel 2019, based on the physical characteristics of the soil, such as the bulk density and percentage content of the particle composition. The parameters required for the V-G model were output using RETC, the data computed by the model is fitted to the measured data and with SPSS 27.0 coefficient R² is obtained. One-way analysis of variance was used to assess for significance (One-Way ANOVA). The Pearson correlation coefficient method was used to determine the correlation between each parameter and Origin 9.0 were used to organize the figures.

RESULTS

Basic Physical and Chemical Properties of Soil: The soil water content in the poor area was significantly higher than that in other areas ($P \leq 0.05$). The overall performance was as follows: poor growth (9.67%) > moderate growth (7.38%) > well growth (5.93%) > luxuriant growth (4.79%) (Table 2). Under the soil depth of 20 cm, the content of organic matter in the luxuriant growth was close to that in the well growth, which is higher than that in the moderate growth and the poor growth. The overall bulk density was as follows: luxuriant growth (1.44 g/cm³) > well growth (1.37 g/cm³) > moderate growth (1.21 g/cm³) > poor growth (1.19 g/cm³). However, it is significantly lower than the well growth and the luxuriant growth. In terms of porosity, contrary to the law of bulk density, the total soil porosity of the four growth areas was luxuriant growth (35.12%) > well growth (31.47%) > moderate growth (28.49%) > poor growth (26.14%). There was significant difference between luxuriant growth and poor growth ($P \leq 0.05$).

Based on the analysis of clay, sand, and silt contents in the four growing areas, the soil quality type was classified as silty loam according to the classification method of the United States Department of Agriculture (Figure 3). The content of silt (62.41%-71.48%) is the highest, followed by the content of sand (23.44%-33.80%). The content of clay (3.79%-6.56%) is the least. In the mechanical composition of soil, except for the excellent growth, the sand content in well growth is relatively high while; poor growth is the lowest. As far as silt content is concerned, the luxuriant growth is the lowest. Poor growth is the highest with clay content is at moderate growth, and the luxuriant growth is the lowest for the well growth and the moderate growth, the content of sand, silt and clay is between the luxuriant growth and the poor growth.

Output Parameters of V-G Model and Correlation Analysis of Each Index:

The soil physical properties measured by the experiment are inputted into RETC software, the initial parameters (θ_s , θ_r , α , n) of V-G model in each region are obtained. Where θ_r the soil moisture content is whose derivative of the soil moisture characteristic curve is zero. θ_s is the soil moisture content whose soil suction is close to zero. Based on the initial parameters obtained and the measured soil water content of different millimeter water column under different water suction, the soil moisture characteristic curves of 0-20 cm soil depth in different regions were obtained by fitting with VG model. The curves are all in the shape of "S" and their determination coefficients R² are all greater than 0.99. All of them reached a significant level ($P \leq 0.01$). As shown in table 3, the values of the θ_r in four regions are between 0.0033 cm³/cm³ and 0.0071 cm³/cm³. The values of θ_s are between 0.2379 cm³/cm³ and 0.2974 cm³/cm³. The values of θ_r and θ_s of each region are different, in which the value of θ_s of poor growth is the smallest while the value of luxuriant area is the largest. The value of θ_r of luxuriant growth is the smallest while the value of moderate growth is the largest. The values of α are between 0.0284cm⁻¹ to 0.0301cm⁻¹. The values of n range from 4.2253 to 4.5015.

Table 2. Analysis of physical and Chemical Properties and Mechanical composition of topsoil in different growing areas

Growth Regions	Water Content (%)	Organic matter (g·kg ⁻¹)	weight capacity (g·cm ⁻³)	Total porosity (%)	Mechanical composition (%)		
					Sand(mm)	Silt(mm)	Clay(mm)
Poor growth	9.67±1.09 ^a	8.21±2.31 ^a	1.63±0.10 ^a	26.14±2.57 ^c	23.44±2.31 ^b	71.48±2.24 ^a	5.08±0.39 ^b
Moderate growth	7.38±1.57 ^a	10.67±2.64 ^a	1.51±0.07 ^{ab}	28.49±3.42 ^{bc}	26.35±5.34 ^b	67.09±6.39 ^{ab}	6.56±0.28 ^a
Well growth	5.93±0.79 ^b	13.44±3.77 ^a	1.44±0.02 ^b	31.47±1.64 ^{ab}	31.44±4.19 ^a	64.14±3.61 ^b	4.42±1.02 ^{bc}
Luxuriant growth	4.79±1.04 ^b	12.45±7.00 ^a	1.37±0.04 ^c	35.12±2.25 ^a	33.80±4.79 ^a	62.41±4.93 ^b	3.79±0.16 ^c

Values carrying different superscripts in a column differ significantly ($P \leq 0.05$)

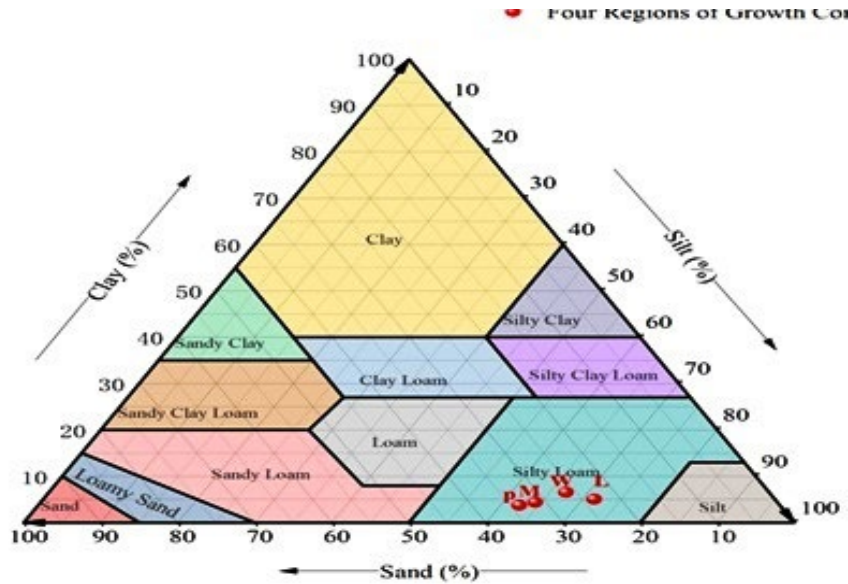


Figure 3. Ternary map of soil properties.

Table 3. VG model parameters of different growth conditions in tea-producing region area Correlation analysis of related parameters of VG model.

Growth Regions	θ_r (cm ³ /cm ³)	θ_s (cm ³ /cm ³)	α (cm ⁻¹)	n	m=1-1/n	R ²
Poor growth	0.0058	0.3974	0.0184	5.6253	0.7838	0.9999
Moderate growth	0.0071	0.3691	0.0189	5.1631	0.7598	0.9996
Well growth	0.0042	0.3431	0.0193	5.2996	0.7674	0.9999
Luxuriant growth	0.0033	0.3379	0.0201	5.3456	0.7699	0.9998

VG model data from various tea growing areas and regression, where θ_r is the residual water content of the soil (cm³/cm³), θ_s is the saturated water content of the soil (cm³/cm³), α (cm⁻¹) is approximately the reciprocal (cm⁻¹), n and m soil-specific water capacity (cm³/cm³.kPa).

Table 4 reveals a significant negative correlation between porosity and θ_s . The correlation coefficient was -0.968 (P≤0.01), indicating that greater porosity corresponds to lower saturated water content in the soil. Additionally, there was a significant negative correlation between silt content and parameters n and m (P ≤0.05), while sand content showed a positive correlation with

parameters n and m. The shape of the soil moisture characteristic curve is determined by three parameters: α , n and m in the V-G model. Generally, a larger value of parameter n results in a steeper soil moisture characteristic curve, indicating greater water release from the soil and corresponding changes in soil water content.

Table 4. Correlation analysis of related parameters of VG model.

	Porosity	Organic matter	Clay	Silt	Sand	θ_s	θ_r	α	n	m
Porosity	1	-0.909	0.600	0.997**	-0.989	-0.968**	0.755	-0.172	-0.973*	-0.973*
Organic matter	/	1	-0.474	-0.937	0.908	0.782	-0.639	0.389	0.980*	0.979*
Clay	/	/	1	0.588	-0.704	-0.688	0.977*	-0.657	-0.540	-0.536
Silt	/	/	/	1	-0.988*	-0.949	0.746	-0.253	-0.988*	-0.987*
Sand	/	/	/	/	1	0.965*	-0.839	0.163	0.967*	0.966*
θ_s	/	/	/	/	/	1	-0.814	-0.159	0.887	-0.968*
θ_r	/	/	/	/	/	/	1	-0.789	-0.704	-0.702
α	/	/	/	/	/	/	/	1	0.894	0.893
n	/	/	/	/	/	/	/	/	1	1.000**
m	/	/	/	/	/	/	/	/	/	1

Correlation between soil properties such as porosity, soil organic matter, clay sand, silt and the VG model, where θ_r is the residual water content of the soil (cm³/cm³), θ_s is the saturated water content of the soil (cm³/cm³), α is approximately the reciprocal (cm⁻¹), n and m soil-specific water capacity (cm³/cm³.kPa).

Water Retention Characteristics of Soil: The shape characteristics of the soil moisture characteristic curve are indicative of the soil's water retention properties. Under identical suction conditions, a higher curve corresponds to greater soil water content, reflecting stronger soil water holding capacity. Figure 4 illustrates that the soil moisture characteristic curve exhibits a similar shape across the four different growth areas, depicting a nonlinear "S" shaped process with a consistent changing trend. In the suction stage before 3.5 kPa, the soil moisture content was high, which led to the excess or even saturation of soil moisture. In the suction section of 3.5-9.5 kPa, the soil water is mainly capillary gravity water. Soil water content decreased significantly with the increase of water suction. In the suction section

after 9.5 kPa, due to the suction of soil capillary pipe to soil water, the change of soil water content in this suction section tends to be smooth. The offset of water characteristic curves between different regions is relatively concentrated and there are many overlapping points. This shows that the water holding capacity of the four regions is closed. Before 3.5 kPa suction section, the water holding capacity of the four regions are arranged from large to small is poor growth, moderate growth, well growth and luxuriant growth. In the 3.5-9.5 kPa suction section, the water-holding capacity of the poor growth was better than that of the moderate growth, the well growth and the luxuriant growth. Meanwhile, there was almost no difference between the well growth and the luxuriant growth.

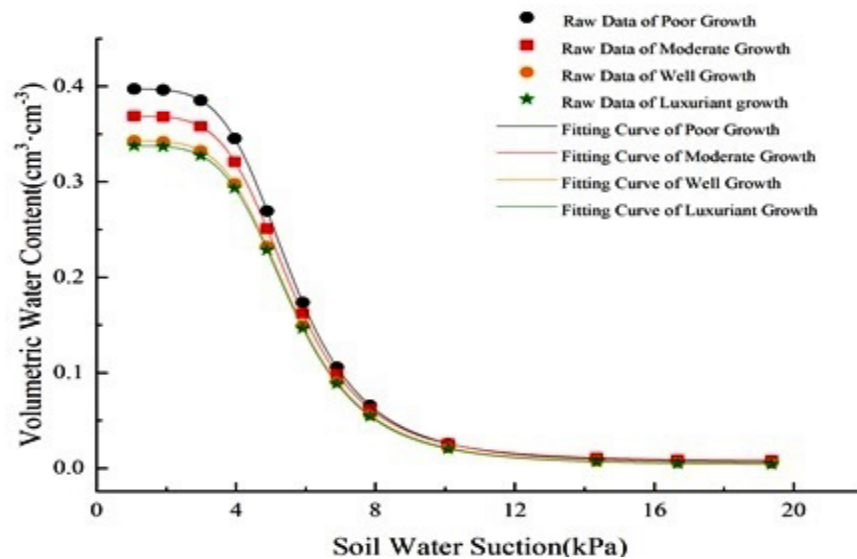


Figure 4. Moisture characteristic curves of different growth regions.

The figure shows the soil moisture characteristic curve exhibits a similar shape across the four different growth areas with poor growth, moderate growth, well growth and luxuriant regions in Qinba Mountain.

Specific Water Capacity of Soil: There are some differences in soil specific water capacity in different suction stages of the four tea growth regions (Figure 5). At 0-4.5 kPa suction, the specific water capacity curve of each region increased sharply with the increase of soil water suction. This suction section releases gravity water. The peak value of specific water capacity in the area with poor growth reached the maximum, which was $8.9 \times 10^{-3} \text{ cm}^3/(\text{cm}^3 \cdot \text{kPa})$. After 4.5 kPa, the specific water capacity curve of each region decreased sharply and then tended to be stable. This shows that with the increase of soil water suction, the specific water capacity decreases rapidly and then decrease. Finally, the specific water capacity is basically the same in all areas with high water suction. At this time, the soil pores slowly release slow-acting water.

It shows that in the range of 0-20 cm soil depth, the four kinds of regional water release processes mainly occur in the suction section of 0-4.5 kPa. There are differences in water release capacity among different regions at 4.5 kPa. Among them, the poor growth has the best water release capacity, the luxuriant growth takes the second place and the well growth is the worst. There is no significant difference between moderate growth and well growth.

The figure shows the differences in soil specific water capacity in different suction stages of the four Poor growth, moderate growth, well growth and luxuriant tea growth regions Qinba Mountain

Analysis of Soil Unsaturated Hydraulic Conductivity: Unsaturated hydraulic conductivity plays a crucial role in soil water movement and solute transport, closely intertwining with soil physical properties. It ultimately reflects the conductivity characteristics of soil water. Figure 6 illustrates the measured values of unsaturated hydraulic conductivity in tea-producing areas. To model

the relationship between suction and unsaturated hydraulic conductivity, an exponential function $K(x)=a*\exp(b*x)$ is employed, where 'a' and 'b' serve as

fitting parameters. Specifically, when x equals 0, 'a' represents the unsaturated hydraulic conductivity.

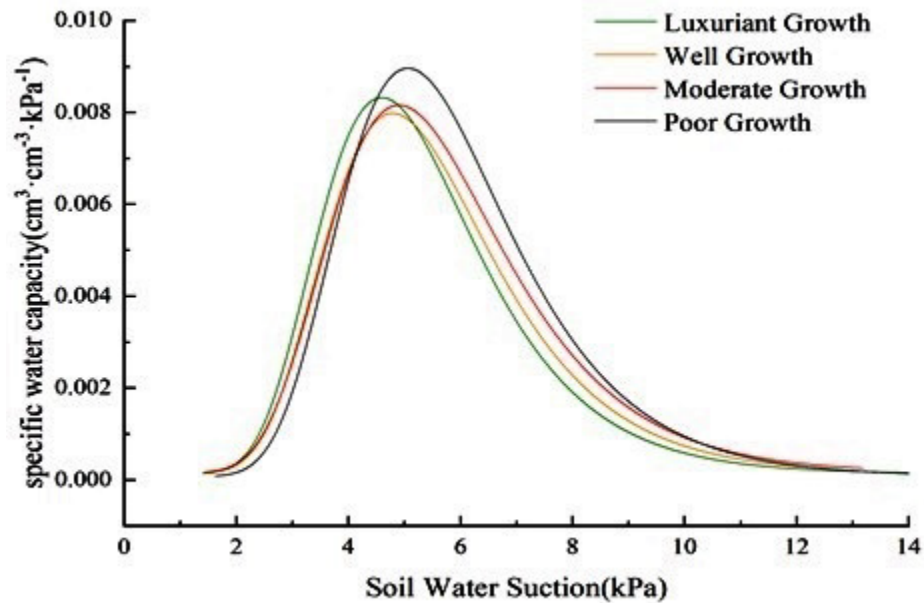


Figure 5. Specific water capacity curves for different growth regions.

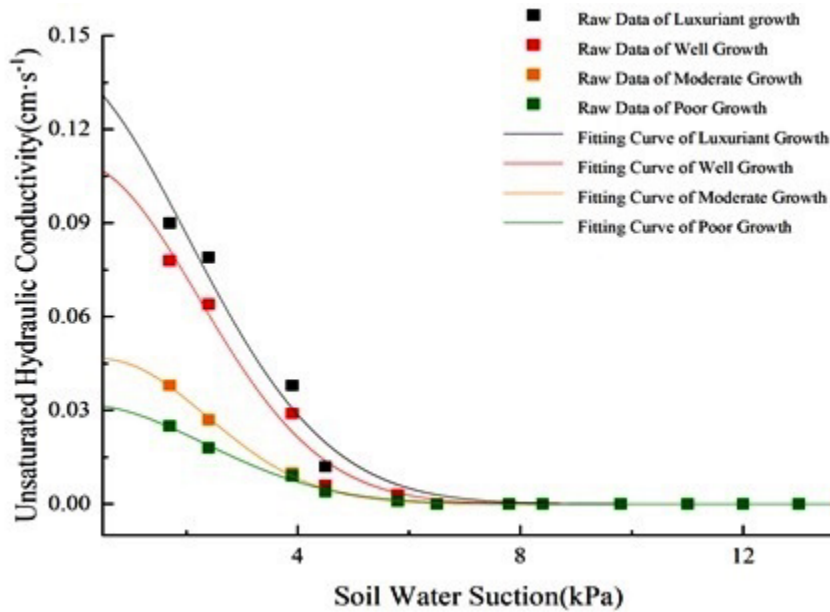


Figure 6. Measured values of unsaturated water conductivity of different growth regions.

The figure shows the unsaturated hydraulic conductivity in different suction stages of the four Poor growth, moderate growth, well growth and luxuriant tea growth regions Qinba Mountain

Figure 6 illustrates that unsaturated hydraulic conductivity in different regions exhibits a nonlinear decrease with increasing suction. The degree of change in unsaturated hydraulic conductivity varies across different

suction sections. When suction is below 4.5 kPa, unsaturated hydraulic conductivity undergoes a sharp decline, indicating high soil water content and filled macropores. As suction increases, macropores begin to drain, leading to a rapid decrease in unsaturated hydraulic conductivity. Notably, the luxuriant growth region exhibits the highest initial unsaturated hydraulic conductivity and the most rapid decline in this suction

section. In contrast, when suction exceeds 4.5 kPa, soil water content decreases, with water mainly present in small and medium pores. Gas fills the pores, reducing water-passing area and velocity. Additionally, water adsorption and friction between soil particles and flow increase pore resistance. Consequently, the variation

range of hydraulic conductivity is smaller under a unit suction gradient. Table 5 demonstrates that the exponential function effectively captures the relationship between unsaturated hydraulic conductivity and suction, with determination coefficients (R2) exceeding 0.90 for each region, all reaching a significant level ($P \leq 0.01$).

Table 5. Fitting results of unsaturated water conductivity in four regions.

Growth Regions	a	b	R2
Poor growth	0.0324	- 0.3618	0.946
Moderate growth	0.0459	- 0.3665	0.940
Well growth	0.1182	- 0.3789	0.965
Luxuriant growth	0.1437	- 0.3821	0.951

Parameters, a and b (model data) and R2 of regression models for Unsaturated conductivity

The correlation between total porosity and unsaturated hydraulic conductivity at suction values of 0.36 kPa, 1.72 kPa, 2.49 kPa, 3.91 kPa, 4.55 kPa, 5.80 kPa and 6.52 kPa was analyzed. The results indicate a significant positive correlation between unsaturated hydraulic conductivity and soil porosity, as shown in Table 6. At the same suction level, smaller soil porosity corresponds to lower unsaturated hydraulic conductivity.

Generally, unsaturated hydraulic conductivity is arranged from smallest to largest in the following order: poor growth, moderate growth, well growth, and luxuriant growth. These findings suggest that the soil structure of luxuriant growth is superior, followed by well growth in the study area, while the grasslands in moderate growth and poor growth exhibit relatively inferior soil structures.

Table 6. Correlation analysis of unsaturated water conductivity and total porosity.

Correlation analysis	Soil water suction (kPa)						
	0.36	1.72	2.49	3.91	4.55	5.80	6.52
Porosity	0.957*	0.970*	0.963*	0.934*	0.977*	0.954*	0.941*

Correlation between soil water suction and porosity, *suggested that the results are significant ($p \leq 0.05$)

Soil water diffusivity: Soil volume moisture content and water diffusivity, represented by $D(\theta)-\theta$, are effectively fitted by the exponential function $D(\theta)=aeb\theta$. The fitting results are presented in Table 7. It is evident that soil volume moisture content and water diffusivity in all four

regions can be accurately modeled by the exponential function. With determination coefficients (R2) exceeding 0.99, the statistical significance of the fittings is substantial.

Table 7. Fitting analysis of soil volume water content and soil water diffusivity index function.

Growth Regions	Fitting equation	A	b	R2
Poor growth	$D(\theta)=0.00086e22.736\theta$	0.00086	22.736	0.998
Moderate growth	$D(\theta)=0.00096e24.492\theta$	0.00096	24.492	0.998
Well growth	$D(\theta)=0.00106e26.129\theta$	0.00106	26.129	0.998
Luxuriant growth	$D(\theta)=0.00104e26.524\theta$	0.00104	26.524	0.997

Parameters, a and b (model data) and R2 of regression models

The regression analysis of soil volumetric water content and soil water diffusivity reveals a consistent trend in soil water diffusivity across the four different regions, as depicted in Figure 7. At low moisture content, water diffusion primarily occurs in the form of water vapor movement, increasing gradually with rising moisture content. During this stage, water mainly moves through small pores, with minimal influence from soil solution viscosity. Consequently, the disparity in water

diffusion among the four regions is negligible at low moisture content levels.

However, at high moisture content levels, water predominantly moves through large and medium pores, resulting in reduced soil resistance to water flow despite the larger gradient of soil water potential. Consequently, the diffusion rate of soil water increases, with $D(\theta)$ sharply rising with increasing θ . Moreover, as the volume

moisture content approaches saturation, water diffusivity tends to increase infinitely.

The figure shows regression analysis of soil volumetric water content and soil water diffusivity in different four Poor growth, moderate growth, well growth and luxuriant tea growth regions Qinba Mountain. Additionally, from Table 7, it is evident that the parameter 'a' for the four regions is arranged from largest to smallest as follows:

well growth, luxuriant growth, moderate growth, and poor growth. Consequently, the potential water transport capacity of the four regions follows this order: well growth, luxuriant growth, moderate growth, and poor growth. The rate of water diffusion in well growth and luxuriant growth mirrors the changes in water content most closely, followed by moderate growth. Conversely, poor growth exhibits the slowest rate of change.

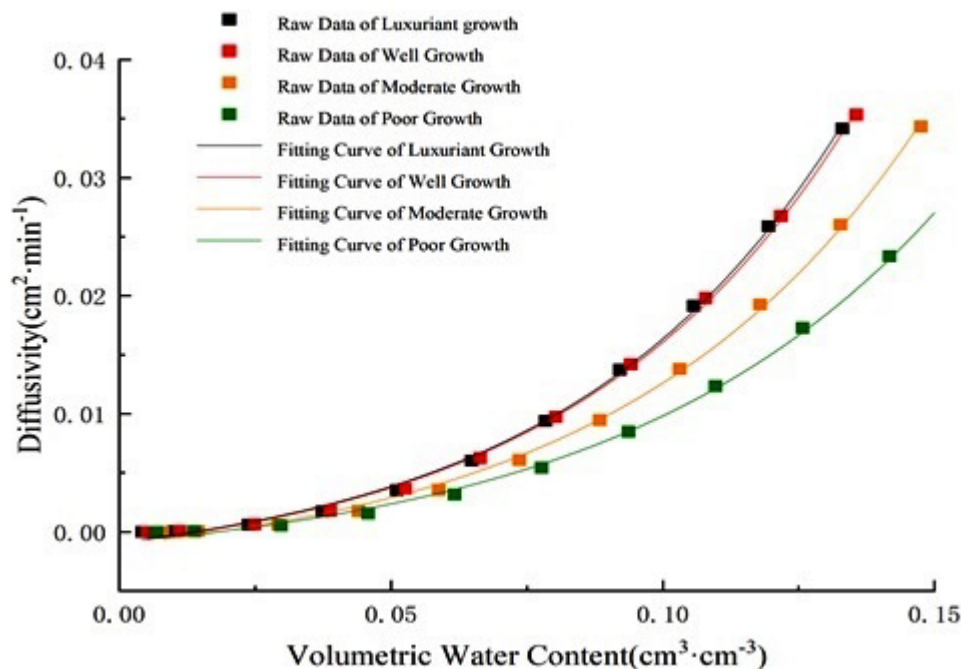


Figure 7. Fitting of soil water diffusivity and volume water content of different growth regions.

DISCUSSION

In regard to soil mechanical composition, compared to luxuriant growth, the sand content in well growth, moderate growth, and poor growth is lower, while the silt content is higher. This discrepancy can be attributed to the specific soil texture requirements of tea trees. Tea trees typically thrive in loose and well-aerated soil (Haghverdi *et al.*, 2020), which facilitates root development and extension, enhancing the absorption of oxygen and nutrients. Conversely, overly sticky soil can impede root respiration, leading to root anoxia and adversely affecting tea tree growth. Moreover, tea trees in luxuriant growth areas typically have longer growth periods compared to other regions, a phenomenon supported by Pan *et al.* (2019). Over time, the soil particle composition and texture types tend to optimize alongside the extended growth years of tea trees.

In this study, it was observed that in the soil water characteristic curve, during the suction stage before 3.5 kPa, the water holding capacity of the luxuriant growth was the lowest. This can be attributed to factors such as high root density, the lowest soil bulk density

(1.37 g/cm³), the highest content of organic matter (12.45 g/kg), and the highest total soil porosity (35.12%) within the 20 cm soil layer. This finding aligns with previous research by Mishra *et al.*, (2020). Furthermore, according to the study of Wang and Ni (2023), there exists a significant negative correlation between porosity and the parameter θ_s of the V-G model of the soil water characteristic curve (Table 4).

In the low suction section, soil water is discharged primarily in the form of gravity water, resulting in poor water holding capacity of the luxuriant growth before 3.5 kPa. Additionally, Long *et al.*, (2022) research indicates that soil water holding capacity is positively correlated with clay and silt content, and negatively correlated with sand content and bulk density. In this study, it was found that the water holding capacity of the poor growth is relatively better, followed by the moderate growth. This difference can be attributed to the significantly higher porosity of the luxuriant growth (35.12%) compared to the poor growth (26.14%), consistent with the negative correlation was observed (Wang and Ni, 2023).

Soil particle size composition profoundly affects soil ventilation, permeability, and fertility, thus influencing soil water holding capacity. In this study, the V-G model utilized in the soil moisture characteristic curve was obtained by fitting soil particle size data using the RETC method. Combined with Figure 2, which illustrates the soil textures of the four types of growth regions as silty loam, it was noted that except for the significantly higher silt and clay content in the poor growth compared to other growth regions, there were no significant differences in the content of sand and silt between well growth and moderate growth ($P>0.05$) (Table 1). Consequently, there were few differences in water holding capacity among these regions. Additionally, the V-G parameter 'n' exhibited minimal variation among the four growth regions, ranging from 5.1631 to 5.6253, resulting in consistent alterations in soil moisture characteristic curves across these regions.

When the specific water capacity drops below 10-2, the soil's capacity to release water significantly diminishes, posing challenges for vegetation to access water (Zhang *et al.*, 2020). Figure 4 illustrates that the specific water capacity of the four growth regions is 10-3, indicating that vegetation growth in these tea-producing areas is constrained by water availability. To facilitate optimal tea growth, it may be necessary to augment soil moisture levels appropriately. In this study, a positive correlation was observed between unsaturated hydraulic conductivity and porosity, which is consistent with the results of (Zhang *et al.*, 2020). In lush growing areas, the accumulation of litter and a high root density within the 20 cm long soil layer contribute to soil loosening. As a result, the increased number of pores results in higher porosity (Shi *et al.*, 2022), resulting in the highest unsaturated hydraulic conductivity observed in luxuriant growth regions.

In this study, it was observed that $D(\theta)$ increases with the rise in θ , which corresponds to the empirical formula $D(\theta)=aeb\theta$ (Prematilake *et al.*, 2004). At lower soil moisture content levels, soil moisture primarily moves as water vapor, resulting in gradual changes in soil water movement. Conversely, as soil moisture increases, the rate of change in soil water movement decreases, and soil resistance to water diminishes. Consequently, soil water diffusivity escalates sharply with increasing soil water content, consistent with findings by Hao *et al.*, (2008).

According to the study of Nelson and Sommers (1982), soil type, mechanical composition, bulk density, porosity, and organic matter content influence soil water diffusivity, with soil porosity exhibiting a positive correlation with soil water diffusivity. In this study, under identical water content conditions, soil water diffusivity is ranked as follows: luxuriant growth, well growth, moderate growth, and poor growth, from highest to lowest. This ranking can be attributed to the lowest

viscous weight and porosity of the soil structure in poor growth areas, while the porosity in luxuriant areas is the highest.

Conclusion: The soil texture in the four different growth regions in the tea-growing areas of the Qinba Mountains consists primarily of silty clay. In particular, the region with poor growth had the highest water content and highest bulk density, significantly exceeding the figures of the other growth regions. In addition, the region with poor growth had the lowest levels of sand, organic matter, and porosity. Conversely, the lush growing region had the highest sand content and the lowest silt content, which was a stark contrast to the poor growth region. These results suggest that tea trees grow better in loose soil conditions in Qinba Mountain. The soil moisture characteristic curve was effectively modeled using the V-G model, with an R2 value exceeding 0.99 ($P\leq 0.01$). Additionally, the index $K(x)=a^*\exp(b^*x)$ was employed to fit the relationship between water suction and unsaturated hydraulic conductivity, resulting in an R2 value greater than 0.90. Moreover, soil volume moisture content and soil water diffusivity were accurately described by the exponential function $D(\theta)=aeb\theta$, with an impressive R2 value surpassing 0.99.

The water holding capacity in the four growth regions was uniform. However, when looking at the entire suction range, the water holding capacity was in the following order: weak growth > moderate growth > well growth = luxuriant growth. It is noteworthy that the process of water delivery took place primarily in the suction range of 0-4.5 kPa, with the optimal water delivery capacity observed in the region with poor growth and the weakest in the region with well growth. A significant positive relationship was observed between soil porosity and unsaturated hydraulic conductivity. The order of unsaturated hydraulic conductivity in the four regions was as follows: lush growth, well growth, moderate growth, and poor growth. In addition, the soil structure of the lush vegetation had the highest degree of development.

The diffusivity of soil water gradually increases as the moisture content of the soil volume increases. As the volume moisture content approaches saturation, the water infusibility tends to escalate infinitely. Among growth regions, lush growth has the highest potential for water transmissibility, whereas in the well growth region, water diffusivity changes most rapidly when moisture content changes. Overall, when choosing hilly areas for growing tea, the optimal soil texture should be loose and well-ventilated clay soil with higher sand content and lower silt content, high porosity, low bulk density and high organic matter content. In addition, high water diffusion capacity and moderate water holding capacity enable effective drainage and water retention under various conditions. A high-quality tea plantation should

look back on a long tradition of tea cultivation. The composition and texture of soil particles should be optimized over time to promote continuous, high-quality growth of tea plants.

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Institutional Review Board Statement: The use of plants in the present study complies with international, national and/or institutional guidelines. For the collection of soil and vegetation samples in the study area, we have obtained local permission.

Data Availability Statement: The datasets generated and analysed during the current study are not publicly available due this experiment was a collaborative effort, the trial data does not belong to me alone but are available from the corresponding author on reasonable request.

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REFERENCES

- Assouline, S., D. Tessier and A. Bruand (1998). A conceptual model of the soil water retention curve. *Water Resour. Res.* 34(2):223-231. <https://doi.org/10.1029/97WR03039>.
- Balkhair, K.S. (2016). Impact of treated wastewater on soil hydraulic properties and vegetable crop under irrigation with treated wastewater, field study and statistical analysis. *J. Environ. Biol.* 37(5):1143-1145. <https://pubmed.ncbi.nlm.nih.gov/29989747/>
- Bieganowski, A., M. Ryzak, A. Sochan, G. Barna, H. Hernadi, M. Beczek, C. Polakowski and A. Mako (2018). Laser diffractometry in the measurements of soil and sediment particle size distribution. *Adv. Agron.* 151:215-279. <https://doi.org/10.1016/bs.agron.2018.04.003>.
- Bormann, H. and K. Klaassen (2008). Seasonal and land use dependent variability of soil hydraulic and soil hydrological properties of two Northern German soils. *Geoderma.* 145(3-4):295-302. <https://doi.org/10.1016/j.geoderma.2008.03.017>.
- De Silva, M.S.D.L (2007). The effects of soil amendments on selected properties of tea soils and tea plants (*Camellia sinensis* L.) in Australia and Sri Lanka. Doctoral dissertation, James Cook University. <https://doi.org/10.25903/ns0d-1a64>
- Du, C., (2020). Comparison of the performance of 22 models describing soil water retention curves from saturation to oven dryness. *Vadose Zone J.* 19(1):20072. <https://doi.org/10.1002/vzj2.20072>
- Duwig, C., B. Prado, A.J. Tinet, P. Delmas, N. Dal Ferro, J.P. Vandervaere, H. Denis, P. Charrier, A.G. Strozzi and F. Morari (2019). Impacts of land use on hydrodynamic properties and pore architecture of volcanic soils from the Mexican Highlands. *Soil Res.* 57(6):629-641. <https://doi.org/10.1071/SR18271>.
- Grossman, R.B. and T.G. Reinsch (2002). 2.1 Bulk density and linear extensibility. *Methods of soil analysis: Part 4 physical methods.* 5:201-228. <https://doi.org/10.2136/sssabookser5.4.c9>.
- Haghverdi, A., M. Najarchi, H.S. Ozturk and W. Durner (2020). Studying unimodal, bimodal, PDI and bimodal-PDI variants of multiple soil water retention models: I. direct model fit using the extended evaporation and dewpoint methods. *Water.* 12(3):900. <https://doi.org/10.3390/w12030900>.
- Hao, X., B.C. Ball, J.L.B. Culley, M.R. Carter and G.W. Parkin (2008). Soil density and porosity. *Soil Samp. Methods Anal.* 2:743-759. <https://pure.sruc.ac.uk/en/publications/soil-density-and-porosity>
- Hasan, R., A.F.M. Islam, M.A. Maleque, M.S. Islam and M.M. Rahman (2023). Effect of drought stress on leaf productivity and liquor quality of tea: a review. *Asian J. Soil Sci. Plant Nutr.* 9(4):1-10. <https://doi.org/10.9734/ajsspn/2023/v9i4187>.
- Jabro, J.D., W.B. Stevens, W.M. Iversen, B.L. Allen and U.M. Sainju (2020). Irrigation scheduling based on wireless sensors output and soil-water characteristic curve in two soils. *Sensors.* 20(5):1336. <https://doi.org/10.3390/s20051336>.
- Ji, H.G., Y.R. Lee, M.S. Lee, K.H. Hwang, E.H. Kim, J.S. Park and Y.S. Hong (2017). Metabolic phenotyping of various tea (*Camellia sinensis* L.) cultivars and understanding of their intrinsic metabolism. *Food Chem.* 233:321-330. <https://doi.org/10.1016/j.foodchem.2017.04.079>.
- Köhne, J.M., S. Kohne and J. Simunek (2009). A review of model applications for structured soils: a) Water flow and tracer transport. *J. Contam. Hydrol.* 104(1-4):4-35. <https://doi.org/10.1016/j.jconhyd.2008.10.002>.

- Le, V.S., D. Lesueur, L. Herrmann, L. Hudek, L.N. Quyen and L. Brau (2021). Sustainable tea production through agroecological management practices in Vietnam: a review. *Environ. Sustain.* 4(4):589-604. <https://doi.org/10.1007/s42398-021-00182-w>.
- Liu, Z., D. Yang, G. Zhang, L. Zheng, C. Chen, X. Sun and F. Yu (2023). Effects of soil physical and chemical properties on the quality of nanjing 'Yuhua' Tea, a type of famous green tea. *Horticulturae*. 9(2):189. <https://doi.org/10.3390/horticulturae9020189>.
- Long, L., Y. Shi, L. Ma and J. Ruan (2022). Characterization of young shoot population, yield, and nitrogen demands of tea (*Camellia sinensis* L.) harvested under different standards. *Horticulturae*. 8(4):275. <https://doi.org/10.3390/horticulturae8040275>.
- Malama, B. and K.L. Kuhlman (2015). Unsaturated hydraulic conductivity models based on truncated lognormal pore - size distributions. *Groundwater*. 53(3):498-502. <https://doi.org/10.1111/gwat.12220>.
- Mishra, V., W.L. Ellenburg, K.N. Markert and A.S. Limaye (2020). Performance evaluation of soil moisture profile estimation through entropy-based and exponential filter models. *Hydrol. Sci. J.* 65(6):1036-1048. <https://doi.org/10.1080/02626667.2020.1730846>.
- Moreno-Maroto, J.M. and J. Alonso-Azcarate (2022). Evaluation of the USDA soil texture triangle through Atterberg limits and an alternative classification system. *Appl. Clay Sci.* 229:106689. <https://doi.org/10.1016/j.clay.2022.106689>.
- Nelson, D.W. and L.E. Sommers (1982). Total carbon, organic carbon, and organic matter. *Methods of soil analysis: Part 2 chemical and microbiological properties* 9:539-579. <https://doi.org/10.2134/agronmonogr9.2.2ed.c29>
- Pan, T., S. Hou, Y. Liu and Q. Tan (2019). Comparison of three models fitting the soil water retention curves in a degraded alpine meadow region. *Sci. Rep.* 9(1):18407. <https://doi.org/10.1038/s41598-019-54449-8>.
- Prematilake, K.G., R.J. Froud-Williams and P.B. Ekanayake, (2004). Weed infestation and tea growth under various weed management methods in a young tea *Camellia sinensis* L. *Kuntze* plantation. *Weed Biol. Manag.* 4(4):239-248. <https://doi.org/10.1111/j.1445-6664.2004.00144.x>.
- Rheingantz, M.L. and J.W. Duckworth (2021). Misleading use of IUCN Red List terminology to define neotropical otter local conservation status. *IUCN Otter Spec. Group Bull.* 38(5):254-257. https://www.iucnosgbull.org/Volume38/Rheingantz_Duckworth_2021.html
- Shi, G., Y. Wu, T. Li, Q. Fu and Y. Wei (2022). Mid-and long-term effects of biochar on soil improvement and soil erosion control of sloping farmland in a black soil region, China. *J. Environ. Manage.* 320:115902. <https://doi.org/10.1016/j.jenvman.2022.115902>.
- Wang, H. and W. Ni (2023). Soil-water retention behavior of a loess-paleosol sequence and its significance for hydrology and paleoclimate: a case study from the Luochuan profile of the Loess Plateau, China. *Can. Geotech. J.* 61(4):700-716. <https://doi.org/10.1139/cgj-2023-0144>.
- Zhang, C., M. Wang, J. Chen, X. Gao, C. Shao, Z. Lv, H. Jiao, H. Xu and C. Shen (2020). Survival strategies based on the hydraulic vulnerability segmentation hypothesis, for the tea plant [*Camellia sinensis* (L.) O. Kuntze] in long-term drought stress condition. *Plant Physiol. Biochem.* 156:484-493. <https://doi.org/10.1016/j.plaphy.2020.09.034>.
- Zhang, Q., T. Li, Q. Wang, J. LeCompte, R.L. Harkess and G. Bi (2020). Screening tea cultivars for novel climates: Plant growth and leaf quality of *Camellia sinensis* cultivars grown in Mississippi, United States. *Front. Plant Sci.* 11:280. <https://doi.org/10.3389/fpls.2020.00280>.
- Zhao, Y., Y. Xu, L. Zhang, M. Zhao and C. Wang (2022). Adapting tea production to climate change under rapid economic development in China from 1987 to 2017. *Agronomy.* 12(12):3192. <https://doi.org/10.3390/agronomy12123192>.