

Article

Soil Hydrology Characteristics among Forest Type, Stand Age and Successive Rotation in *Eucalyptus* Plantations in Southern China

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Abstract: The water holding capacity of forest soil plays a crucial role in ensuring forest productivity, particularly in *Eucalyptus urophylla* plantations. In this study, we investigated the soil water holding capacity and hydrological properties of *Eucalyptus* in a subtropical area of Guangxi, China. Different stand ages (five years old, seven years old, and 15 years old) and successive rotations (first, second, and third) of *Eucalyptus* plantations were compared, with *Cunninghamia lanceolata* (Chinese Fir) and *Pinus massoniana* (Pine) plantations serving as references. Soil physical properties, soil hydrological parameters, and litter characteristics were analyzed to assess soil water retention and conservation variations. Our findings revealed that *Eucalyptus* and *Chinese Fir* plantation forests exhibit superior soil physical characteristics compared to *Pine* plantations, resulting in better soil water retention. However, an increase in the age of *Eucalyptus* plantations significantly diminished the capillary water holding capacity of the soil, despite an increase in surface litter accumulation and litter moisture content. Furthermore, successive rotations led to a notable reduction in soil capillary porosity, soil moisture content, soil saturated permeability, and overall soil water holding capacity. In addition, soil bulk density emerged as a critical factor relating to the hydrological characteristics of *Eucalyptus* plantation forests. Decreasing soil bulk density in *Eucalyptus* forests may offer potential for optimizing their water retention function. These results reveal that *Eucalyptus* management practices significantly alter the hydrological properties of soil through their effects on soil and litter properties, and consequently, stand age, rotation, and species mixing should be given intensive attention in maintaining the maximization of soil water holding capacity.

Keywords: successive rotation; stand age; soil water holding capacity; soil property



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1. Introduction

The water conservation function of forest soil is a vital ecosystem feature that mitigates the potential impacts of extreme rainfall and drought on forest ecosystems [1]. It is a crucial regulatory factor for the growth of aboveground vegetation and underground roots [1,2]. Understanding the hydrological characteristics of forest ecosystems has become essential due to the rising frequency of extreme rainfall events resulting from global climate change.

Eucalyptus, a rapidly growing tree species, has been extensively planted in southern China due to its economic value [3]; thus, it has become a dominant component of the timber plantations that have been established in the region over the past few decades [4,5]. Previous studies on *Eucalyptus* trees have primarily focused on their role as exotic species

in local ecosystems [6], exploring their impact on soil physicochemical properties [7], microbial community structure and function [8], and plant diversity [9]. These studies have provided insight into the effects of increasing *Eucalyptus* age on soil physicochemical properties, including stimulating enzyme activities such as phenol oxidase, peroxidase, and acid phosphatase [10]. Additionally, the expansion of *Eucalyptus* rotations has significantly influenced soil properties, microbial characteristics, and aboveground plant characteristics [11].

Soil hydrology in *Eucalyptus* ecosystems is influenced by various factors, including water use, soil erosion, soil quality and hydrological processes [12,13]. *Eucalyptus* plantations have both positive and negative impacts on soil hydrology. One of the main characteristics of soil hydrology in *Eucalyptus* ecosystems is water use [14]. *Eucalyptus* trees are known for their high water demand, which can lead to water depletion in the soil [14]. The water use efficiency of *Eucalyptus* plantations varies depending on factors such as climate, soil type, and management practices [15]. The high water demand for *Eucalyptus* trees can affect the water balance in the ecosystem and potentially reduce the availability of water for other plants [16]. Soil erosion is another critical aspect of soil hydrology in *Eucalyptus* ecosystems. *Eucalyptus* plantations can significantly impact soil erosion due to their shallow root systems [17]. Reductions in native vegetation and the planting of *Eucalyptus* trees can lead to increased soil erosion rates, especially on steep slopes [18]. The impact of soil erosion in *Eucalyptus* ecosystems can result in the loss of topsoil, reduced soil fertility, and increased sedimentation in water bodies [19]. Hydrological processes such as water infiltration, runoff, and evapotranspiration are also influenced by *Eucalyptus* plantations. *Eucalyptus* trees can affect water infiltration rates by improving soil structure and increasing macropore formation [20]. Moreover, the impact of *Eucalyptus* plantations on soil hydrology can vary depending on factors such as stand age and rotation [13,21,22].

In *Eucalyptus* plantations, stand age influences root development and the physical properties of the soil, affecting water uptake and soil infiltration rates [23,24]. For example, the fine roots of a *Eucalyptus* tree can explore the soil down to a depth of 10 m throughout the entire rotation, contributing to high water use and potentially affecting water availability in the ecosystem [25]. Moreover, rotation-related factors, such as the frequency of harvesting and replanting, can impact soil nutrient availability and soil organic matter (SOM) content, influencing soil water holding capacity and infiltration rates. This necessitates intensive management practices, including short rotation periods, which can lower SOM content [7] and alter soil hydrological characteristics [26]. Furthermore, removing trees during harvesting can expose the soil surface, increasing the risk of soil erosion and altering water runoff patterns [11]. Despite the significant influence of stand age and rotation on aboveground biomass characteristics, as well as soil nutrient and physicochemical properties in *Eucalyptus* plantations, the effects of these factors on soil and litter hydrological properties have yet to be studied.

Guangxi has the largest *Eucalyptus* plantation forest area in China, with its *Eucalyptus* plantation forest area spanning more than 30,340 km². In this study, we selected *Eucalyptus* plantations with different stand ages and three successive rotations to investigate the effects of stand age and plantation rotation on soil hydrological properties. To achieve our objectives, we examined soil properties, litter properties, and soil water evapotranspiration parameters in *Eucalyptus* plantations with different stand ages and rotations. Additionally, we compared soil hydrology between *Eucalyptus* plantations and adjacent *Cunninghamia lanceolata* (Chinese Fir) and *Pinus massoniana* (Pine) plantations. We hypothesized that (1) the hydrological characteristics of soil and litter may significantly differ among various plantation forests due to the different environmental conditions; (2) the accumulation of the litter layer may increase with an increase in the stand age of *Eucalyptus* plantations, thus prompting an increase in soil water storage capacity in older plantations; and (3) the soil structure may be disrupted with successive rotations, reducing surface water storage capacity and litter storage efficiency.

2. Materials and Methods

2.1. Study Site

The study was conducted at the Huangmian *Eucalyptus* Forest Research Station in the Guangxi Zhuang Autonomous Region of China (24.7583° N, 109.8933° E) in a *Eucalyptus urophylla* × *Eucalyptus grandis* plantation forest plot with a tree density of 1425 trees per hectare (Figure 1) [27]. The plot is 226 m above sea level and has a surface slope of approximately 25 degrees. The study site is in a mid-subtropical monsoon climate, with the average annual temperature being 19 °C [28]. The average temperatures recorded for the lowest month (January) and the highest month (August) are 8.3 °C and 27.9 °C, respectively. The long-term (1981–2010) mean annual precipitation is approximately 1960 mm, and precipitation is distributed unevenly among the seasons. The growing season ranges from March to November, but 70% percent of the annual precipitation falls from April to August, leading to a distinct wet and dry period [29]. The bedrock in the area is shale-based, and the soil used is heavy loam with a pH range of 3.5 to 4.3. The contents of SOM and total nitrogen were 27 g kg^{−1} and 1.29 g kg^{−1}, respectively. The soil depth ranges from 40 to 80 cm.



Figure 1. Study site and pictures of the Chinese Fir, Pine, and Eucalyptus Plantations. The Guangxi Zhuang Autonomous Region is located in the south of mainland China.

2.2. Experimental Design and Soil Sampling

The research plots of the *Eucalyptus* plantations included 1st rotation plots of -year, 7-year, and 15-year trees; 2nd rotation plots of 4-year trees; and a 3rd rotation plot of 4-year trees. Among them, the 1st rotation plots of the 7-year and 15-year *Eucalyptus* trees are closed and protected, while the others are generally managed through cultivation measures such as fertilization and weeding. We selected three sample plots of *Chinese Fir* plantations with ages of 6, 7, and 10 years, respectively, and *Pinus massoniana* plantations with an age of 10 years as the control treatment for different forest types. Soil sampling was carried out using a cutting ring and an aluminum box at 0–15 cm and 15–30 cm, respectively, to assess the physical properties of the soil, such as soil permeability, in the laboratory. Three profiles plot with similar slope directions and locations were collected in each. Additionally, we collected all litter within a 1 m × 1 m sample near each soil profile and measured its moisture content and maximum water capacity in the laboratory.

2.3. Determination of Soil Physical Characteristics

In each plot, three small quadrats with an area of 1 m × 1 m were randomly selected along the diagonal direction to measure the physical properties of the soil. In each small quadrat, a 100 cm³ cutting ring (5 cm diameter and 5 cm height) was used to take samples of undisturbed soil at depths of 0–15 and 15–30 cm, with three replicates per soil layer. The

samples were taken back to the laboratory to measure soil infiltration and the physical properties of the soil. The cutting ring method was used to measure soil bulk density, capillary porosity, and total porosity [1].

$$P_b = G/V$$

$$P_n = 0.1 \times (W_1 - W_2) \times P_b/P_w$$

$$P_c = 0.1 \times W_2 \times P_b/P_w$$

$$P = P_n + P_c$$

where P_b is the soil bulk density (g cm^{-3}), G is the weight of the dried soil inside the cutting ring (g), V is the in-ring cutter size (cm^3), P_n is the non-capillary porosity (%), P_c is the capillary porosity (%), W_1 is the maximum water holding capacity (g kg^{-1}), W_2 is the capillary moisture capacity (g kg^{-1}), P_w is the water density (kg m^{-3}), and P is the total porosity (%). The soil bulk density is the dry bulk density, equal to the soil density [30]. The water density is 1000 kg m^{-3} [31].

2.4. Determination of the Water Holding Capacity of the Soil

Three sampling points with similar slope aspects and positions were randomly selected in the first, second, and third rotations of four-year *Eucalyptus* plantations, as well as sixth- and seventh-year *Chinese Fir* forests and *Pinus massoniana* plantations. The ground cover was removed, and a PVC pipe with an inner diameter of 20 cm and a length of 12 cm was vertically driven into the soil so that the upper edge of the PVC pipe was level with the ground. Water was slowly added into the pipe until the soil was saturated. The daily moisture content of the soil in the pipe was measured using a TDR soil moisture meter for six consecutive days during sunny weather. Additionally, in situ soil infiltration experiments were conducted near each PVC pipe using a Guelph permeameter to determine soil saturation permeability.

Infiltration and drying methods were used to sample unit weight and determine the mass water content of the soil [1], maximum water holding capacity [2], minimum water holding capacity [2], and capillary water holding capacity [2]. The calculation formula for each soil water retention index is as follows:

$$W_{swc} = (G_1 - G_2)/G_2 \times 1000$$

$$W_1 = (G_3 - G_1)/G_1 \times 1000$$

$$W_2 = (G_4 - G_1)/G_1 \times 1000$$

$$W_3 = (G_5 - G_1)/G_1 \times 1000$$

where W_{swc} is the soil water content (g kg^{-1}), W_1 is the maximum water holding capacity (g kg^{-1}), W_2 is the capillary moisture capacity (g kg^{-1}), W_3 is the minimum water holding capacity (g kg^{-1}), G_1 is the quality of the dried soil in the in-ring cutter (g), G_2 is the mass of the wet soil in the in-ring cutter (g), G_3 is the mass of the wet soil in the ring cutter after 12 h infiltration (g), G_4 is the mass of the wet soil in the in-ring cutter after 2 h on dry sand (g), and G_5 is mass of the wet soil in the in-ring cutter after 72 h on dry sand (g).

2.5. Determination of the Water Holding Capacity of the Litter

Three random quadrats measuring $1 \text{ m} \times 1 \text{ m}$ were employed along the diagonal direction to quantify the accumulation of litter within each sampling plot. The mass of the litter per unit was measured using a steel tape ruler. Subsequently, the living vegetation was removed, and the non-decomposed and decomposed litter layers were collected. These collected litter samples were weighed and placed in net bags for storage. Subsequently, the samples were transported to the laboratory, where they were subjected to oven-drying at

65 °C until a constant weight was achieved. The final weight of the dried litter samples was used to calculate the overall litter accumulation within the study area.

In each small quadrat, 50 g of dried litter was put into a 100-mesh nylon net bag (15 cm × 20 cm) and immersed in water. After 24 h, the litter was taken out, and excess water was removed. The samples were weighed, oven-dried at 65 °C to constant weight, then weighed again to determine the water holding capacity [32,33]. The calculation formula is as follows:

$$R_{hmax} = (G_{24} - G_d) / G_d \times 100\%$$

$$W_{hmax} = M \times R_{hmax}$$

where R_{hmax} is the water holding rate of the litter (%), G_{24} is the weight of the litter after immersion in water for 24 h (g), G_d is the dry weight of the litter (g), W_{hmax} is the maximum water holding capacity of the litter (g kg⁻¹), and M is the litter accumulation per unit (g m⁻²).

2.6. Statistical Analysis

SPSS 20.0 was used to conduct an analysis of variance and correlation analysis, while Origin 2021 was used for drawing. A one-way analysis of variance (ANOVA) was conducted to examine the soil physical properties across various forest types, ages of *Eucalyptus* forests, and rotations. A two-factor ANOVA was employed to analyze the effects of forest type and soil layer, forest age and soil layer, and rotation and soil layer on both soil physical and hydrological characteristics. Pearson correlation analysis was performed to examine the interrelationships between the physical properties of soil and litter leaves, as well as between the age and rotation of *Eucalyptus* plantations, and their impact on soil hydrological characteristics. Principal Component Analysis (PCA) was conducted to explore the interrelationships between soil and litter physical properties and their influence on soil hydrological characteristics across various forest types, ages of *Eucalyptus* forests, and rotations. The PCA was performed using the ‘ggplot2’ and ‘factoextra’ packages [34,35]. The data used for multivariate analyses were visualized as a heatmap using the hiplot website (<https://hiplot.com.cn>, accessed on 15 August 2023).

3. Results

3.1. Soil Physical Properties

Soil density ranged from 1.16 to 1.49 g cm⁻³ (Tables 1 and 2), and soil density was significantly affected by forest type, stand age, and rotation ($p < 0.05$, Table 3). Soil depth also significantly affected soil bulk density in forest type ($F = 6.62$, $p < 0.05$) and rotation ($F = 9.66$, $p < 0.01$). The soil capillary porosity, non-capillary porosity, and soil aeration of *Eucalyptus* only significantly differed in stand age and rotation, while no forest type was different (Table 3). Total porosity was considerably affected by forest type, stand age, and rotation ($p < 0.05$), while soil depth had no significant effect. With increasing stand age, the total porosity decreased significantly (Tables 1 and 2).

Table 1. Physical properties of soil in different forest types (mean ± standard error, $n = 3$).

Factors		Sd (cm)	Pb (g cm ⁻³)	Pc (%)	Pn (%)	P (%)	Sa (%)
Forest type	<i>Eucalyptus</i>	0–15	1.31 ± 0.03 b	45.51 ± 0.70 a	11.32 ± 0.57 a	56.83 ± 0.94 ab	41.17 ± 0.72 a
		15–30	1.38 ± 0.02 ab	45.55 ± 0.66 a	10.62 ± 0.55 ab	56.16 ± 0.80 ab	40.14 ± 0.59 ab
	<i>Chinese Fir</i>	0–15	1.36 ± 0.04 ab	46.96 ± 1.42 a	11.65 ± 0.82 a	58.61 ± 1.63 a	40.83 ± 0.93 ab
		15–30	1.42 ± 0.04 a	46.84 ± 1.06 a	10.38 ± 0.77 ab	57.22 ± 1.42 ab	39.34 ± 0.95 ab
	<i>Pine</i>	0–15	1.44 ± 0.04 ab	43.97 ± 1.73 a	9.71 ± 1.27 a	53.68 ± 1.75 ab	38.76 ± 0.94 ab
		15–30	1.46 ± 0.02 ab	45.89 ± 0.96 a	7.98 ± 0.59 b	53.87 ± 1.14 ab	37.25 ± 0.90 b

Values that share similar letters within a column are not significantly different at a 95% significance level. Where, Sd is soil depth (cm), Pb is soil bulk density (g cm⁻³), Pc is capillary porosity (%), Pn is non-capillary porosity (%), P is total capillary porosity (%), Sa is soil aeration (%).

Table 2. Soil physical properties of *Eucalyptus* plantations with different stand ages and generations (mean $\pm$ standard error, $n = 3$).

Factors		Sd (cm)	Pb (g cm ⁻³)	Pc (%)	Pn (%)	P (%)	Sa (%)
Stand age	5-year	0–15	1.28 $\pm$ 0.04 b	50.85 $\pm$ 0.95 a	9.94 $\pm$ 0.83 a	60.80 $\pm$ 1.12 a	41.11 $\pm$ 0.87 a
		15–30	1.38 $\pm$ 0.03 b	49.97 $\pm$ 0.92 a	8.77 $\pm$ 0.74 a	58.74 $\pm$ 1.29 a	38.93 $\pm$ 0.91 a
	7-year	0–15	1.40 $\pm$ 0.10 ab	44.73 $\pm$ 2.91 ab	9.97 $\pm$ 0.64 a	54.70 $\pm$ 3.03 ab	37.86 $\pm$ 1.72 a
		15–30	1.42 $\pm$ 0.08 ab	45.28 $\pm$ 2.62 ab	10.43 $\pm$ 1.34 a	55.71 $\pm$ 2.56 ab	38.34 $\pm$ 1.43 a
	15-year	0–15	1.44 $\pm$ 0.05 a	41.36 $\pm$ 0.69 b	7.77 $\pm$ 0.83 a	49.13 $\pm$ 0.52 b	37.60 $\pm$ 0.61 a
		15–30	1.49 $\pm$ 0.04 a	41.76 $\pm$ 1.18 b	7.25 $\pm$ 1.30 a	49.01 $\pm$ 0.77 b	37.08 $\pm$ 0.90 a
Generation	1st	0–15	1.28 $\pm$ 0.04 ab	50.85 $\pm$ 0.95 a	9.94 $\pm$ 0.83 b	60.8 $\pm$ 1.12 ab	41.11 $\pm$ 0.87 bc
		15–30	1.38 $\pm$ 0.03 a	49.97 $\pm$ 0.92 a	8.77 $\pm$ 0.74 b	58.74 $\pm$ 1.29 ab	38.93 $\pm$ 0.91 c
	2nd	0–15	1.16 $\pm$ 0.04 b	47.79 $\pm$ 0.97 ab	15.00 $\pm$ 1.04 a	62.79 $\pm$ 1.46 a	45.71 $\pm$ 1.20 a
		15–30	1.27 $\pm$ 0.04 ab	47.61 $\pm$ 1.07 ab	15.07 $\pm$ 1.31 a	62.68 $\pm$ 0.55 a	45.41 $\pm$ 1.02 a
	3rd	0–15	1.29 $\pm$ 0.05 ab	44.03 $\pm$ 0.91 b	14.67 $\pm$ 1.16 a	58.70 $\pm$ 1.78 ab	45.84 $\pm$ 1.28 a
		15–30	1.38 $\pm$ 0.04 a	43.86 $\pm$ 1.12 b	13.32 $\pm$ 1.11 a	57.18 $\pm$ 1.30 b	43.57 $\pm$ 1.03 b

Values that share similar letters within a column are not significantly different at a 95% significance level. Where, Sd is soil depth (cm), Pb is soil bulk density (g cm⁻³), Pc is capillary porosity (%), Pn is non-capillary porosity (%), P is total capillary porosity (%), Sa is soil aeration (%).

Table 3. F values from the two-factor ANOVA of soil physical properties in different types of forests and in *Eucalyptus* plantations with different stand ages and generations ($n = 18$).

Factors	Pb	Pc	Pn	P	Sa
Forest type	3.51 *	1.39	2.05	2.38 *	2.25
Soil depth	6.62 *	0.04	2.46	0.61	2.86 *
Interaction	0.20	0.24	0.16	0.10	0.05
Stand age	2.31 *	12.58 ***	3.92 *	17.72 ***	2.95 *
Soil depth	1.18	0.00	0.26	0.07	0.64
Interaction	0.24	0.10	0.35	0.37	0.70
Generation	5.59 **	21.46 ***	16.57 ***	6.88 **	15.71 ***
Soil depth	9.66 **	0.26	0.91	1.33	3.35 *
Interaction	0.04	0.09	0.27	0.29	0.55

*, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$. Where, Pb is soil bulk density, Pc is capillary porosity, Pn is non-capillary porosity, P is total capillary porosity, Sa is soil aeration.

3.2. Litter Properties

The dry litter weight, litter moisture content, and litter maximum water holding capacity were significantly influenced by both forest type and the *Eucalyptus* stand age (Table 4, $p < 0.05$). Notably, *Chinese Fir* exhibited lower values for dry litter weight and maximum water holding capacity than *Eucalyptus*. Within *Eucalyptus* plantations, the dry litter weight and litter maximum water holding capacity were significantly higher in 7-year-old trees (1220.94 ± 106.6 g m⁻² and 1637.39 ± 126.82 g kg⁻¹) compared to 5-year-old trees (604.76 ± 56.27 g m⁻² and 666.91 ± 58.98 g kg⁻¹) and 15-year-old trees (788 ± 82.39 g m⁻² and 1045.33 ± 131.55 g kg⁻²). Additionally, the litter moisture content in the 5-year-old trees was significantly lower than in the 7-year-old and 15-year-old trees. Regarding the rotation of *Eucalyptus*, only the litter moisture content showed a significant increase with increasing rotations ($F = 38.15$, $p < 0.0001$).

3.3. Hydrological Characteristics of the Soil

Forest type significantly influenced the soil moisture content (Figure 2d, $F = 4.18$, $p < 0.05$), which was highest in the *Chinese Fir* forest type, while forest type marginally affected the minimum and maximum water holding capacities (Figure 2a,b, $p < 0.1$). All minimum water holding capacity, maximum water holding capacity, capillary water holding, and soil moisture content values were significantly decreased with an increase in stand age (Figure 3a–d, $p < 0.001$), and there was no effect on soil layer. For a generation of

Eucalyptus, both rotation and soil layer had a significant impact on the minimum water holding capacity (Figure 4a, both $p < 0.05$), maximum water holding capacity (Figure 4b, both $p < 0.05$), and capillary water holding capacity (Figure 4c, both $p < 0.05$) values. The second rotation had the highest value of maximum water holding capacity at soil depths of 0–15 and 15–30 cm (Figure 4b). Soil moisture content significantly decreased with an increase in rotations (Figure 4d, $F = 27.45$, $p < 0.05$). In contrast, the soil layer had no significant effect.

Table 4. Physical and hydrological characteristics of litters in different types of forests and in *Eucalyptus* plantations with different stand ages and generations (mean $\pm$ standard error, $n = 3$).

Factors		Gd (g)	WL (%)	Whmax (g kg ⁻¹)
Forest type	<i>Eucalyptus</i>	811.91 $\pm$ 45.91 a	8.51 $\pm$ 0.18 b	1054.14 $\pm$ 71.80 a
	<i>Chinese Fir</i>	564.41 $\pm$ 91.24 b	8.36 $\pm$ 0.19 b	800.93 $\pm$ 119.95 b
	<i>Pine</i>	611.08 $\pm$ 87.78 ab	9.72 $\pm$ 0.67 a	897.25 $\pm$ 126.99 ab
Stand age	5-year	604.76 $\pm$ 56.27 b	7.64 $\pm$ 0.13 b	666.91 $\pm$ 58.98 c
	7-year	1220.94 $\pm$ 106.6 a	8.63 $\pm$ 0.28 a	1637.39 $\pm$ 126.82 a
	15-year	788 $\pm$ 82.39 b	9.01 $\pm$ 0.24 a	1045.33 $\pm$ 131.55 b
Generation	1st	604.76 $\pm$ 56.27 a	7.64 $\pm$ 0.13 c	666.91 $\pm$ 58.98 a
	2nd	584.36 $\pm$ 39.66 a	8.21 $\pm$ 0.39 b	665.64 $\pm$ 51.81 a
	3rd	709.17 $\pm$ 94.69 a	10.22 $\pm$ 0.38 a	724.83 $\pm$ 81.27 a
F Value	Forest type	8.521 ***	6.945 **	3.739 *
	Stand age	30.990 ***	21.24 ***	42.830 ***
	Generation	2.159	38.15 ***	0.591

Here, 5-year, 7-year, and 15-year refer to the stand ages of the *Eucalyptus* plantation; 1st, 2nd, and 3rd refer to the generations of the *Eucalyptus* plantation. Where Gd is the dry weight of the litter (g); WL is the litter moisture content; W_{hmax} is the maximum water holding capacity of the litter (g kg⁻¹). Values that share similar letters within a column are not significantly different at a 95% significance level. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

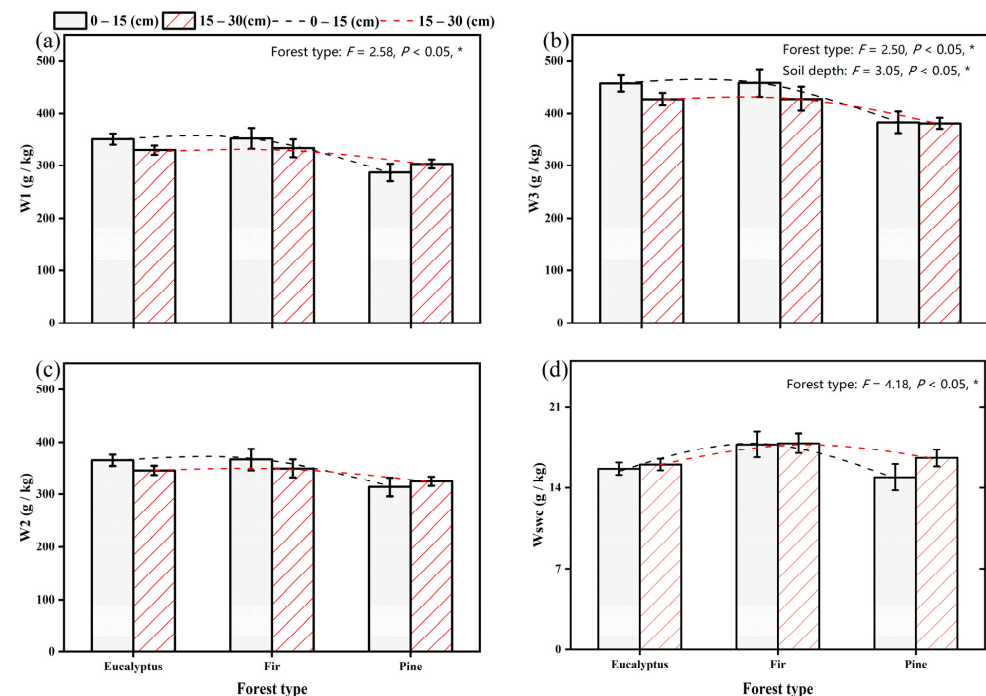


Figure 2. Soil characteristics at different soil depths among the forest types (a–d). The error bars indicate the standard errors of the means ($n = 3$). Figure (a), (b), (c), and (d) represent the maximum soil water holding capacity (W1), the minimum soil water holding capacity (W3), capillary moisture capacity (W2), and soil water content (Wswc) at different soil depths and forest types, respectively. The main significant effects of soil depth and forest type, as determined by a two-factor ANOVA, are indicated by * $p < 0.05$.

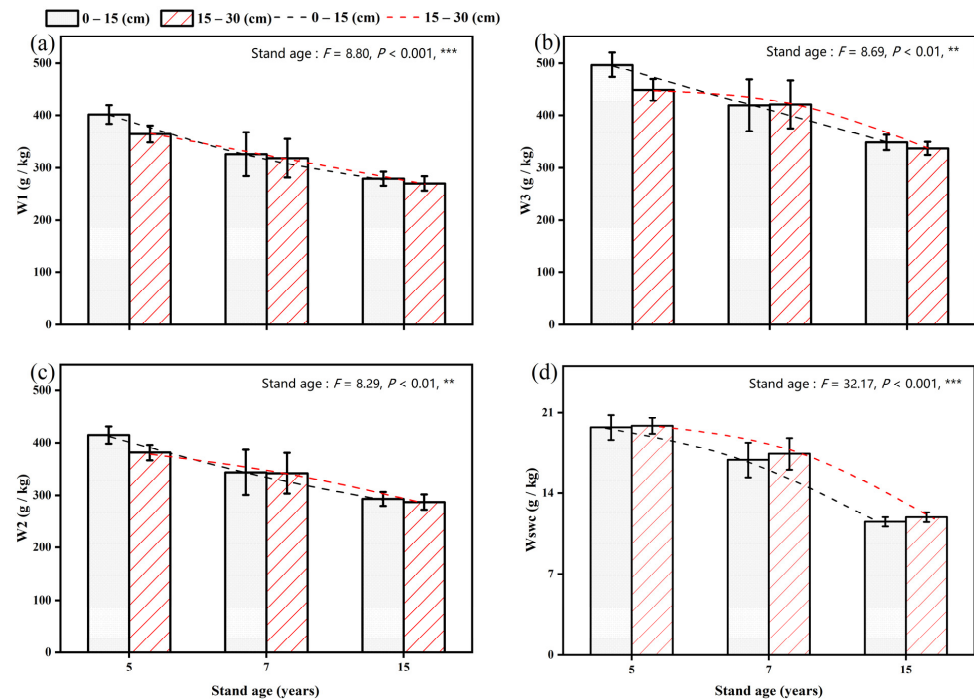


Figure 3. Soil hydrology of *Eucalyptus* plantations at different soil depths and stand ages (a–d). The error bars indicate the standard errors of the means ($n = 3$). Figure (a), (b), (c), and (d) represent the maximum soil water holding capacity (W1), the minimum soil water holding capacity (W3), capillary moisture capacity (W2), and soil water content (Wswc) at different soil depths and stand ages. The main significant effects of soil depth and stand age, as determined by a two-factor ANOVA, are indicated by $** p < 0.01$; and $*** p < 0.001$.

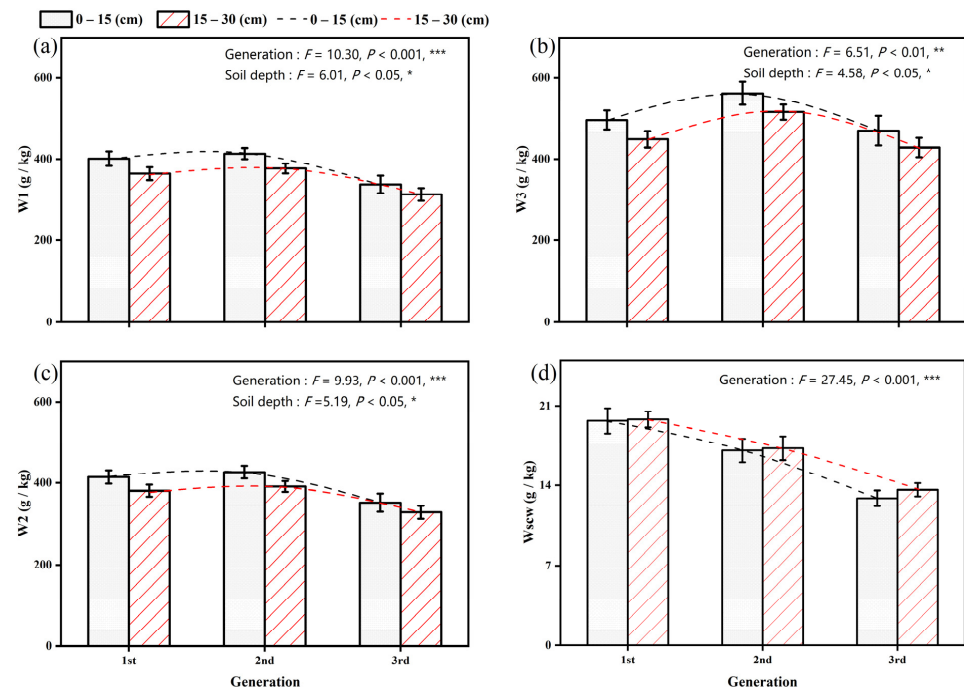


Figure 4. Soil hydrological characteristics of *Eucalyptus* plantations at different soil depths among generations. The error bars indicate the standard errors of the means ($n = 3$). Figure (a), (b), (c), and (d) represent the maximum soil water holding capacity (W1), the minimum soil water holding capacity (W3), capillary moisture capacity (W2), and soil water content (Wswc) at different soil depths and generations. The main significant effects of the different soil depths and generations, as determined by a two-factor ANOVA, are indicated by $* p < 0.05$; $** p < 0.01$; and $*** p < 0.001$.

3.4. Correlations among the Properties of the Soil and Litter and the Hydrological Characteristics

For the ages of the stands in the *Eucalyptus* plantation, our Pearson correlation analysis showed that bulk density was significantly negatively correlated with soil physical properties and soil water holding capacity (Figure 5a, $p < 0.001$). Capillary porosity was positively correlated with soil water holding capacity ($p < 0.01$) but significantly negatively correlated with litter characteristics (dry litter mass, litter moisture content, and maximum water holding capacity) ($p < 0.05$). The capillary water holding capacity of the soil was significantly positively related to soil aeration, soil moisture content, capillary porosity, total porosity, and maximum water holding capacity ($p < 0.001$). For the successive rotations of the *Eucalyptus* plantations, soil hydrological capacity was negatively correlated with bulk density. At the same time, it showed a significant positive correlation with total porosity and soil moisture content (Figure 5b). No significant correlations between the daily evaporation rate and soil-saturated permeability and the other parameters were found.

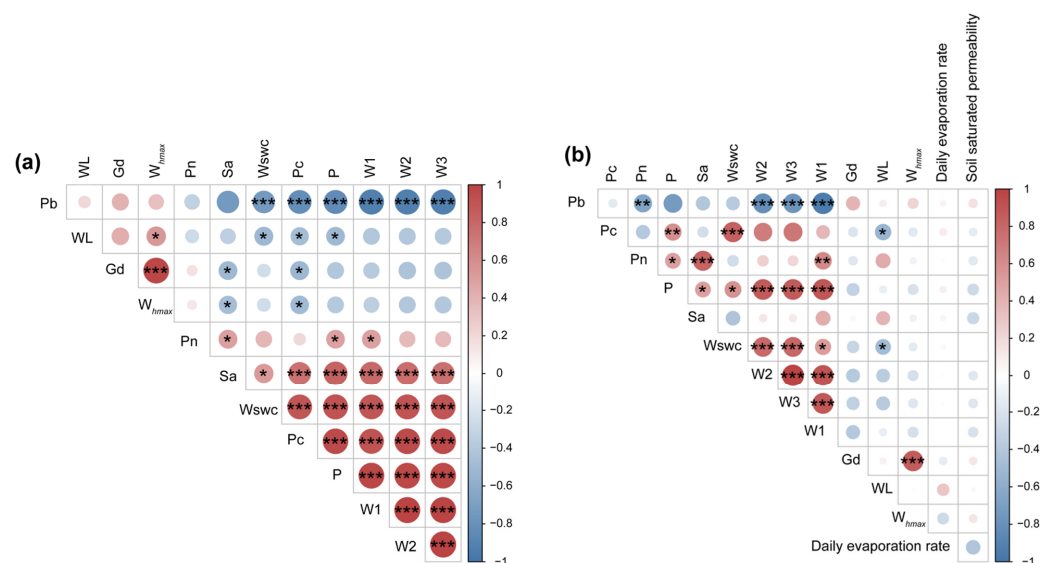


Figure 5. Pearson correlation analysis for the hydrological characteristics of the soil and litter for the different stand ages (a) and generations (b) of *Eucalyptus* plantations. Where, Pb is soil bulk density, Pc is capillary porosity, Pn is non-capillary porosity, P is total capillary porosity, Gd is the dry weight of the litter, WL is the litter moisture content, W_{hmax} is the maximum water holding capacity of the litter, Sa is soil aeration, W1 is the maximum soil water holding capacity, W2 is capillary moisture capacity, W3 is the minimum soil water holding capacity, Wswc is soil water content. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

To analyze the relationships between the hydrological characteristics of the soil and the physical properties of the soil and litter, a Principal Component Analysis (PCA) was conducted. The PCA results showed that PC1 explained 48.3%, 63.40%, and 48.4% of the variation in forest type, stand age, and successive rotation (Figure 6a–c). PC2 explained 14.3%, 17.8%, and 14.3% of the variation in forest type, stand age, and successive rotation, respectively. Maximum water holding capacity was also shown to be positively correlated with total porosity, but it was found to be negatively correlated with bulk density.

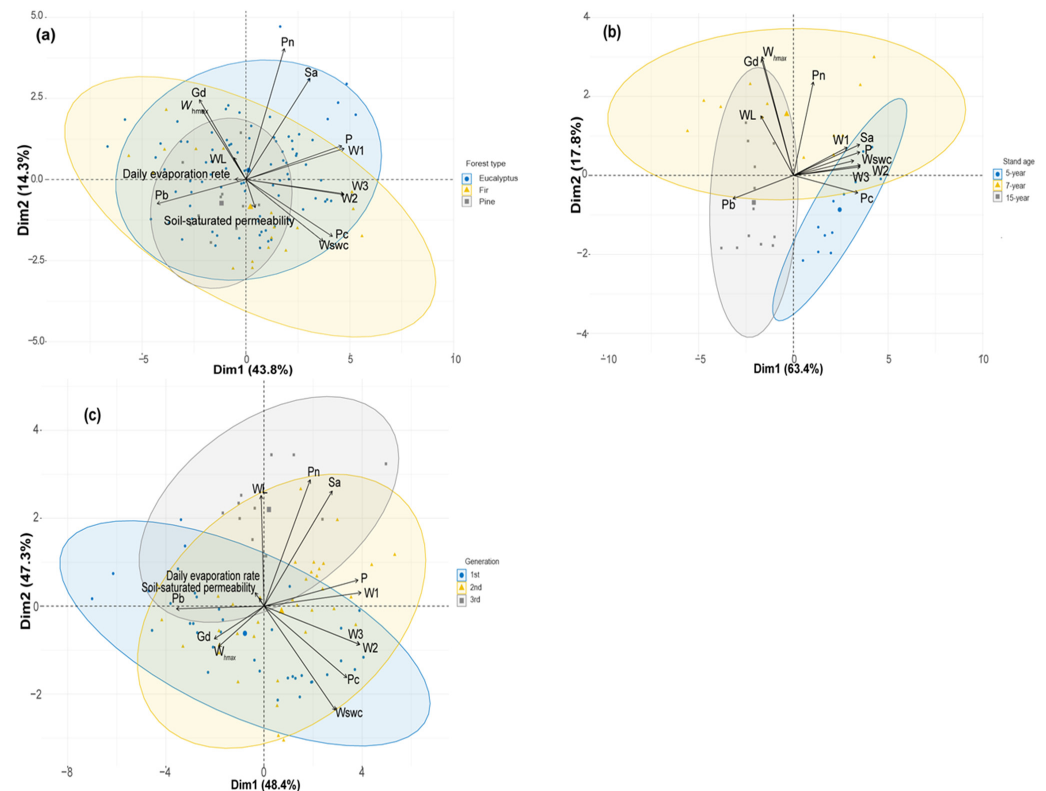


Figure 6. Principal component analysis (PCA) of the soil hydrological characteristics among different forest types (a), stand ages (b), and generations (c). Pb is soil bulk density, Pc is capillary porosity, Pn is non-capillary porosity, P is total capillary porosity, Gd is the dry weight of the litter, WL is the litter moisture content, W_{hmax} is the maximum water holding capacity of the litter, Sa is soil aeration, W1 is the maximum soil water holding capacity, W2 is capillary moisture capacity, W3 is the minimum soil water holding capacity, Wswc is soil water content. Ellipses represent 95% confidence levels for each treatment group.

4. Discussion

4.1. Forest Type Affects the Soil Hydrological Characteristics

Soil physicochemical properties and hydrological characteristics have been observed to vary significantly across diverse vegetation types [33,36,37]. In terms of water holding capacity, the maximum soil water retention of the three forests in our study ($381.45\text{--}458.05\text{ g kg}^{-1}$) is notably lower compared to other ecosystems, such as meadow ecosystems ($863.82\text{--}1318.87\text{ g kg}^{-1}$) [2], secondary forests, and other natural forests. These differences in soil hydrological properties are attributed to the substantial impact of soil physicochemical properties, which are influenced by both the aboveground canopy and belowground root systems of different plant types [37,38]. For instance, the aboveground canopy density significantly affected precipitation, light, and litter inputs, creating a unique understory microenvironment that affected SOM formation and soil moisture status [33,37]. However, our results only show that forest type strongly affected soil water holding capacity (maximum and minimum), soil moisture content, and total porosity ($p < 0.1$), and the *Eucalyptus* plantations exhibited better water holding capacity values compared to the other two forest types, which may be related to aboveground litter properties.

Significant impacts on litter characteristics and water holding capacity due to changes in forest type were observed in our study (Table 4). The dry mass of *Eucalyptus* litter was significantly greater than that of the *Pine* and *Chinese Fir* forests, which can be attributed to the deciduous nature of *Eucalyptus* as an evergreen broad-leaved species in contrast to the evergreen needle-leaf nature of the other two species, coupled with lower leaf production [37]. Moreover, our findings revealed a significant positive correlation between the

maximum water holding capacity of *Eucalyptus* litter and its dry mass, consistent with the results of Zagvyai (2019), who conducted a study on *Pine* forest sites, the results of which demonstrated that the water holding capacity solely depends on the weight of litter after oven-drying [38]. In addition, while numerous studies have indicated that soil hydrological properties are influenced by soil depth, with a gradual decrease in physicochemical properties and water holding capacity as depth increases, our analysis did not find significant interactions between soil depth and forest types. This nonsignificant interaction may be attributed to the inadequate differentiation of the physicochemical and hydrological properties of the soil at soil depths of 0–15 cm and 15–30 cm in our investigation, as these soil layers have low SOM contents.

4.2. Stand Age Weakens the Soil and Litter Hydrological Characteristics

The age of *Eucalyptus* plantation stands is primarily determined by the demand for wood, but the impact of stand age on the hydrological characteristics of the soil and ecosystem needs to be adequately considered. The dry mass of litter did not exhibit a successive increase with stand age. Notably, we observed that the dry litter mass and the maximum water holding capacity of the litter were highest at 7 years of age, showcasing a significant positive correlation between these variables (Figure 5). Conversely, increasing stand age did not consistently increase the dry litter mass. This outcome could be attributed to the decomposition and conversion of most litter into SOM in the 15-year-old trees. Relevant studies have indicated a significant increase in deadwood storage capacity with advancing forest age [39], and in [40], *Eucalyptus* demonstrated the ability to enhance SOM content in soil. Also, the accumulation of surface SOM favored water interception and led to a gradual increase in water content within the senesced litter, aligning with our findings.

Our findings demonstrate the significant influence of *Eucalyptus* stand age on the hydrological characteristics of soil. Specifically, as the stand age increases, a noticeable increase in bulk density occurs ($p < 0.05$), while capillary porosity, total porosity, and water holding capacity (capillary, minimum and maximum) significantly decrease ($p < 0.05$). This is because the increasing age of the *Eucalyptus* forests leads to a greater demand for soil moisture by the *Eucalyptus* trees, reducing soil moisture content and increasing soil bulk density. The roots of older trees can penetrate deeper into the soil, increasing the capillary porosity of the soil. Additionally, older trees can create more litter and organic matter on the forest floor [41], increasing capillary porosity. However, this *Eucalyptus* showed the opposite result: stand age decreased capillary and total porosity as we found that the age of the *Eucalyptus* stands significantly reduced the capacity of soil hydrology, which means a reduction in soil water holding capacity and an increase in soil erosion. Our findings also indicate that an increase in stand age does not improve soil's water holding capacity, but it does significantly decrease soil hydrological performance.

Eucalyptus trees are known for their high water consumption rates, which can affect soil moisture levels [14]. The water use rates of *Eucalyptus* for transpiration can lead to reduced streamflow and have implications for water resources. The impact of *Eucalyptus* plantations on soil moisture can also be influenced by the specific climatic conditions and soil characteristics of the region.

4.3. Successive Rotations Significantly Affected the Hydrological Characteristics of the Soil

Although previous studies have shown a significant reduction in the aboveground biomass productivity of *Eucalyptus* forests due to successive rotations, there is a lack of research on the hydrological properties of soil [42]. In contrast to the pronounced effect of stand age on litter properties, the influence of rotations on dry litter mass and maximum moisture content is not statistically significant. However, there is a substantial increase in litter moisture content with increasing rotations ($p < 0.05$). This phenomenon can be attributed to the effect of the rotation process on the proportion of undecomposed and partially decomposed litter within the litter layer, leading to notable disparities in litter moisture content despite the absence of differences in dry litter mass [39]. Furthermore,

previous studies have highlighted that rotations exert a discernible effect on the litter layer. Hence, implementing suitable forest management practices can help to considerably alter the water storage capacity of surface litter. The successive rotation of *Eucalyptus* plantations has been found to exert significant influences on aboveground factors such as plant biomass and species diversity, as well as belowground factors, such as soil nutrient dynamics, microbial activity, and physicochemical properties [10,22,42]. Consequently, these above- and belowground alterations can impact the physical properties and hydrological characteristics of soil, as shown by the findings of our study (Tables 1–3).

Our findings indicate that the second rotation of *Eucalyptus* trees displayed superior hydrological characteristics compared to the first and third rotations. This could potentially be attributed to the fact that the highest total porosity was found in the second rotation (Figure 6c). Our correlation analysis further substantiated the significant positive association between total porosity and maximum water holding capacity (Figure 6). Conversely, in the third rotation, a substantial reduction in total porosity was observed, likely resulting from forest management practices that led to a notable decrease in capillary porosity (Tables 1 and 2). Moreover, an increase in *Eucalyptus* rotation cycles was found to correspond with a significant reduction in soil moisture content (Figure 4d). This phenomenon may be attributed to the greater water utilization demands during the juvenile stage of *Eucalyptus* in the context of short-term rotation loading [23] and root uptake [25]. The decrease in the capillary porosity of the soil led to a decrease in soil moisture ($p < 0.05$). Significant shifts in microbial communities, diversity, microbial biomass, and enzyme activity in response to the successive planting of *Eucalyptus* indicated a change in the SOM and soil characteristics [10,43].

The saturated permeability of soil is primarily determined by factors such as pore-size distribution, soil depth, and soil properties like hydraulic conductivity [44]. Our findings also suggest that an increase in rotation significantly impacts soil-saturated permeability, decreasing soil hydrophobicity. These results are in agreement with our third hypothesis.

5. Conclusions

This study examined the impact of changes in the physical properties of soil and litter on forest soil hydrological characteristics by comparing three forest types, different ages of *Eucalyptus* forests, and continuous *Eucalyptus* rotation. Our first hypothesis was partly supported by the significant difference in litter properties (dry litter weight, litter maximum water holding capacity), soil bulk density, and total porosity. *Pine* exhibited the lowest water holding capacity, potentially attributed to the increase in soil bulk density. In contrast to the second hypothesis, the water storage capacity was significantly decreased with increasing stand age, a result attributed to the significant increase in bulk density and decreases in capillary porosity and total porosity. Our results partly agree with our third hypothesis, as successive rotation significantly affected soil properties and litter moisture content. We found that water holding capacity was considerably higher in the second rotation than in the first and third rotations, which may be related to the decreased soil bulk density and the increased total porosity. Notably, the water holding capacity of forest soil is a crucial indicator for assessing the ecological functions of forest ecosystems. Therefore, to balance eucalyptus production while maximizing the hydrological function of the soil, we recommend retaining as much of the plant residues on the soil as possible and harvesting after 5–7 years of cultivation.

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