Soil Infiltration Characteristics of Typical Plantations in Kunming City and Its Effects on Soil Water Repellency

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Abstract [**Objectives**] The soil permeability and its influencing factors in typical plantations were studied to provide a scientific basis for tending and managing plantations in the Haikou forest area of Kunming City. [**Methods**] With three kinds of typical forest stands, *i. e.*, over-mature *Pinus armandii Franch.*, mid-mature *Eucalyptus robusta Smith*, and over-mature *E. robusta Smith* in this region as the research objects, soil infiltration changes and the effects on soil water retention in different stands, soil layers, and gap conditions under different moisture conditions were analyzed. [**Results**] ① Under all three moisture conditions, the over-mature *P. armandii* forest demonstrated higher overall infiltration rates than the other two forest stands, which showed relatively similar infiltration rates. In all three stands, the soil infiltration rate decreased as the depth of the soil increased. Significant fluctuations in soil infiltration rate were observed during the initial 0 -5 min, followed by gradual stabilization or regular fluctuations after 5 min. The infiltration process generally reached saturation after approximately 20 min. ② The average infiltration rate was identified as the key factor affecting soil infiltration. Comprehensive evaluation of soil permeability revealed that the over-mature *P. armandii* forest exhibited optimal soil permeability. ③ Various soil physical and chemical properties significantly affected different indexes of soil permeability under varying conditions, with soil organic carbon content and water repellency demonstrating particularly notable effects on infiltration under different conditions. [**Conclusions**] Soil infiltration rates gradually decreased with the deepening of the soil layer. Principal component analysis (PCA) showed that the soil permeability of the over-mature *P. armandii* forest was stronger than that of the other two stands under the three moisture conditions, especially in non-gap positions. All soil indexes affected soil permeability, and soil organic carbon and water repellency were the key factors affecting soil permeability.

Key words Plantation; Soil permeability; Soil water repellency; Influencing factor

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Soil permeability is a critical physical parameter for describing soil infiltration characteristics, referring to the process by which water on the soil surface moves downward into deeper soil layers under the influence of gravitational force. It is a highly complex dynamic process, as the cycle of water within the soil is significantly influenced by the strength of infiltration. Consequently, soil permeability largely determines the redistribution of soil moisture in natural environments, profoundly impacting water movement in plantation soils and thereby affecting the survival and growth of vegetation in plantation forests[1]. Soil infiltration determines the replenishment of soil moisture, its movement within the soil profile, the degree of water loss and soil erosion, and water retention in the soil. With the growth and development of plants, the root system will spread around in the soil for better contact with water and absorbing nutrients for their growth, so the permeability of soil determines the growth characteristics of plants to a certain extent[2]. Soil permeability is used to describe the rate at which water infiltrates into the soil[3]. Higher soil permeability enables the soil to rapidly absorb and store water through non-capillary pores when encountering extreme weather events such as heavy rainfall or excessive irrigation under the influence of gravitational force, or to generate subsurface runoff within the soil. Conversely, soils with poor permeability exhibit low non-capillary porosity, limiting their capacity to absorb and retain water during extreme weather, intense precipitation, or excessive irrigation. Such a condition will result in significant water loss and soil erosion. Moreover, in the process of water loss, a lot of soil will be carried away, and some nutrients needed by plants will inevitably flow away with soil loss. and finally, the surface runoff formed in the process of soil erosion will aggravate the degree of soil erosion in forest land. Thus, soil permeability critically influences the redistribution of soil moisture, the formation of runoff pathways, and the severity of soil erosion. Similar to soil water repellency, soil permeability serves as an important observation index in plant and soil hydrology, which is of great significance for the research on soil and water conservation in forest ecosystems[4].

Soil permeability, serving as a crucial index for studying vegetation and soil hydro-ecological functions, influences indices including soil nutrient content and structural properties, and reflects a region's soil water conservation capacity and runoff distribution function[5]. It significantly affects runoff allocation in plantation soils, where proper regulation can enhance both economic and ecological benefits while increasing tree survival rates. Up to now, numerous studies have investigated soil permeability and water repellency[6], including research on soil infiltration models and the impact of water repellency on soil permeability, revealing that permeability is influenced by various external and internal factors[7]. Key influencing factors include vegetation type[8-9], forest litter characteristics[10], soil biota[11-12], and soil physicochemical properties[13-14]. Yan *et al.*[8] studied surface roots of different vegetation types in the Danjiangkou Reservoir area and found that the initial infiltration rate and steady infiltration rate of soil under different plant types were significantly correlated with root length

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density and root surface area density. Both initial and steady infiltration rates showed consistent trends among different vegetation types, with broad-leaved forests and mixed coniferous-broadleaf forests exhibiting the best soil permeability among the four types of forests. Additionally, surface soil layers demonstrated significantly higher initial and steady infiltration rates compared to deeper layers. Xu *et al*. [9] investigated five types of public welfare forests in Jiangxi Province through analysis of soil moisture, physical properties, and chemical characteristics, revealing that soils in mixed coniferous-broadleaf forests were more porous and looser. Such structural advantage resulted in richer soil nutrients and the best permeability and water retention capacity in mixed coniferous-broadleaf forests. Current research has extensively investigated soil permeability and its influencing factors under different sites and forest stands. However, relatively few studies have examined variations in soil permeability under different moisture conditions in plantations or their effects on soil water repellency. As soil moisture plays a crucial functional role in forest ecosystems, and soil water repellency affects the movement process of soil water to a certain extent, there exists a certain connection between repellency and water infiltration. Studying soil permeability and its effects on water repellency under varying moisture conditions in different plantation types will help evaluate the water conservation capacity of forest soils. Such understanding can effectively prevent and control the loss of nutrients and water in the soil to a certain extent and increase the soil water storage capacity. Based on this, in this study, taking Haikou Forest Farm in Kunming City as the study base, soil permeability and its influencing factors were explored at both gap and non-gap positions in different plantations under different moisture conditions, aiming to elucidate the relationship between soil permeability and water repellency.

Materials and Methods

General situation of study area

The study area was located in Haikou Forest Farm, Xishan District, Kunming City, Yunnan Province (102°28′ – 102°38′ E; 24°43′ – 24°56′ N). The terrain consists primarily of low hills and mountains, with elevations ranging from 1 972 to 2 482 m. The region has a subtropical monsoon climate characterized by uneven precipitation distribution, and the rainy season is from July to September. The annual average temperature is 15.4 ℃. Haikou Forest Farm is rich in plant resources, dominated by soil and water conservation forests and water retention forests. Main tree species include *Pinus armandii* Franch., *Pinus yunnanensis* Franch., *Sabina chinensis* L., and *Eucalyptus robusta* Smith.

Sample plot setting and sampling methods

Given that the typical plantations in the forest farm are primarily composed of *P. armandii* forests and *E. robusta* forests, three representative plots were selected in this study: overmature *P. armandii* forest, mid-mature *E. robusta* forest, and overmature *E. robusta* forest. During the dry season (February – May 2022), both gap and non-gap positions were randomly selected within each forest type to establish 1 m × 1 m quadrats, with three quadrats per plot (totaling six sampling points per stand). Within each quadrat, soil profiles were excavated to collect undisturbed core samples at 20 cm intervals (0 – 100 cm depth) using cutting rings. From each layer, 18 core samples were collected for the measurement of soil permeability and water repellency under the three moisture conditions, and 1 kg of soil was taken back to the laboratory and air-dried for analysis. All labeled core samples were transported to the laboratory for further testing.

Study methods

Soil permeability and water repellency were measured under three moisture conditions: natural soil moisture content, field moisture content, and saturated moisture content. Soil permeability was determined by the double-ring infiltration method combined with the constant head method using the Mariotte bottle system. The collected soil cores were fixed with an additional empty cutting ring on top and sealed with tape to prevent water leakage during the experiment. The Mariotte bottle maintained a constant water head to ensure no overflow in the upper ring. Water level changes in the Mariotte bottle were recorded at 1-minute intervals. The infiltration rate was calculated based on the observed decline of the water surface in the Mariotte bottle. The average permeability within 5 min after the first drop of water was recorded as the initial permeability. The steady infiltration rate was considered achieved when the infiltration rate showed no change or exhibited consistent fluctuations within a five-minute observation period. The recorded steady infiltration rate was then regarded as the saturated infiltration rate of the soil sample.

Soil water repellency was measured using the Water Drop Penetration Time (WDPT) method[15] with three replicates for each soil layer. The specific procedure involved dropping eight drops of distilled water (approximately 0.05 ml per drop) from a standard burette onto the surface of undisturbed soil samples. The penetration criterion was defined as the complete disappearance of the water drop from the soil surface as observed visually. The time required for each drop to fully infiltrate into the soil was recorded using a stopwatch, and the arithmetic mean of the infiltration time required by the eight drops was calculated as the final WDPT value for each sample. During measurement, the drops were released from a height of approximately 1 cm above the soil surface to minimize the influence of kinetic energy on soil-water interaction. The soil water repellency was classified according to the following criteria[16]: WDPT < 5 s indicating non-repellent, 5 s $\leqslant$ WDPT < 60 s indicating slightly repellent, 60 s $\leqslant$ WDPT < 600 s indicating strongly repellent, 600 s $\leqslant$ WDPT $< 3\ 600$ s indicating severely repellent, and WDPT $\geqslant 3\ 600$ s indicating extremely repellent.

Data processing

The original data were statistically analyzed using Excel 2021. Data analysis was performed using SPSS 21.0. One-way ANOVA was adopted to test significant differences ($P < 0.05$) among three replicates, and multiple comparisons were conducted by Tukey's test. Finally, Origin 2021 was employed for plotting.

Results and Analysis

Basic physical and chemical properties of soil in different forest stands

Table 1 shows the basic physical and chemical properties of soil in different forest stands. Overall, whether in gap or non-gap areas, soils from all three forest types exhibited weakly acidic characteristics (pH <6). Soil organic carbon content and porosity decreased with increasing depth of the soil, while bulk density showed an opposite trend. The soil water-holding capacity exhibited inconsistent variations (natural moisture content, saturated moisture content, and field moisture content). Notably, in the 80 – 100 cm layer of the over-mature *P. armandii* forest, 40 – 80 cm layer of the mid-mature *E. robusta* forest and 80 – 100 cm layer of the over-mature *E. robusta* forest, the soil organic carbon content was higher at gap positions than at non-gap positions, while the opposite pattern was observed in other soil layers. All three forest stands showed significantly higher organic carbon content in the 0 – 20 cm layer at non-gap positions than deeper layers. The over-mature *E. robusta* forest exhibited higher bulk density in corresponding soil layers than other two stands, and minimal differences between gap and non-gap positions for the same layer. At gap positions, the over-mature *P. armandii* forest showed notably higher soil porosity than other two stands, while the over-mature *E. robusta* forest generally maintained relatively lower porosity values. Both at gap and non-gap positions, the over-mature *P. armandii* forest exhibited higher natural moisture content, saturated moisture content and field moisture content than other two forest stands, indicating its superior water conservation capacity.

Table 1 Basic physical and chemical properties of soil in different stands

Stand	Soil layer//cm	pH	Organic carbon//g/kg	Bulk density g/cm³	Porosity//%	Natural moisture content//%	Saturated moisture content//%	Field moisture content//%
Gap conditions								
Over-mature	0 – 20	5.61 ±0.02 Ad	19.56 ±0.25 Aa	1.21 ±0.01 Bb	54.58 ±0.70 Aa	9.84 ±0.34 Cc	20.07 ±0.17 Aa	5.43 ±0.30 Bb
P. armandii	20 – 40	5.69 ±0.02 Ac	16.88 ±0.26 Ab	1.22 ±0.02 Bb	53.86 ±0.50 Aa	10.29 ±0.58 Cb	19.84 ±0.57 Aa	5.62 ±0.43 Bb
	40 – 60	5.77 ±0.01 Ab	8.31 ±0.41 Ac	1.21 ±0.02 Bb	55.01 ±0.67 Aa	9.54 ±0.26 Ca	18.29 ±0.12 Ab	5.95 ±0.25 Bb
	60 – 80	5.83 ±0.01 Aab	5.14 ±0.43 Ad	1.19 ±0.02 Bb	54.66 ±0.73 Aa	9.42 ±0.25 Ca	18.27 ±0.32 Ab	8.29 ±0.30 Baa
	80 – 100	5.89 ±0.05 Aa	4.42 ±0.24 Ad	1.35 ±0.01 Ba	49.38 ±0.01 Ab	8.59 ±0.00 Cb	18.06 ±0.49 Ab	5.96 ±0.00 Bb
Mid-mature	0 – 20	5.56 ±0.02 Aa	11.60 ±0.15 Aa	1.24 ±0.03 Ba	54.02 ±0.91 A	3.86 ±0.14 Aab	19.48 ±0.58 Aa	9.85 ±0.37 Aa
E. robusta	20 – 40	5.80 ±0.14 Aa	10.95 ±1.01 Aa	1.23 ±0.03 Ba	53.22 ±1.08 Aaa	6.18 ±0.26 Aa	18.84 ±0.19 Aab	9.84 ±0.09 Aa
	40 – 60	5.58 ±0.04 Aa	10.68 ±0.53 Aa	1.31 ±0.07 Ba	52.87 ±2.48 Aa	7.72 ±0.10 Ab	18.48 ±0.33 Abc	9.93 ±0.07 Aa
	60 – 80	5.70 ±0.13 Aa	10.95 ±0.72 Aa	1.33 ±0.05 Ba	52.41 ±2.65 Aa	8.42 ±0.30 Ab	18.47 ±0.37 Abc	10.15 ±0.71 Aa
	80 – 100	5.82 ±0.17 Aa	3.28 ±0.44 Ab	1.29 ±0.04 Ba	51.52 ±1.24 Aa	9.28 ±0.11 Ac	17.65 ±0.12 Ac	10.63 ±0.34 Aa
Over-mature	0 – 20	5.33 ±0.08 Bb	24.16 ±0.38 Aa	1.29 ±0.01 Ab	52.17 ±1.24 Ba	3.43 ±0.30 Bd	16.37 ±0.27 Bb	7.86 ±0.20 Bc
E. robusta	20 – 40	5.38 ±0.01 Bb	8.67 ±0.14 Ab	1.41 ±0.02 Aa	46.19 ±0.72 B	5.82 ±0.47 Bc	16.51 ±0.31 Bb	8.34 ±0.27 Bc
	40 – 60	5.43 ±0.08 Bb	3.69 ±0.01 Ac	1.44 ±0.03 Aa	45.97 ±0.68 Bbb	7.53 ±0.13 Bb	19.02 ±0.09 Ba	10.31 ±0.24 Bb
	60 – 80	5.40 ±0.11 Bb	3.01 ±0.09 Ac	1.44 ±0.03 Aa	46.28 ±1.12 Bb	7.44 ±0.29 Bb	18.86 ±0.52 Ba	10.41 ±0.38 Bb
	80 – 100	5.68 ±0.03 Ba	1.66 ±0.26 Ad	1.45 ±0.02 Aa	47.71 ±0.44 Bb	5.02 ±0.16 Ba	19.61 ±0.44 Ba	11.35 ±0.27 Ba
Non-gap conditions								
Over-mature	0 – 20	5.59 ±0.01 Ab	25.42 ±0.37 Aa	1.21 ±0.01 Ba	57.93 ±1.54 Aa	9.87 ±0.17 Cc	9.79 ±0.68 Aa	21.85 ±0.57 Ba
P. armandii	20 – 40	5.36 ±0.01 Ad	20.41 ±0.63 Ab	1.21 ±0.01 Ba	53.94 ±0.38 Aab	10.30 ±0.25 Ca	10.06 ±0.08 Ab	18.21 ±0.35 Ba
	40 – 60	5.52 ±0.01 Ac	9.54 ±0.40 Ac	1.23 ±0.07 Ba	53.29 ±2.21 Aab	10.28 ±0.31 Ca	9.72 ±0.06 Ac	16.80 ±0.52 Ba
	60 – 80	5.72 ±0.03 Aa	8.04 ±0.53 Ad	1.27 ±0.08 Ba	51.90 ±2.78 Ab	9.82 ±0.08 Cb	9.98 ±0.33 Ad	15.31 ±0.39 Ba
	80 – 100	5.72 ±0.03 Aa	3.93 ±0.52 Ae	1.35 ±0.05 Ba	49.30 ±1.60 Ab	9.61 ±0.02 Cc	9.69 ±0.12 Ad	15.13 ±0.21 Ba
Mid-mature	0 – 20	5.31 ±0.03 Ac	17.83 ±0.65 Aa	1.14 ±0.04 Bb	58.76 ±0.52 Aa	4.64 ±0.19 Aa	9.19 ±0.42 Aa	20.30 ±0.58 Ab
E. robusta	20 – 40	5.59 ±0.04 Ab	12.13 ±0.18 Ab	1.19 ±0.05 Bab	56.95 ±0.43 Aab	6.31 ±0.68 Aa	10.66 ±0.85 Aa	20.08 ±0.22 Aa
	40 – 60	5.64 ±0.13 Ab	10.46 ±0.28 Ac	1.27 ±0.01 Ba	55.17 ±0.59 Aabc	9.74 ±0.17 Aa	11.04 ±0.51 Aab	19.31 ±0.11 Aa
	60 – 80	5.77 ±0.15 Aab	9.27 ±0.20 Ad	1.25 ±0.08 Bab	52.61 ±2.59 Abc	9.95 ±0.31 Aa	10.41 ±0.05 Aab	18.94 ±0.39 Aa
	80 – 100	6.01 ±0.07 Aa	8.79 ±0.20 Ad	1.23 ±0.01 Bab	51.75 ±2.69 Ac	11.42 ±0.48 Aa	10.66 ±0.38 Ab	18.62 ±0.20 Aa
Over-mature	0 – 20	5.24 ±0.05 Bc	26.72 ±0.65 Aa	1.32 ±0.03 Ab	50.24 ±0.98 Ba	5.80 ±0.09 Bd	6.37 ±0.45 Ba	20.21 ±0.30 Bc
E. robusta	20 – 40	5.20 ±0.02 Bc	11.11 ±0.34 Ab	1.37 ±0.00 Aab	48.59 ±2.12 Bab	7.81 ±0.20 Bc	6.84 ±0.34 Ba	19.42 ±0.25 Bc
	40 – 60	5.32 ±0.03 Bb	5.29 ±0.22 Ac	1.46 ±0.01 Aa	46.60 ±1.08 Bb	8.08 ±0.33 Bb	8.37 ±0.14 Bb	15.77 ±0.57 Bb
	60 – 80	5.60 ±0.02 Ba	3.56 ±0.10 Ad	1.46 ±0.01 Aa	45.61 ±0.29 Bb	6.92 ±0.50 Bb	8.78 ±0.28 Bbc	15.36 ±0.20 Bb
	80 – 100	5.37 ±0.02 Bb	1.39 ±0.25 Ae	1.47 ±0.02 Aa	46.01 ±0.58 Bb	6.12 ±0.02 Ba	9.77 ±0.51 Bc	14.62 ±0.17 Ba

Different capital letters indicate significant differences ($P < 0.05$) among the three forest stands, while different lowercase letters denote significant differences ($P < 0.05$) among different soil layers within the same forest stand under the same gap condition. The same below.

Soil water repellency characteristics in different forest stands

As shown in Table 2, under the three moisture conditions, the soil water repellency showed an order of over-mature *E. robusta* stand (slightly repellent) > over-mature *P. armandii* stand (non-repellent) > mid-mature *E. robusta* stand (non-repellent). Different soil layers in both the over-mature *P. armandii* and mid-mature *E. robusta* stands all exhibited non-repellent or slightly repellent characteristics. In contrast, the 0 – 20 cm layer of the over-mature *E. robusta* stand showed strong repellency, while its deeper layers were either slightly repellent or non-repellent. Furthermore, in all stands, the degree of soil water repellency decreased with increasing soil depth under different soil moisture conditions, and the 0 – 20 cm layer consistently demonstrated the strongest repellency, showing significant differences from deeper layers. The subsoil layers maintained relatively low and stable repellency levels, with the 80 – 100 cm layer exhibiting the weakest repellency, being substantially non-repellent in most cases.

Under natural moisture conditions, both over-mature *P. armandii* and over-mature *E. robusta* stands showed stronger repellency in the 0 – 20 cm layer at gap positions than at non-gap positions, while the opposite pattern was observed in the mid-mature *E. robusta* stand. Regarding field repellency, the over-mature *P. armandii* and mid-mature *E. robusta* stands exhibited stronger soil water repellency at gap positions than at non-gap positions in different soil layers (except for the 80 – 100 cm layer in the over-mature *P. armandii* stand). Under the saturated moisture content condition, all three stands displayed weak repellency (non-repellent or slightly repellent) at non-gap positions in different soil layers. Similarly, the over-mature *P. armandii* and mid-mature *E. robusta* stands showed only non-repellent or slightly repellent characteristics at gap positions in different soil layers, whereas the over-mature *E. robusta* stand demonstrated strong repellency at gap positions.

Table 2 Soil water repellency in different forest stands under different moisture conditions

Stand	Soil layer//cm	Gap			Non-gap		
		Natural water repellency//s	Field water repellency//s	Saturated water repellency//s	Natural water repellency//s	Field water repellency//s	Saturated water repellency//s
Over-mature *P. armandii*	0 – 20	21 ± 10.74 Ba	7 ± 2.96 Ba	11 ± 5.98 Ba	20 ± 12.23 Ba	3 ± 1.70 Ba	2 ± 1.46 Bc
	20 – 40	7 ± 4.89 Bb	3 ± 1.72 Bb	7 ± 4.84 Bb	12 ± 6.63 Bb	3 ± 1.37 Ba	5 ± 4.70 Bb
	40 – 60	8 ± 3.98 Bb	3 ± 2.21 Bb	5 ± 2.79 Bc	6 ± 3.82 Bc	3 ± 1.76 Ba	5 ± 3.45 Ba
	60 – 80	3 ± 1.73 Bc	3 ± 1.83 Bb	3 ± 1.97 Bd	5 ± 1.85 Bc	3 ± 1.64 Ba	4 ± 2.68 Bab
	80 – 100	3 ± 1.58 Bc	2 ± 0.77 Bb	3 ± 1.88 Bd	3 ± 1.79 Bd	2 ± 0.89 Ba	3 ± 2.03 Bbc
Mid-mature *E. robusta*	0 – 20	5 ± 1.98Ca	4 ± 2.14 Ba	5 ± 1.89 Ba	5 ± 2.29 Ca	5 ± 1.86 Ba	4 ± 1.53 Ba
	20 – 40	5 ± 2.48 Ca	4 ± 2.08 Ba	3 ± 1.65 Bb	4 ± 1.93 Cab	4 ± 1.60 Bab	3 ± 1.33 Bab
	40 – 60	5 ± 1.76 Ca	4 ± 1.89 Ba	3 ± 1.49 Bb	4 ± 2.03 Cab	3 ± 1.20 Bbc	2 ± 1.06 Bb
	60 – 80	4 ± 1.80 Cab	3 ± 1.59 Bab	2 ± 1.01 Bb	3 ± 1.85 Cb	2 ± 1.13 Bc	2 ± 0.90 Bb
	80 – 100	3 ± 1.10 Cb	2 ± 1.48 Bb	2 ± 1.01 Bb	3 ± 1.34 Cb	2 ± 0.78 Bc	2 ± 0.95 Bb
Over-mature *E. robusta*	0 – 20	38 ± 11.43 Aa	30 ± 14.73 Aa	30 ± 15.29 Aa	29 ± 13.67 Aa	35 ± 21.03 Aa	27 ± 14.50 Aa
	20 – 40	19 ± 9.00 Ab	18 ± 8.79 Ab	24 ± 9.78 Ab	17 ± 6.30 Ab	14 ± 6.16 Ab	10 ± 3.63 Ab
	40 – 60	11 ± 4.14 Ac	6 ± 2.56 Ac	17 ± 5.79 Ac	13 ± 7.08 Ac	9 ± 3.84 Ac	9 ± 3.27 Ab
	60 – 80	7 ± 2.27 Ad	5 ± 2.14 Ac	9 ± 2.16 Ad	9 ± 3.85 Ad	6 ± 1.89 Ad	4 ± 1.54 Ac
	80 – 100	4 ± 2.12 Ae	3 ± 1.23 Ad	3 ± 1.40 Ae	4 ± 2.28 Ae	3 ± 1.91 Ae	2 ± 1.35 Ad

Variation patterns of soil infiltration rate over time in different forest stands

Variation pattern of soil infiltration rate over time under natural moisture content As shown in Fig. 1, under natural moisture content, the soil infiltration rate in the 0 – 20 cm layer was significantly higher than that in other layers, and noticeable differences were observed among different soil layers in different forest stands. In the 0 – 20 cm layer, the overall infiltration rates from high to low were as follows: over-mature *P. armandii* at non-gap positions, over-mature *P. armandii* at gap positions, and mid-mature *E. robusta* at non-gap positions. The infiltration rates of other stands showed minimal temporal variation differences. Notably, the mid-mature *E. robusta* stand exhibited significant infiltration rate fluctuations at non-gap positions with time, particularly within the first 20 min, while other stands demonstrated relatively stable infiltration patterns over time until reaching saturated infiltration rates. In the 20 – 40 cm soil layer, the overall infiltration rate was higher in the over-mature *P. armandii* forest than in other forest stands, with the highest rate observed under non-gap conditions. The infiltration rates of the other two forest stands were both below 0.8 mm/min, with significant fluctuations during the infiltration process, particularly in the mid-mature *E. robusta* forest, where the lowest infiltration rate was reflected in no infiltration within one minute. In the 40 – 60 cm soil layer, the overall infiltration rates were relatively low, all fluctuating within 1 mm/min. The over-mature *P. armandii* stand still showed the highest infiltration rates, with gap positions exhibiting higher values than non-gap positions. Of the other two stands, the mid-mature *E. robusta* stand demonstrated higher infiltration rates under the gap condition, followed by the over-mature *E. robusta* stand under both non-gap and gap conditions, while the mid-mature *E. robusta* stand under the non-gap condition showed the lowest infiltration rates. In the 60 – 80 cm soil layer, the three forest stands exhibited a distinct infiltration rate pattern: mid-mature *E. robusta* > over-mature *P. armandii* > over-mature *E. robusta*, and gap positions consistently showed higher rates than non-gap positions in all stands. In the

80 – 100 cm layer, the mid-mature *E. robusta* stand maintained a higher overall infiltration rate than the other two stands, while the over-mature *P. armandii* and over-mature *E. robusta* stands showed minimal differences, which fluctuated within a narrow range of 0.1 mm/min.

Overall analysis revealed that the soil infiltration rate consistently decreased with increasing depth in all three forest stands. The over-mature *P. armandii* stand showed the highest infiltration rate in the upper soil layers, while below 60 cm, the mid-mature *E. robusta* stand showed the highest infiltration rate. In most cases, the infiltration rate exhibited significant variations during the initial 5 min, followed by gradual stabilization or regular fluctuations after 5 min, and saturated infiltration conditions were gradually achieved after approximately 20 min.

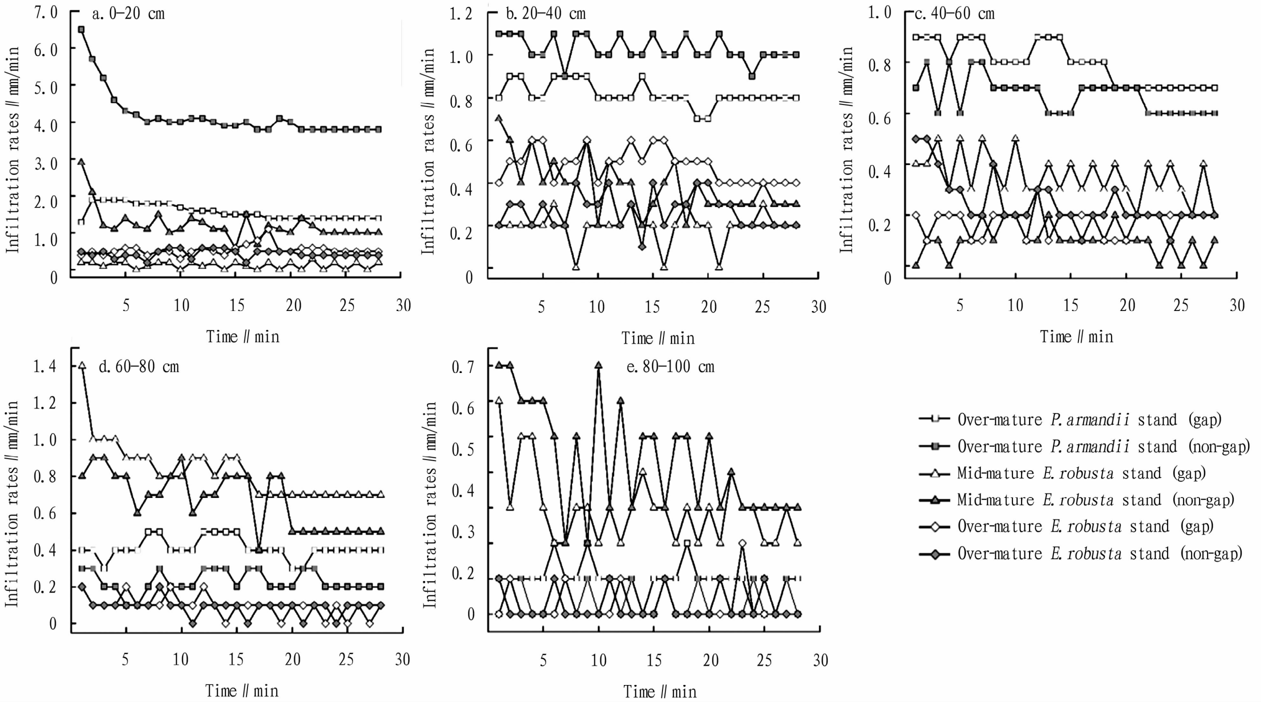

Fig. 1 Infiltration rates in various soil layers of different forest stands under natural moisture content

Variation in soil infiltration rate over time under field moisture content As shown in Fig. 2, in the 0 – 20 cm soil layer, the infiltration rates of the over-mature *P. armandii* forest at both gap and non-gap positions were higher than those of other forest stands, while the remaining stands exhibited infiltration rates fluctuating from 0 to 1.5 mm/min. In the 20 – 40 cm soil layer, except for the significantly higher infiltration rate of the over-mature *P. armandii* forest under gap conditions than other stands, the infiltration rates under other conditions were relatively low and similar, ranging from 0 to 1.5 mm/min. In the 40 – 60 cm soil layer, the infiltration rate was also relatively higher in the over-mature *E. robusta* forest, while the overall infiltration rates in the three forest stands were lower, ranging from 0 to 1.8 mm/min. In the 60 – 80 cm soil layer, the variation in infiltration rate followed a pattern similar to that in the 20 – 40 cm layer for the three kinds of forest stands. In the 80 – 100 cm soil layer, the over-mature *P. armandii* forest under non-gap conditions exhibited the highest infiltration rate, while the infiltration rates under gap conditions in other forest stands were relatively lower and similar.

Overall, under the field moisture condition, the soil infiltration rate was highest in the over-mature *P. armandii* forest, while other two forest stands exhibited relatively similar and lower rates. Additionally, the variation in infiltration rate over time was minor, generally showing a decreasing trend within the first 5 min and a gradual stabilizing trend after 5 min.

Variation in soil infiltration rate over time under saturated moisture content As shown in Fig. 3, the soil infiltration rate was higher in the 0 – 20 cm layer under saturated conditions. The over-mature *P. armandii* forest exhibited significantly higher infiltration rates at both gap and non-gap positions in this layer. In the mid-mature *E. robusta* forest, the infiltration rate at non-gap positions was relatively higher in the first minute (reaching 3 mm/min) than in other periods. In the 20 – 40 cm soil layer, the infiltration rates of all forest stands fluctuated between 0.2 and 2.1 mm/min under both gap and non-gap conditions, with minor differences observed among them. In the 40 – 60 cm soil layer, the over-mature *P. armandii* forest showed relatively higher infiltration rates at non-gap positions during the first 12 min, reaching 4.0 – 4.4 mm/min, which sharply decreased to 2 mm/min after 12 min and then showed a gradually stabilizing trend with fluctuations. Other forest stands maintained lower infiltration rates (below 1.5 mm/min) under both gap and non-gap conditions with minor fluctuations over time. In the 60 – 80 cm soil layer, the infiltration rates of all forest stands under both gap and non-gap conditions fluctuated between 0 and 0.5 mm/min over time. In the 80 – 100 cm soil layer, the infiltration rates varied within the range of 0 – 1 mm/min at both gap and non-gap positions.

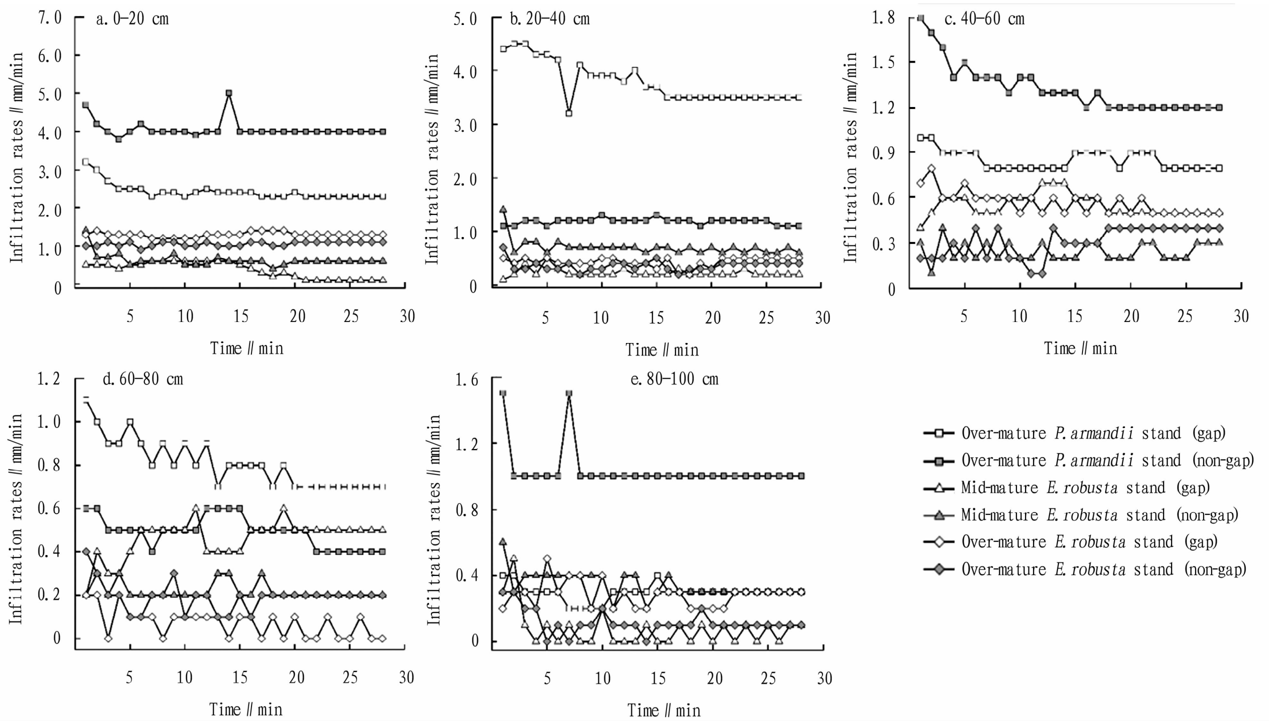

Fig. 2 Infiltration rates of soil layers in different forest stands under field moisture conditions

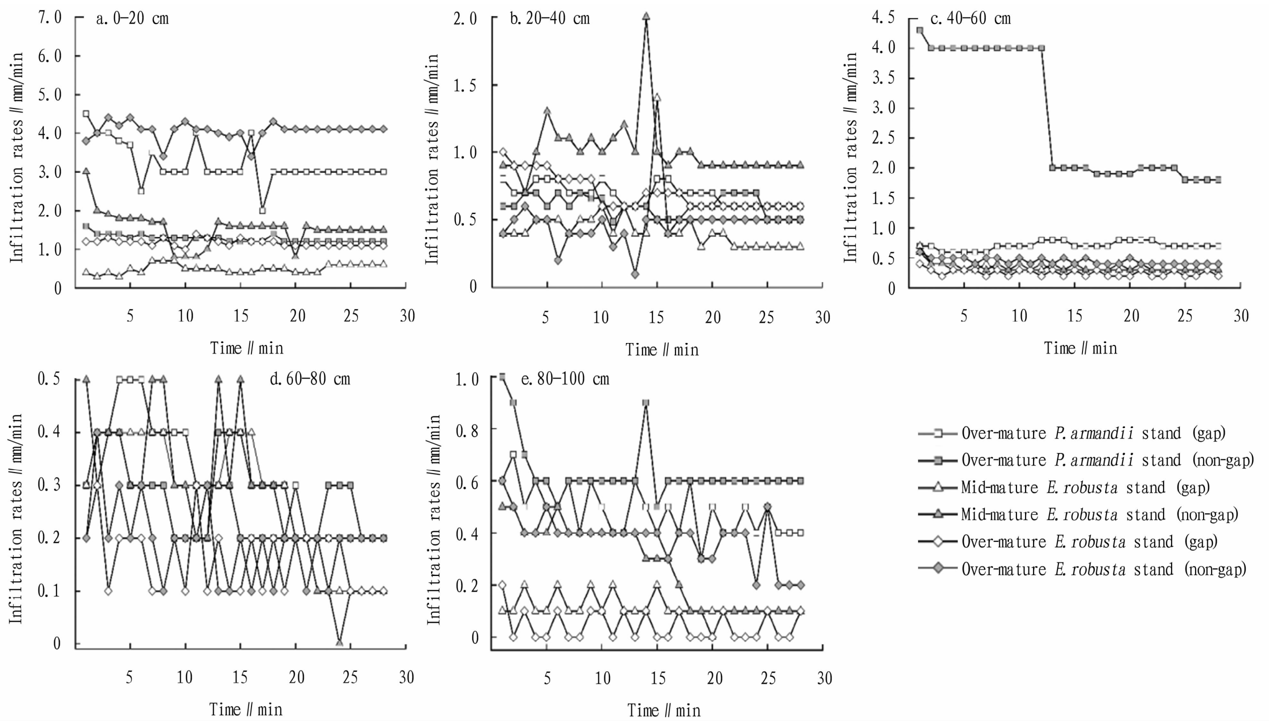

Fig. 3 Infiltration rates of soil layers in different forest stands under saturated moisture content

Evaluation of soil permeability To comprehensively assess the soil permeability under different plantations, principal component analysis was conducted on total infiltration, average infiltration, initial infiltration rate, and steady infiltration rate. Principal components with eigenvalues greater than 1 were extracted to show the contribution of each parameter to soil permeability. The results of principal component analysis are shown in Table 3. Under all three moisture conditions, one principal component with an eigenvalue greater than 1 was extracted, and the contribution rate was above 90%, which could explain the total variance. The loading values of the four principal component factors showed minor differences, with the average infiltration rate consistently demonstrating the highest loading, indicating that the average infiltration rate was the key factor for evaluating soil permeability.

Table 3 Principal component analysis of soil permeability

Parameter	Principal component		
	Natural moisture content	Field moisture content	Saturated moisture content
Total infiltration	0.995	0.996	0.986
Average infiltration	0.998	0.997	0.996
Initial infiltration rate	0.994	0.995	0.984
Steady infiltration rate	0.992	0.994	0.992
Eigenvalue	3.957	3.964	3.916
Contribution rate//%	98.927	99.112	97.890

To thoroughly evaluate soil permeability under different forest stands, soil layers, and moisture conditions, comprehensive scoring was conducted on soil permeability in different stands and soil layers. Under natural moisture content conditions (Table 4), the soil permeability of all forest stands decreased with increasing soil depth, and non-gap conditions consistently exhibited stronger permeability than gap conditions. Overall, the over-mature *P. armandii* forest demonstrated the best permeability, followed by the mid-mature *E. robusta* forest, while the over-mature *E. robusta* forest showed the lowest permeability. From the perspective of soil permeability under field moisture conditions (Table 5), the average scores indicated that the over-mature *P. armandii* forest exhibited higher soil permeability in both gap and non-gap conditions. The results from saturated moisture conditions (Table 6) further confirmed the strong permeability of the over-mature *P. armandii* forest, particularly in non-gap conditions and especially in the 0-20 cm soil layer.

Table 4 Evaluation of soil permeability in different forest stands and soil layers under natural moisture content conditions

		Over-mature *P. armandii*		Mid-mature *E. robusta*		Over-mature *E. robusta*	
		Gap	Non-gap	Gap	Non-gap	Gap	Non-gap
0-20 cm	Score	0.50	1.66	-1.04	0.16	-0.61	-0.66
	Ranking	2	1	6	3	4	5
20-40 cm	Score	0.96	1.30	-1.23	-0.13	-0.51	-0.40
	Ranking	2	1	6	3	5	4
40-60 cm	Score	1.49	0.83	0.05	-0.86	-0.85	-0.66
	Ranking	1	2	3	6	5	4
60-80 cm	Score	-0.11	-0.47	1.63	0.50	-0.77	-0.78
	Ranking	3	4	1	2	5	6
80-100 cm	Score	-0.54	-0.79	0.58	1.69	-0.70	-0.23
	Ranking	4	6	2	1	5	3
Average score		0.46	0.506	0.002	0.272	-0.688	-0.546
Ranking		2	1	4	3	6	5

Table 5 Evaluation of soil permeability in different forest stands and soil layers under field moisture content conditions

		Over-mature *P. armandii*		Mid-mature *E. robusta*		Over-mature *E. robusta*	
		Gap	Non-gap	Gap	Non-gap	Gap	Non-gap
0-20 cm	Score	0.58	1.56	-1.28	-0.62	0.13	-0.37
	Ranking	2	1	6	5	3	4
20-40 cm	Score	1.98	-0.01	-0.57	-0.38	-0.58	-0.44
	Ranking	1	2	5	3	6	4
40-60 cm	Score	0.09	1.97	-0.44	-0.56	-0.59	-0.47
	Ranking	2	1	3	5	6	4
60-80 cm	Score	1.30	0.02	0.63	-0.42	-0.19	-1.34
	Ranking	1	3	2	5	4	6
80-100 cm	Score	-0.09	1.99	-0.56	-0.32	-0.60	-0.41
	Ranking	2	1	5	3	6	4
Average score		0.772	1.106	-0.444	-0.46	-0.366	-0.606
Ranking		2	1	4	5	3	6

Relationship between soil permeability and other properties

Under natural moisture conditions, in the over-mature *P. armandii* forest, the average infiltration rate at gap positions showed a highly significant negative correlation with pH ($P<0.01$), while exhibiting significant positive correlations with organic carbon and water repellency ($P<0.05$). At non-gap positions, the average infiltration rate was significantly positively correlated with organic carbon and porosity ($P<0.05$), and in an extremely significant positive correlation with water repellency ($P<0.01$). For the mid-mature *E. robusta* forest under gap conditions, no significant correlations were observed between the average infiltration rate and any factors. However, under non-gap conditions, it was in an extremely significant positive correlation with organic carbon ($P<0.01$) and an extremely significant negative correlation with bulk density ($P<0.01$). In the over-mature *E. robusta* forest, the average infiltration rate exhibited a significant positive correlation with water repellency under gap conditions ($P<0.05$). Under non-gap conditions, it showed a significant negative correlation with bulk density ($P<0.05$) and a significant positive correlation with porosity ($P<0.05$) (Table 7).

Table 6 Evaluation of soil permeability in different forest stands and soil layers under saturated moisture content

		Over-mature *P. armandii*		Mid-mature *E. robusta*		Over-mature *E. robusta*	
		Gap	Non-gap	Gap	Non-gap	Gap	Non-gap
0 – 20 cm	Score	0.24	0.77	–1.20	–0.30	–0.87	1.36
	Ranking	3	2	6	4	5	1
20 – 40 cm	Score	1.55	–0.59	–0.98	0.36	0.25	–0.58
	Ranking	1	5	6	2	3	4
40 – 60 cm	Score	–0.03	1.97	–0.41	–0.47	–0.74	–0.31
	Ranking	2	1	4	5	6	3
60 – 80 cm	Score	1.58	0.42	–0.57	–0.03	–0.87	–0.54
	Ranking	1	2	5	3	6	4
80 – 100 cm	Score	0.60	1.73	–0.72	–0.47	–0.70	–0.44
	Ranking	2	1	6	4	5	3
Average score		0.788	0.86	–0.776	–0.182	–0.586	–0.102
Ranking		2	1	6	4	5	3

Table 7 Correlation analysis between average soil infiltration rate and soil properties under different moisture contents

	Over-mature *P. armandii*		Mid-mature *E. robusta*		Over-mature *E. robusta*	
	gap	Non-gap	gap	Non-gap	gap	Non-gap
Natural moisture content			Average infiltration rate			
pH	–0.976**	–0.311	–0.163	–0.789	–0.804	–0.825
Organic carbon	0.932*	0.913*	–0.457	0.964**	0.834	0.820
Bulk density	–0.501	–0.649	0.255	–0.970**	–0.820	–0.949*
Porosity	0.549	0.941*	–0.310	0.805	0.493	0.947*
Natural moisture content	0.717	0.126	0.356	–0.877	–0.483	–0.057
Natural water repellency	0.924*	0.979**	0.004	0.791	0.905*	0.829
Field moisture content			Average infiltration rate			
pH	–0.928*	–0.087	0.294	–0.644	–0.638	–0.628
Organic carbon	0.976**	0.389	0.464	0.810	0.947*	0.981**
Bulk density	–0.481	–0.311	0.215	–0.967**	–0.943	–0.971**
Porosity	0.439	0.589	0.022	0.697	0.874	0.964**
Field water-holding capacity	–0.532	–0.704	0.118	–0.813	–0.731	–0.850
Field water repellency	0.729	0.718	0.043	0.673	0.879*	0.969**
Saturated moisture content			Average infiltration rate			
pH	–0.952*	–0.173	–0.738	–0.939*	–0.715	–0.478
Organic carbon	0.925*	0.377	0.741	0.987**	0.837	0.975**
Bulk density	–0.586	–0.438	–0.553	–0.890*	–0.820	–0.863
Porosity	0.556	0.619	0.962**	0.928*	0.533	0.877
Saturated water-holding capacity	0.930*	0.610	–0.887*	0.924*	–0.990**	0.776
Saturated water repellency	0.940*	–0.413	0.945*	0.994*	0.918*	0.980**

* and ** indicate $P < 0.05$ and $P < 0.01$, respectively.

Under field moisture conditions, no significant correlations were observed between average soil infiltration rate and any factors for the over-mature *P. armandii* forests at non-gap positions and the mid-mature *E. robusta* forest at gap positions. Additionally, in the over-mature *P. armandii* forest at gap positions, the average infiltration rate showed an extremely significant positive correlation with organic carbon ($P < 0.05$) and a significant negative correlation with pH ($P < 0.05$). In the mid-mature *E. robusta* forest at non-gap positions, the average soil infiltration rate showed an extremely significant negative correlation with bulk density ($P < 0.01$). However, in the over-mature *E. robusta* forest under gap conditions, it exhibited a significant positive correlation with organic carbon and water repellency ($P < 0.05$) and a significant negative correlation with bulk density ($P < 0.05$). Under non-gap conditions, its infiltration rate demonstrated extremely significant positive correlations with organic carbon, porosity, and water repellency ($P < 0.01$) and an extremely significant negative correlation with bulk density ($P < 0.01$).

Under saturated moisture conditions, the relationships between average soil infiltration rate and soil physical and chemical factors were also analyzed. In the over-mature *P. armandii* forest, the infiltration rate showed a significant negative correlation with pH ($P < 0.05$) and a significant positive correlation with organic carbon, water holding capacity, and water repellency ($P < 0.05$) under gap conditions, while no significant correlations were observed with any factors under non-gap conditions. In the mid-mature *E. robusta* forest under gap conditions, the infiltration rate showed an extremely significant positive correlation with porosity

($P<0.01$), a significant negative correlation with water holding capacity ($P<0.05$), and a significant positive correlation with water repellency ($P<0.05$). Under non-gap conditions, it was in significant negative correlation with pH and bulk density ($P<0.05$), significant positive correlation with porosity and water holding capacity ($P<0.05$), and extremely significant positive correlation with organic carbon and water repellency ($P<0.01$). In over-mature *E. robusta* forest under gap conditions, the infiltration rate showed an extremely significant negative correlation with water holding capacity ($P<0.01$) and a significant positive correlation with water repellency ($P<0.05$). Under non-gap conditions, it demonstrated an extremely significant positive correlation with both organic carbon and water repellency ($P<0.01$).

The analysis revealed that under all three moisture conditions, the average soil infiltration rate was closely correlated with soil organic carbon and water repellency. Both organic carbon content and water repellency positively affected average soil infiltration rate. Higher organic carbon content and stronger water repellency corresponded to faster average infiltration rate. Conversely, pH and soil porosity exhibited negative effects on average soil infiltration rate.

Discussion

Soil infiltration characteristics are influenced by multiple factors, including surface litter, root quantity, organic carbon content, and porosity conditions. Under different forest stands, soil permeability varies significantly. In this study, soil infiltration under various moisture conditions in different forest stands was analyzed, revealing that the *P. armandii* forest exhibited better soil permeability than mid-mature and over-mature *E. robusta* forests, particularly in the 0–20 cm soil layer. These findings demonstrate that soil permeability differs according to different forest stand types, indicating that both land types and vegetation species affect soil permeability, which is consistent with the research conclusions of Liu *et al.* [17]. Moreover, soil permeability under non-gap conditions was generally better than that at gap positions. It might be attributed to the larger pore spaces in gap areas where surface vegetation and herbaceous plants are scarce, particularly in the mid-mature and over-mature *E. robusta* stands, where weeds and other plants hardly grow. Moreover, the soil in gap positions tends to be more compacted and denser with reduced porosity, resulting in poorer permeability[18]. Meanwhile, gap areas exhibit lower litter biomass and consequently reduced root biomass, leading to higher bulk density and tighter soil structure, which further diminishes soil permeability. Furthermore, soil moisture represents another critical factor influencing soil infiltration[19]. As evidenced by the fundamental physical and chemical properties, both mid-mature and over-mature *E. robusta* stands exhibited relatively lower natural moisture content and field moisture content in their surface soils. Such conditions not only restrict root development but also significantly contribute to the reduction of soil permeability.

Soil permeability under different moisture conditions follows distinct patterns with varying soil depths[20], generally showing a weakening trend as depth increases. Such a phenomenon may be attributed to the combined effects of soil moisture content, bulk density, and porosity[11]. With the soil depth increasing, the soil becomes more compacted, exhibiting higher bulk density and reduced porosity. Plant roots rarely penetrate deep soil layers, allowing better water retention in deeper soils. While this leads to increased moisture content in deeper layers, the reduced porosity and higher water content simultaneously reduce water infiltration saturation time and weaken soil permeability[21]. Additionally, the superior soil permeability of surface soil may be related to the concentration of roots in this layer. The presence of roots alters soil structure, particularly porosity[22], resulting in more developed pore spaces and consequently better permeability in surface soils. In this study, soil porosity showed significant or extremely significant positive effects on all evaluated infiltration indexes, consistent with previous research findings[23]. Greater porosity[24] corresponds to stronger soil permeability.

Correlation analysis revealed that soil permeability was also influenced by soil organic carbon content and water repellency intensity[25]. Soil organic carbon and water repellency showed an extremely significant positive correlation with average infiltration rate under all moisture conditions[26] ($P<0.01$). Higher organic carbon content indicates greater presence of hydrophobic organic substances, resulting in stronger soil water repellency and consequently better soil permeability[27]. Furthermore, under different moisture conditions, both positive and negative correlations were observed between water content and soil permeability in gap and non-gap positions. It further demonstrated the complex and diverse nature of soils in different forest stands, exhibiting varying properties under different soil structures. Future research should adopt a more comprehensive analytical approach to better understand the relationship between soil water repellency and soil permeability under different moisture conditions in various forest stand soils.

Conclusions

(1) Under all three moisture conditions, the over-mature *P. armandii* forest demonstrated higher overall infiltration rates than other two forest stands. In all three stands, the soil infiltration rate decreased as the depth of the soil increased. Significant fluctuations in soil infiltration rate were observed during the initial 0–5 min, followed by gradual stabilization or regular fluctuations after 5 min. The infiltration process generally reached saturation after approximately 20 min.

(2) The average infiltration rate was identified as the key factor affecting soil infiltration. Comprehensive evaluation of soil permeability revealed that the over-mature *P. armandii* forest exhibited optimal soil permeability.

(3) Various soil physical and chemical properties significantly affected different indexes of soil permeability under varying conditions, with soil organic carbon content and water repellency demonstrating particularly notable effects on infiltration under different conditions.

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