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RESEARCH ARTICLE

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Relation between Growth and Vertical Distribution of Fine Roots and Soil Density in the Weibei Loess Plateau

Abstract The influence of woodland soil bulk density on the growth and distribution of fine root system of main planting tree species in the Weibei Loess Plateau was investigated by means of pot culture and field survey. Results indicated that in the woodland of *Pinus tabulaeformis*, soil bulk density increased with the depth at different sites, while in the woodland of *Robinia pseudoacacia*, soil bulk density was higher than that in *P. tabulaeformis*, and there was no clear difference across the profile. Further analysis implied that there existed negative correlations between soil bulk density and fine root length in the woodland of *P. tabulaeformis*. Results from pot culture indicated that although the effects of pot culture media on the fine root growth and development of different tree species seedlings were different, all treated seedlings grew better in the soil matter with medium bulk density and porosity and with the biggest biomass. Bulk density of pot culture media had clear effects on the growth and development of *P. tabulaeformis* and *R. pseudoacacia* seedling roots, especially on the former, whereas it had little effect on that of *Platycladus orientalis* and *Prunus armeniaca* var. *ansu*, whose fine root biomass changed little in different pot culture media.

Keywords soil bulk density, Weibei Loess Plateau, main planting tree species, fine roots

1 Introduction

The physical properties of soil are an important factor affecting the growth of forest as well as an index crucial to soil fertility. Different physical properties of soil affect the characteristics of moisture, air, heat, and nutrient as well as the supply of minerals, and consequently affect the growth and development of plants [1]. In the last 20 years, many studies have been conducted on the influence of soil physical properties on the growth of crops, most of which focus on the effective soil moisture content, soil density, and functions of porosity. As one of the most important soil properties, soil bulk density affects not only the size and distribution of pores, soil penetration resistance and changes of soil water, fertility, aeration, and heat directly but also the plant growth, penetrating ability, and activities of root system indirectly [2]. It was once verified that the number of plant root system would be reduced obviously when soil moisture content is less than 60% of the field moisture capacity, and that 40% of the field moisture capacity is a limit index of drought [3]. For the growth of crops, the optimum soil density varies between 1.1 and 1.3 Mg/m^3 [4], and the roots lose their penetrating ability when it is more than 1.8 Mg/m^3. Previous studies proved that a positive relationship existed between capillary porosity and soil density and a negative one between soil aeration porosity and bulk density. In the soil with a low density, a large number of thin and long roots were distributed evenly and vertically, whereas they became much fewer and shorter in the high-density soil [5].

Although much progress was achieved on the influence of soil physical properties on the growth of roots [1], our understanding of the root system and its functions, however, remains inadequate in general since the growth and development of the root system mainly occurred underground, and more studies are needed to further reveal the functions of roots and their mechanisms. In addition, the investigation on the effects of soil density on forest root system, especially on the growth of fine roots, is important to further ecological studies of root system in the Loess Plateau and reveal the mechanisms regarding the soil desiccation in this region.

In this study, the influence of soil bulk density on the growth and distribution of the root system of main planting tree species in the Weibei Loess Plateau was studied by field investigation and pot culture, at an attempt to reveal the relationship between the root system of artificial forests

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Table 1 Condition of sample plots for root system survey of *P. tabulaeformis* and *R. pseudoacacia*

No.	Tree species	Slope aspect	Grade /(°)	Slop position	Stand age /year	Average height /m	DBH /cm
1	*P. tabulaeformis*	E	10	Upper	16	11.17	14.03
2	*P. tabulaeformis*	W	2	Upper	11	6.93	12.06
3	*P. tabulaeformis*	W	3	Middle	10	6.45	11.70
4	*P. tabulaeformis*	E	3	Middle	15	9.53	14.17
5	*R. pseudoacacia*	E	3	Upper	10	9.67	9.27
6	*R. pseudoacacia*	E	2	Upper	10	9.04	9.21
7	*R. pseudoacacia*	W	4	Upper	10	9.83	11.09
8	*R. pseudoacacia*	W	5	Upper	10	10.01	10.80

and the environment and provide scientific bases for eco-environmental restoration in this area.

2 Materials and methods

2.1 Investigation site description

The investigation site, Huaiping forest farm, is located in the gully region of the Loess Plateau in Yongshou County, West China's Shaanxi Province, with a temperate continental monsoon climate. Its elevation varies from 1,100 to 1,492 m, with an annual average temperature of 10.8°C; the annual rainfall is 601.6 mm, mainly concentrating from July to September. The frost-free period lasts for more than 171 days. Local soil in the woodland is limy drab earth developing on the loess medium. In the forest farm, temporary sample plots were selected in the artificial forests at different sites, and root samples and root distribution of *Pinus tabulaeformis* and *Robinia pseudoacacia* were determined by soil drilling. The general situation of sample plots is shown in Table 1.

2.2 Sampling methods

In each sample plot, the 1/4 sampling circle method was used for root sampling [6]. With the sample tree as the center of the circle, three points that have the same arc space on the radiuses of 0.5 and 1.5 m, respectively, were determined as sampling points. At each point, a soil auger (Φ=6.8 cm) was used to drill earth on a soil layer 10 cm deep until there is no root in the soil. At the same time, with the pie slice of each sample tree as sampling area, another point on the middle arc with a radius of 1.0 m was determined for the investigation of soil bulk density in different soil layers (each 10 cm deep) by soil drilling (Φ=9.0 cm) and by the ring sampler (inner radius 4.9 cm, 5.1 cm high) method.

Sampled roots from the soil of each layer were taken back in the plastic bags after numbered and rinsed with water. Their morphological indexes were analyzed by the root scanner of the WINRhizo Image Analysis System. Then, they were classified into four grades according to Φ<0.5 mm, 0.5 mm≤Φ<1 mm, 1 mm≤Φ<3 mm, and Φ≥3 mm, and then, the root length in each soil layer was measured. Roots in each single class from each soil layer were weighed after they were oven-dried at 85°C for more than 8 h. Roots from each tree in different directions were pooled, and the root system distribution eigenvalue (RSDE; m/m^3) in each soil layer was calculated according to Eq. (1).

$$\mathrm{RSDE} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{k} m}{nk} \times \frac{1}{100\pi R^2 h} \tag{1}$$

where R is the soil auger radius (0.034 m), h the soil depth (0.1 m), m is the root length (cm), n is the number of sampling trees, and k is the number of sampling points.

2.3 Pot culture media

A mixture of crude loess, perlite, and sand was used as pot culture media according to the proportion shown in Table 2. Crude loess was sieved through 2×2 mm grids and air-dried; perlite was crushed and sieved through 3×3 mm grids; sand was sieved through 3×3 mm grids after removing impurities.

The seedlings of four main planting tree species, *P. tabulaeformis*, *R. pseudoacacia*, *Platycladus orientalis*,

Table 2 Proportion of pot culture media and the bulk density (Mg/m^3)

No.	Loess	Sand	Perlite	Bulk density	
				Before pot culture	After pot culture
1	2	0	3	0.84	1.15
2	3	0	2	0.99	1.32
3	5	0	0	1.20	1.59
4	2	3	0	1.36	1.63

Table 3 Seedlings for the pot culture experiment

No.	Tree species	Seedling age /year	Seedling type
1	*Robinia pseudoacacia*	1	Seedling
2	*Platycladus orientalis*	2	Container seedling
3	*Prunus armeniaca* var. *ansu*	1	Seedling
4	*Pinus tabulaeformis*	2	Container seedling

Table 4 Soil moisture content of *P. tabulaeformis* and *R. pseudoacacia* plantations

Soil horizon /cm	*P. tabulaeformis*		*R. pseudoacacia*	
	Sunny slope	Shady slope	Sunny slope	Shady slope
0–10	13.64	14.14	16.05	17.22
10–20	11.19	12.16	14.20	17.01
20–30	11.65	12.72	16.33	17.12
30–40	14.21	12.92	16.25	16.90
40–50	12.49	13.59	16.32	16.91
50–60	13.20	12.41	16.51	17.07
60–70	13.20	13.16	16.30	17.44
70–80	13.69	13.48	16.26	17.97
80–90	14.37	14.31	16.11	17.55
90–100		15.33		17.59

and *Prunus armeniaca* var. *ansu*, were chosen for the pot culture experiment. Details of the seedlings are presented in Table 3.

By adjusting the proportion of crude loess, perlite, and sand, 21 different types of pot culture media were selected. The culture medium density and particle density of each type were measured by means of the ring sampler and weighing methods, respectively.

2.3.1 The design of pot culture experiment

According to the experimental result of the 21 culture media, four types of culture were determined for seedling culture (Table 2). Pot culture experiments of *P. tabulaeformis*, *R. pseudoacacia*, *P. orientalis*, and *P. armeniaca* var. *ansu* seedlings were carried out in March 2002. The seedlings of every tree species in the experiment were all arranged for four soil moisture gradients with five repeats, and only one seedling was cultured in each pot. Target soil moisture was maintained at a designed level during the whole experiment.

2.3.2 Determination of the experimental index

Water supply for seedlings was stopped 1 week before the end of the experiment. Upper parts (above the root) of the seedlings were cut for the measurement of aboveground biomass after drying. The densities of soil and particles were measured by the ring sampler method (Table 2). All roots of the seedlings were picked up and rinsed, and 10 g of roots was sampled for the measurement of root system length and surface area. Afterward, the total root biomass of each seedling was determined using the weighing method.

3 Results and analyses

3.1 Vertical distribution of fine roots of *P. tabulaeformis* and *R. pseudoacacia*

Analysis of soil moisture content indicated that soil moisture near the forestland surface (0–100 cm deep) was about 12%, and no water deficiency was observed in soil. Soil moisture on the shady slope was better than that on the sunny slope, which was in accordance with previous researches [7]. Soil moisture contents on *R. pseudoacacia* land at different sites were more than 16% and better than those on *P. tabulaeformis* land (Table 4), which was probably related to physiological and bionomic characteristics of trees, land surface coverage, and land evapotranspiration.

Analysis of root length indicated (Table 5) that on the shady slope, the length of the fine roots (Φ<1 mm) of both *P. tabulaeformis* and *R. pseudoacacia* decreases with the increase in soil depth at the points 0.5 and 1.5 m away from the trunk, and roots at 1.5 m were longer than those at 0.5 m. As for the same soil layer, there was no obvious difference in the root length of the two tree species, which indicated that both tree species would show good growth potential when soil water supply was better on shady slopes (Table 4). On sunny slopes, the root length of the two

Table 5 Vertical distribution of fine root (Φ<1 mm) length of *P. tabulaeformis* and *R. pseudoacacia* at different sites

Soil depth /cm	*P. tabulaeformis*				*R. pseudoacacia*			
	Shady slope		Sunny slope		Shady slope		Sunny slope	
	0.5 m	1.5 m	0.5 m	1.5 m	0.5 m	1.5 m	0.5 m	1.5 m
10	905.57	1,146.52	430.71	497.25	860.46	1,098.65	528.60	174.02
20	625.95	678.29	414.62	437.02	696.08	842.55	662.45	621.47
30	575.09	689.65	324.74	389.82	612.40	662.79	437.69	514.37
40	480.97	466.52	209.38	235.32	492.68	611.48	372.26	488.31
50	418.52	421.16	202.26	122.82	482.11	414.62	505.88	324.62
60	302.24	354.12	118.14	128.33	390.97	398.55	533.54	389.59
70	242.32	207.31	102.39	88.96	472.13	282.73	333.23	245.42
80	140.96	145.67	50.51	19.51	354.81	76.11	310.96	188.48
90	171.84	46.72	4.59	18.83	276.99	41.55	365.03	271.71
100	43.62	14.58	5.62	15.84	94.82	21.70		

Table 6 Vertical distribution of fine root (Φ<1 mm) biomass of *P. tabulaeformis* and *R. pseudoacacia* at different sites

Soil depth /cm	*P. tabulaeformis*				*R. pseudoacacia*			
	Shady slope		Sunny slope		Shady slope		Sunny slope	
	0.5 m	1.5 m	0.5 m	1.5 m	0.5 m	1.5 m	0.5 m	1.5 m
10	0.21	0.43	0.12	0.09	0.18	0.96	0.07	0.02
20	0.15	0.26	0.11	0.08	0.10	0.12	0.06	0.08
30	0.13	0.20	0.10	0.08	0.07	0.08	0.04	0.05
40	0.12	0.18	0.05	0.06	0.07	0.08	0.04	0.05
50	0.11	0.11	0.05	0.04	0.06	0.05	0.07	0.03
60	0.07	0.10	0.02	0.03	0.04	0.06	0.06	0.05
70	0.06	0.06	0.02	0.02	0.06	0.04	0.42	0.02
80	0.04	0.05	0.01	0.01	0.04	0.01	0.04	0.02
90	0.05	0.02	0.00	0.00	0.04	0.01	0.05	0.04
100	0.01	0.01	0.00	0.01	0.02	0.01	0.00	0.00

species was smaller than that on shady slopes at the same depth of the same point, and the roots of *R. pseudoacacia* were longer than those of *P. tabulaeformis*. This trend indicated that the distributing space and the effective absorption space of *R. pseudoacacia* roots were larger than those of *P. tabulaeformis* roots, and consequently, it has stronger adaptability to arid and semiarid areas.

In addition, according to the investigation of the root biomass of the two species (Table 6), it was clear that the fine root biomass of both *P. tabulaeformis* and *R. pseudoacacia* decreased with the increase in soil depth at both points 0.5 and 1.5 m away from the trunk on the shady slope. However, in the same depth of soil layer, the fine root biomass of *P. tabulaeformis* is higher than that of *R. pseudoacacia*. Considering the root length distribution, it can be concluded that the root diameter grade of *P. tabulaeformis* was bigger, which might be related to the extent of root lignification and site conditions. On the sunny slope, the fine root biomass of the two trees is less than that on the shady slope. Among them, the fine root biomass of *P. tabulaeformis* was mainly concentrated in the 0- to 50-cm depth, but that of *R. pseudoacacia* was distributed more evenly, and even in the deeper soil layer (more than 90 cm), there were more roots in the soil. According to previous researches, this result might have a close relationship not only with the difference of soil moisture conditions caused by the slope direction, but also with the difference of drought resistance of root system of the two species [8].

Table 7 Soil bulk density on *P. tabulaeformis* and *R. pseudoacacia* plantations

Soil horizons /cm	*P. tabulaeformis*						*R. pseudoacacia*					
	Shady slope			Sunny slope			Shady slope			Sunny slope		
	Bulk density	Standard error	Number of samples	Bulk density	Standard error	Number of samples	Bulk density	Standard error	Number of samples	Bulk density	Standard error	Number of samples
0–10	1.159	0.068	8	1.126	0.088	8	1.258	0.068	8	1.295	0.117	8
10–20	1.166	0.034	8	1.138	0.047	8	1.272	0.034	8	1.254	0.057	8
20–30	1.190	0.047	8	1.174	0.055	8	1.259	0.047	8	1.244	0.044	8
30–40	1.189	0.104	8	1.198	0.078	8	1.234	0.104	8	1.238	0.073	8
40–50	1.228	0.049	8	1.198	0.066	8	1.236	0.049	8	1.251	0.050	8
50–60	1.221	0.079	8	1.232	0.066	8	1.277	0.079	8	1.241	0.053	8
60–70	1.213	0.065	7	1.216	0.104	8	1.280	0.065	8	1.259	0.049	8
70–80	1.254	0.070	6	1.272	0.101	5	1.293	0.070	7	1.245	0.046	7
80–90	1.244	0.076	4	1.227	0.098	5	1.334	0.076	5	1.249	0.051	7
90–100				1.326	0.065	3				1.252	0.040	4

Table 8 The relationship between fine root distribution (m/m^3) of *P. tabulaeformis* and bulk density of wood soil

Root diameter /mm	Shady slope		Sunny slope	
	Equation	Correlation coefficient *r*	Equation	Correlation coefficient *r*
0–0.5	y=−2,187x+2,006.3	−0.83	y=−22,093x+27,301	−0.58
0.5–1.0	y=−2,871.9x+3,707.5	−0.83	y=−747.41x+942.47	−0.91
1.0–3.0	y=−5,515x+6,993.9	−0.74	y=−4,157.4x+5,263	−0.75
>3.0	y=−601.15x+882.9	−0.84	y=−302.24x+387.39	−0.60

y is the vertical RSDE (m/m^3), and *x* is the soil density (Mg/m^3; same in Table 9).

Table 9 The relationship between fine root distribution (m/m^3) of *R. pseudoacacia* and soil bulk density

Root diameter /mm	Shady slope		Sunny slope	
	Equation	Correlation coefficient r	Equation	Correlation coefficient r
0–0.5	y=5,724.2x−7,638.2	0.47	y=225.05x+139.23	0.52
0.5–1.0	y=4,723.8x−6,354.8	0.71	y=24.426x+146.42	0.08
1.0–3.0	y=2,792.5x−3,724.2	0.51	y=−32.749x+129.8	−0.10
>3.0	y=60.629x−53.63	0.04	y=60.484x+22.131	0.51

3.2 Effects of *P. tabulaeformis* and *R. pseudoacacia* on forestland soil density

It was clear from Table 7 that the soil density distribution across the vertical profile on *P. tabulaeformis* and *R. pseudoacacia* forestland has different variation patterns. On *P. tabulaeformis* land, soil bulk density increased with the increase in soil depth, while on *R. pseudoacacia* land, soil bulk density maintained a higher level across the profile. Compared with the density on *R. pseudoacacia* land, soil bulk density on *P. tabulaeformis* land was a little smaller, especially in the root-concentrated layer. Further analysis indicated that the root system of *P. tabulaeformis* improved the physical properties of surface soil, especially on the shady slope, which also increased the soil drought resistance and soil moisture holding capacity. Further researches are needed to reveal such relationship between the improved function and root system and its function mechanism.

3.3 Relationship between fine root distribution and soil density of *P. tabulaeformis* and *R. pseudoacacia*

The relationship between soil density and the root system of *P. tabulaeformis* was analyzed primarily. Results indicated that in the *P. tabulaeformis* forest, an obvious negative relationship existed between the soil density at different sites and the length of the fine roots with different diameter grades (Table 8), which demonstrated that the higher the soil density was, the less root system of *P. tabulaeformis* there was. However, on *R. pseudoacacia* forestland, no such marked relationship was observed (Table 9), which implied that soil density had no obvious restriction to the root system of *R. pseudoacacia*.

3.4 Effects of the density of pot culture media on the growth of root system

The pot culture experiment indicated that the effects of the density of pot culture media on the root system of seedlings were different. All seedling root systems grow best in the no. 2 medium in which the medium density was 1.32 Mg/m^3 (Fig. 1), and the root length and surface area of all seedlings had a maximum value. The density of the culture media has different influences on different seedlings. A culture medium that is too loose or too tough did not benefit the growth and development of the root system of *P. tabulaeformis* and *R. pseudoacacia*. The influence of culture media properties on the root growth of

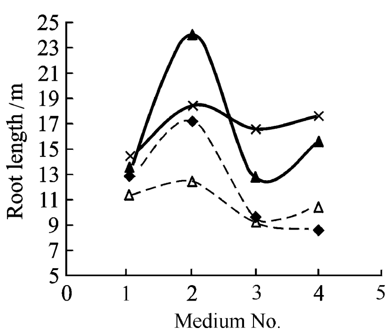

Fig. 1 Influence of culture medium density on root development of four tree species. —▲—, *P. tabulaeformis*; ---△---, *P. orientalis*; —×—, *P. armeniaca* var. *ansu*; ---◆---, *R. pseudoacacia*

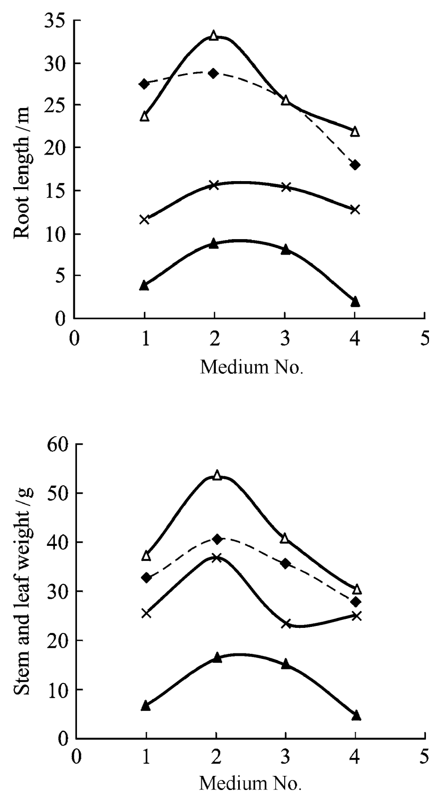

Fig. 2 Influence of medium density of pot culture on root biomass and aboveground biomass of four tree species (The symbols are the same as defined for Fig. 1)

P. tabulaeformis seedlings was more marked, and it was also in accordance with the results mentioned in Section 2.3; the influence of the culture medium on the root system of *P. orientalis* and *R. pseudoacacia* is smaller, and the root system length of these two species seedlings had no obvious variation in different densities of media.

It can be observed from Fig. 2 that an obvious difference existed in the fine root biomass and the aboveground biomass of seedlings in different culture media. The media with a high density (1.63 Mg/m^3) and a low porosity and the media with a low density (1.15 Mg/m^3) and a high porosity both had negative effects on the growth of the root system and aboveground parts; proper soil density (1.32 Mg/m^3) and porosity will promote the growth of both underground and aboveground parts.

4 Conclusions

Through investigation on the distribution characteristics of fine roots and the analysis of the relationship between the fine root growth and soil density, the following conclusions can be reached.

Site conditions had obvious effects on the vertical distribution of *P. tabulaeformis* and *R. pseudoacacia* roots. Since the soil moisture on the shady slope was enough, there was no clear difference in the vertical distribution of fine roots of *P. tabulaeformis* and *R. pseudoacacia*. On the southern slope, however, the distribution patterns of fine roots were different due to the difference in soil moisture. The fine root length of *P. tabulaeformis* decreased with the increase in soil depth, and most of its fine root biomass was concentrated in the soil near the surface (0–50 cm deep), while the fine root length of *R. pseudoacacia* had a slight decrease with the increase in soil depth, and a majority of fine roots appeared in deeper soil.

At the different sites, soil bulk density in *P. tabulaeformis* forestland increased with soil depth, whereas soil bulk density in *R. pseudoacacia* land remained higher across the soil profile. On the soil profile from 0 to 100 cm, soil bulk density on each soil layer in *R. pseudoacacia* land is higher than that on *P. tabulaeformis* land, especially in soil above 50 cm.

The influences of soil bulk density on the root distribution of the two tree species were different. On *P. tabulaeformis* land, a clear negative relationship exists between soil density and length eigenvalue in different root diameter grades, but in the forestland of *R. pseudoacacia*, the relationship between soil density and root system distribution of *R. pseudoacacia* was not marked, which implied that the influence of soil density was relatively smaller compared with *R. pseudoacacia*.

The density of the pot culture medium also had different effects on the growth and development of the seedling root system. The culture medium density had an obvious effect on the root growth and development of both *P. tabulaeformis* and *R. pseudoacacia*, and its influence on the former is greater. However, the culture medium density almost had no marked influence on the root growth and development of *Platycladus orientalis* and *Pinus tabulaeformis*.

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