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Fine root vertical-seasonal distribution of *Robinia pseudoacacia* in relation to abiotic factors in a chronosequence in coastal saline alkali land of the Yellow River Delta, China

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Abstract: Despite the recognized importance of the fine roots in influencing tree growth and stand productivity, knowledge of fine roots is still limited, especially in adverse sites like saline-alkali land. In this paper, we applied sequential soil coring to assess the influence of stand age, soil depth and growth month on fine roots in 3, 16, 30 and 40-year old *Robinia pseudoacacia* stand in coastal saline-alkali land of the Yellow River Delta, China. Besides, the correlations between fine roots characteristics fine root biomass (FRB), fine root length (FRL), fine root surface area (FRSA), specific root length (SRL) and specific root surface area (SRA)) and abiotic factors (temperature, precipitation, soil water content (SWC), soil salt content (SSC) and soil nutrients) were discussed. In this paper, FRB, FRL, FRSA, SWC and soil nutrients increased, while SRL and SSC decreased with increasing stand age. Vertically, fine roots were concentrated in a 0–20 cm soil layer. SRL, SWC and SSC increased, while soil nutrients decreased with increasing soil depth. Temporally, FRB, FRL, FRSA, soil hydrolytic nitrogen and available potassium (AK) shared similar patterns and reached maximum in May or September. In July, SWC, SRL and SRA reached maximum while SSC reached the minimum. Soil total nitrogen (TN) and organic matter (OM) were highest in May or November. Correlation analysis showed that FRB, FRL and FRSA were negatively correlated with SWC and SSC, positively correlated with HN and AK. SRL was positively correlated with temperature, precipitation, SWC and SSC, while negatively correlated with TN. Among abiotic factors, temperature, precipitation and HN played key roles in the study area. This study improves our understanding of the fine roots and belowground ecology of *R. pseudoacacia* stands in coastal saline-alkali land of the Yellow River Delta.

Key words: *Robinia pseudoacacia*, Yellow River Delta, stand age, fine roots, abiotic factors

1. Introduction

Although the rapid increase in the area of plantation seriously affects wood supply, environmental improvement, landscape restoration and climate change mitigation, the decline in stand productivity of existing plantations has caused widespread concern (O'Hehir et al., 2010; Kahanju Chitiki et al., 2020; Usman et al., 2020). At present, relevant researches about stand productivity mainly focus on the aboveground part of trees, such as variations of photosynthetic, nutrition, aboveground biomass allocation and stand structure with stand age (Molchanov, 2000; Cucand Hien, 2020). With high net primary productivity, fast turnover and as the primary pathways for water and nutrient absorption, fine roots are supposed to be closely related to the forest ecosystem productivity (Zeidali et al., 2021a, b).

Two groups of traits are widely used to describe their ability in soil resource acquisition. The first group is related to resource exploitation capacity about the quantity (i.e. fine root biomass, length, and surface area) of the fine root, and the second group reflects resource exploitation efficiency in terms of fine root morphological traits including specific root length (SRL) and specific root surface area (SRA) (Xiang et al., 2015; Beheshti Ale Agha et al., 2018). SRL and SRA are important indicators reflecting physiological functions, and closely related to the plasticity of roots and root proliferation. Roots with greater length and surface development per biomass (high SRL and SRA) can explore larger soil volumes more efficiently and typically have higher resource uptake rates per unit root mass-produced than roots with lower SRL and/or SRA. By adjusting biomass allocation to roots and morphology of roots, trees adopt an optimal foraging strategy to cope with the heterogeneous environment (Azadbakht et al., 2020; Zhu et al., 2021).

Fine roots are affected by abiotic stresses such as drought and salinity, and this has been concluded in

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various reports (Sánchez-Blanco et al., 2014; Imada et al., 2015). Several studies have explored the effects of stand age on fine root characteristics. In the process of stand development, stand structure, species composition and soil properties change along with stand age, all of which could have significant effects on fine root biomass (Finér et al., 2011). Under the influence of site characteristics and species assemblages, fine root biomass would remain relatively static or decreased beyond the period of maximum (Yuan and Chen, 2010). However, it was also found that rather than stand age, the development stage of stand impacts the dynamics of fine roots. In addition, numerous investigations have observed that morphological characteristics of fine roots varied with stand age. In many cases, younger trees have greater SRL than older trees in the forest chronosequence (Jagodziński et al., 2011), which may be determined by both biological characteristics of tree species (Yuan and Chen, 2010; Yuan and Chen, 2012) and site conditions (Yuan and Chen, 2011).

Soil depth and seasonal variation also have important effects on fine roots, which is driven by the variations of soil properties along with different soil depths and seasons. In most ecosystems, fine root biomass decreases with increasing soil depth. In addition to quantitative characteristics, morphological characteristics of fine roots also exhibit obvious and various vertical patterns in different forests. For example, SRL or SRA could be increased (Wu et al., 2019), decreased (Zheng and Shangguan, 2007), or remain constant with increasing soil depth. Temporally, both quantitative and morphological characteristics varied with seasons. The investigations on the temporal variation of fine root biomass are essential for the evaluation of fine root production (Karibu et al., 2013).

Drought and salinity are some of the problems and crises of plants (Chaghakaboodi et al., 2021; Sepahvand et al., 2020). The Yellow River Delta, with a large area of coastal saline-alkali land, high soil salinity, seasonal drought and flood in this region critically restrict the survival and growth of plants. A large area of *Robinia pseudoacacia* plantation planted in the coastal saline-alkali land of the Yellow River Delta in the 1970s–1980s has contributed greatly to NPP and produced extremely significant ecological benefits. However, large-scale forest dieback has resulted in the degradation of tree productivity and ecological benefits. Previous studies on the productivity of *R. pseudoacacia* plantations in coastal saline-alkali land mainly focused on the aboveground part (Xia et al., 2019). Despite the key roles of fine roots play in tree growth and predicting stand productivity, little work has been conducted in fine roots of *R. pseudoacacia* in coastal saline-alkali land of Yellow River Delta.

R. pseudoacacia roots are broad and medium fibrous and have nitrogen-fixing nodes. To propagate the ornamental *R. pseudoacacia* by sowing seeds or separating and planting the roots of pimples in autumn or root cuttings in winter (Némethy et al., 2020).

In this paper, based on 3, 16, 30 and 40-year-old *R. pseudoacacia* stands and employing sequential soil cores method, we investigate the vertical-seasonal distribution of FRB (fine root biomass), FRL (fine root length), FRSA (fine root surface area), SRL (specific root length) and SRA (specific root surface area) along a chronosequence of *R. pseudoacacia* stands, and how these root variables changed in relation to abiotic factors, including climatic factors (temperature, precipitation) and soil properties (soil water content (SWC), soil salt content (SSC) and soil nutrients) in saline-alkali land of the Yellow River Delta. This study cannot only (1) improve our understanding of fine roots and belowground ecology, but also (2) provide basic data for stand productivity estimation of *R.pseudoacacia* stands in coastal saline-alkali land of the Yellow River Delta (Wang et al., 2017). Then finding the Fine root vertical-seasonal distribution of *Robinia pseudoacacia* in relation to abiotic factors in a chronosequence in coastal saline-alkali land of the yellow river delta, china was the aim of this research.

2. Materials and methods

2.1. Study area and experiment design

The Yellow River Delta is located in the estuary of the Yellow River on the coast of the Bohai Sea. Much of the land in this area shows different degrees of salinization due to the special sedimentary environment, climatic conditions and soil parent materials. In this area, the annual average temperature is 12.3 °C; the extreme maximum temperature is 41.9 °C; the extreme minimum temperature is –23.3 °C; the accumulated temperature above 0 °C is 4783.5 °C; the accumulated temperature above 10 °C is 4183 °C, and the average frost-free period is 210 days. The annual average precipitation is 555.9 mm, most of which occurs in summer. The annual evaporation is 1962.1mm, which is 3.6 times of the precipitation. The evaporation is strong in spring, accounting for 51.7% of the whole year.

The experimental site is located in Dongying City, Shandong Province, which belongs to the Yellow River Delta region. 3-year-old *R. pseudoacacia* stand is located in Swan Lake Scenic Area (118°05'E, 38°15'N), and 16-year-old, 30-year-old, 40-year-old stands are all located in Gudao town (118°39'-119°08'E, 37°47'-37°84'N). The 3a, 16a, 30a, 40a *R. pseudoacacia* stands were planted by using 1-year-old seedlings in the spring of 2015, 2002, 1988 and 1978, respectively.

Our research employs the chronosequence approach and sequential soil cores, to study the effects of stand age on fine root biomass (FRB), fine root length (FRL), fine root surface area (FRSA), specific root length (SRL), specific root surface area (SRA), soil water content (SWC), soil salt content (SSC), soil total nitrogen (TN), soil hydrolytic nitrogen (HN), soil available potassium (AK) and soil organic matter (OM), and how fine root characteristics correlate with soil properties in 3, 16, 30, 40-year-old *R. pseudoacacia* stands. The stand characteristics investigated in 2018 are presented in Table 1. Three replicate plots (10m × 10m) for each stand age were set up, with a total of 12 sampling plots.

2.2. The sampling and processing of fine roots and soil samples

2.2.1. Sequential soil coring technique

In the sequential soil coring technique, samples in each plot were randomly taken from 5 points every two months between March and November of 2018, and there were 5 sampling times in total. The soil cores were collected using a 9.5-cm inside diameter steel soil corer driven by a motorized drill from the forest floor surface down to 40 cm depth. The soil cores were divided into four soil depths: 0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm. Samples were transferred into plastic bags, transported and stored at 4 °C until later processing. Roots and soil of cores were separated immediately after being brought back.

2.2.2 Measurement of soil parameters

Soil samples, collected by sequential soil coring method from four layers (0–10 cm, 10–20 cm, and 20–30 cm, 30–40 cm) in each soil profile, were used for the measurement of soil indexes. These samples were taken to the laboratory and air-dried before determining SSC (the mass method with a water/soil ratio of 5:1), SWC (the drying method (105 °C, 8 h)), TN (Kjeldahl method), HN (alkaline hydrolysis diffusion method), AK (flame photometry method), OM (potassium dichromate-external heating method).

2.2.3. Measurement of fine roots

The root with a diameter less than 2 mm is usually defined as a fine root. Fine roots samples (240 each time, 1200 in total) collected by sequential soil coring method from four layers (0–10, 10–20, 20–30 and 30–40 cm) in each soil profile, were washed free of adhering soil and organic matter for later scanning and weighing. Fine root characteristics, including length and surface area, were assessed using the digital image analysis system Win-Rhizo 2007D (Regent Instzo Company, Quebec City, Canada). Before scanning, fine root samples were placed in a water-filled transparent tray on a scanner to facilitate root spreading. After scanning, all fine root samples were first placed at 105 °C for 30 min for fixation and then oven-dried at 65 °C to constant weight for biomass. Total biomass, length and surface area of fine roots were summed for each soil core. The fine root parameters were calculated with the formula:

$$\text{FRB (g m}^{-2}) = \frac{\text{Toal fine root dry weight (g)}}{\pi \times 4.75^2 \times 10^{-2} (\text{m}^2)}$$

$$\text{FRL (mm}^{-2}) = \frac{\text{Total fine root length (m)}}{\pi \times 4.75^2 \times 10^{-2} (\text{m}^2)}$$

$$\text{FRSA (m}^2\text{m}^{-2}) = \frac{\text{Total fine root surface area (m}^2)}{\pi \times 4.75^2 \times 10^{-2} (\text{m}^2)}$$

$$\text{SRL (mg}^{-1}) = \frac{\text{Fine root length (m)}}{\text{Fine root dry weight (g)}}$$

$$\text{SRA (m}^2\text{ g}^{-1}) = \frac{\text{Fine root surface area (m}^2)}{\text{Fine root dry weight (g)}}$$

2.3. Data analysis

Multiple-factor analysis of variance was used to examine the influence of stand age, soil depth and growth month on fine root quantitative characteristics (FRB, FRL and FRSA), fine root morphological characteristics (SRL and SRA), SWC, SSC and soil nutrients (TN, HN, AK and OM) in the forest chronosequence of *R. pseudoacacia* stands. Bivariate correlation analysis was used to determine the correlation between FRB, FRL, FRSA, SRL and SRA with soil properties. Principal component analysis (PCA) was carried out for all abiotic factors (including temperature, precipitation, SWC, SSC and soil nutrients) to figure out the major environmental factors of *R. pseudoacacia* stands in coastal saline-alkali land. All statistical analysis was performed using SPSS 20.0 software (SPSS Inc., Chicago, USA) with the significance level of $\alpha = 0.05$).

3. Results

3.1. Monthly dynamics of temperature and precipitation of experimental sites

According to Figure 1, the monthly average temperature of Swan Lake Scenic Area and Gudao town increased

Table 1. Characteristics of 3-, 16-, 30-, 40-year-old *R. pseudoacacia* stands.

Stand age	3a	16a	30a	40a
Average DBH (cm)	3.68	11.38	16.34	19.22
Average height (m)	2.54	8.51	12.94	13.85

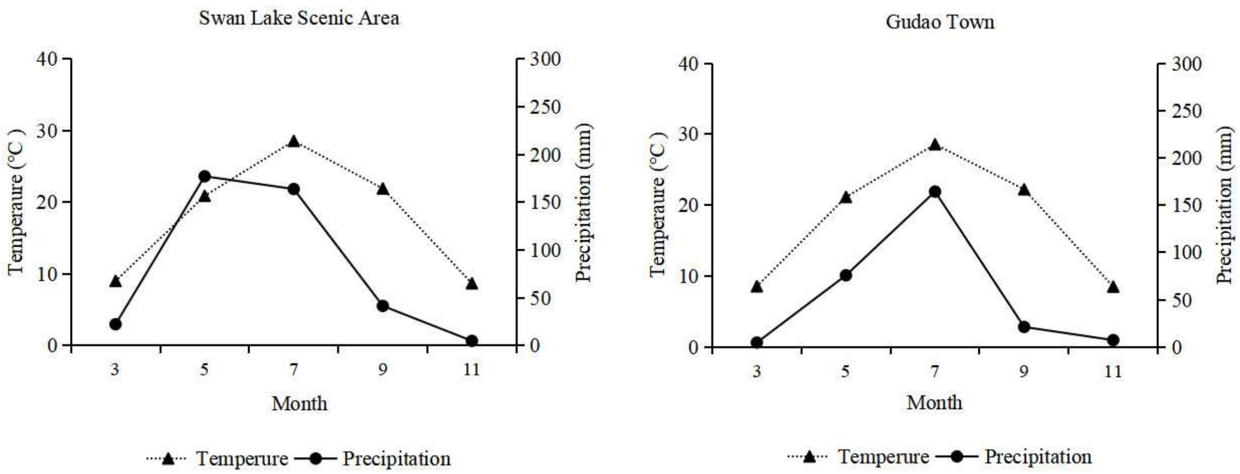

Figure 1. The average temperature and precipitation ingrowth months (March, May, July, September, November 2018) of the experimental sites.

from March until reached maximum July and gradually decreased thereafter. Monthly average precipitation reached the maximum (about 200 mm) in July, while was at a low level in March, September and November, indicating the long period of drought within a year in the study region.

3.2. Fine root quantitative characteristics

FRB, FRL and FRSA of *R. pseudoacacia* were significantly influenced by stand age, soil depth and growth month ($p < 0.01$, Table 2). FRB increased with stand age (Figure 2a), with values of 168.78 ± 101.49 g m $^{-2}$, 186.84 ± 121.05 g m $^{-2}$, 195.64 ± 135.33 g m $^{-2}$, 250.96 ± 172.22 g m $^{-2}$ for 3-, 16-, 30-, 40-year-old stands, respectively. Similar to the age-related pattern of FRB, both FRL and FRSA increased with stand age (Figures 2b and 2c). FRL was 1342.64 ± 762.67 m m^{-2}, 1343.20 ± 825.03 m m^{-2},1455.05 ± 1040.23 m m^{-2}, 1639.21 ± 1025.56 m m^{-2}, FRSA was 3.06 ± 2.41 m^2 m $^{-2}$, 3.14 ± 2.72 m^2 m $^{-2}$, 3.30 ± 2.42 m^2 m^{-2}, 3.42 ± 1.89 m^2 m^{-2} for 3-, 16-, 30-, 40-year-old stands, respectively.

Besides stand age, soil depth and growth month both exhibited significant effects on FRB, FRL and FRSA of *R. pseudoacacia* ($p < 0.01$, Table 2). Among all aged stands in this paper, FRB, FRL and FRSA in the top soil layer (0–20 cm) were significantly larger than those in the deeper layer (20–40 cm) (Figures 2a,–2c). FRB, FRL and FRSA of *R. pseudoacacia* varied seasonally and showed similar temporal patterns for all aged stands, as the FRB, FRL and FRSA were the highest in late spring (May) or autumn (September), lowest in early spring (March), summer (July), or winter (November) (Figures 3a–3c).

3.3. Fine root morphological characteristics

Stand age had significant effects on SRL ($p < 0.01$, Table 2), while had no significant effect on SRA ($P = 0.22$, Table 2). SRL was 8.56 ± 1.78 m g $^{-1}$, 7.83 ± 1.82 m g^{-1}, 8.04 ± 2.28 m g^{-1}, 7.89 ± 2.86 m g $^{-1}$ for 3-, 16-, 30-, 40-year-old stands, respectively (Figures 4a and 4b). Among four aged stands we studied, 3-year-old *R. pseudoacacia* had the largest SRL, while there were no significant differences in SRL between 16-, 30- and 40-year-old stands ($p > 0.05$).

Soil depth and growth month had significant effects on both SRL and SRA ($p < 0.01$, Table 2). In vertical soil profile, SRL and SRA in 0–20 cm soil layer were lower than those in 20–40 cm layer (Figures 4a and 4b). SRL and SRA shared similar seasonal patterns, which were both increased from March until reached maximum in July, then decreased (Figures 5a and 5b).

3.4 .Soil properties

3.4.1. SWC and SSC

Stand age, soil depth and growth month all had significant impacts on soil water content (SWC) ($p < 0.01$, Table 3).

SWC increased with stand age, with values of 16%, 17%, 19%, 19% for 3-, 16-, 30-, 40-year-old stands, respectively (Figure 6a). Vertically, SWC increased with soil depth (Figure 6a). Besides, SWC of younger stands (3a, 16a) and in deeper soil depth (20–40 cm) had larger CV values than those of older stands (30a, 40a) and shallower soil depth (0–20 cm) (Table 4a), indicating that SWC fluctuated more dramatically in younger stands and deeper soil layer. Among growth months, the SWC increased from March until reached maximum in July, then decreased (Figure 7a).

Stand age, soil depth and growth month all had significant effects on soil salt content (SSC) ($p < 0.01$, Table 3). SSC decreased with stand age, with values of 2.2‰, 2.1‰, 1.8‰, 1.7‰ for 3-, 16-, 30-, 40-year-old stands, respectively (Figure 6b). Vertically, SSC increased with increasing soil depth (Figure 6b). Similar to SWC, SSC of younger stands (3a, 16a) and in deeper soil (20–40 cm) fluctuated more dramatically (Table 4b). In contrast

Table 2. ANOVA analyses of the effects of stand age, soil depth and growth month on fine root biomass, fine root length, fine root surface area, specific root length, specific root surface area.

Characteristic	Source	d.f.	p
Fine root biomass	Stand age	3	< 0.01
	Soil depth	3	< 0.01
	Growth month	4	< 0.01
	Stand age × Soil depth	9	< 0.01
	Stand age × Growth month	12	< 0.01
	Soil depth × Growth month	12	< 0.01
	Stand age × Soil depth × Growth month	36	< 0.01
Fine root length	Stand age	3	< 0.01
	Soil depth	3	< 0.01
	Growth month	4	< 0.01
	Stand age × Soil depth	9	< 0.01
	Stand age × Growth month	12	< 0.01
	Soil depth × Growth month	12	< 0.01
	Stand age × Soil depth × Growth month	36	< 0.01
Fine root surface area	Stand age	3	= 0.84
	Soil depth	3	< 0.01
	Growth month	4	< 0.01
	Stand age × Soil depth	9	=0.25
	Stand age × Growth month	12	< 0.01
	Soil depth × Growth month	12	< 0.01
	Stand age × Soil depth × Growth month	36	< 0.01
Specific root length	Stand age	3	< 0.01
	Soil depth	3	< 0.01
	Growth month	4	< 0.01
	Stand age × Soil depth	9	< 0.01
	Stand age × Growth month	12	< 0.01
	Soil depth × Growth month	12	< 0.01
	Stand age × Soil depth × Growth month	36	< 0.01
Specific root surface area	Stand age	3	= 0.22
	Soil depth	3	< 0.01
	Growth month	4	< 0.01
	Stand age × Soil depth	9	< 0.01
	Stand age × Growth month	12	< 0.05
	Soil depth × Growth month	12	< 0.05
	Stand age × Soil depth × Growth month	36	< 0.01

to SWC, SSC decreased from March until reached a minimum in July, then increased gradually (Figure 7b).

3.4.2. Soil nutrient

Stand age had significant effects on TN, HN, AK and OM ($p < 0.01$, Table 4). With the increase of stand age, TN, HN, AK and OM increased. Besides stand age, soil nutrient parameters also varied significantly with soil depth and growth month ($p < 0.01$, Table 4). TN, HN, AK, OM decreased with soil depth (Figures 8a–8d). Although TN, HN, AK and OM all varied significantly.

Among growth months ($p < 0.01$, Table 4), their month-related patterns had some discrepancies. TN and

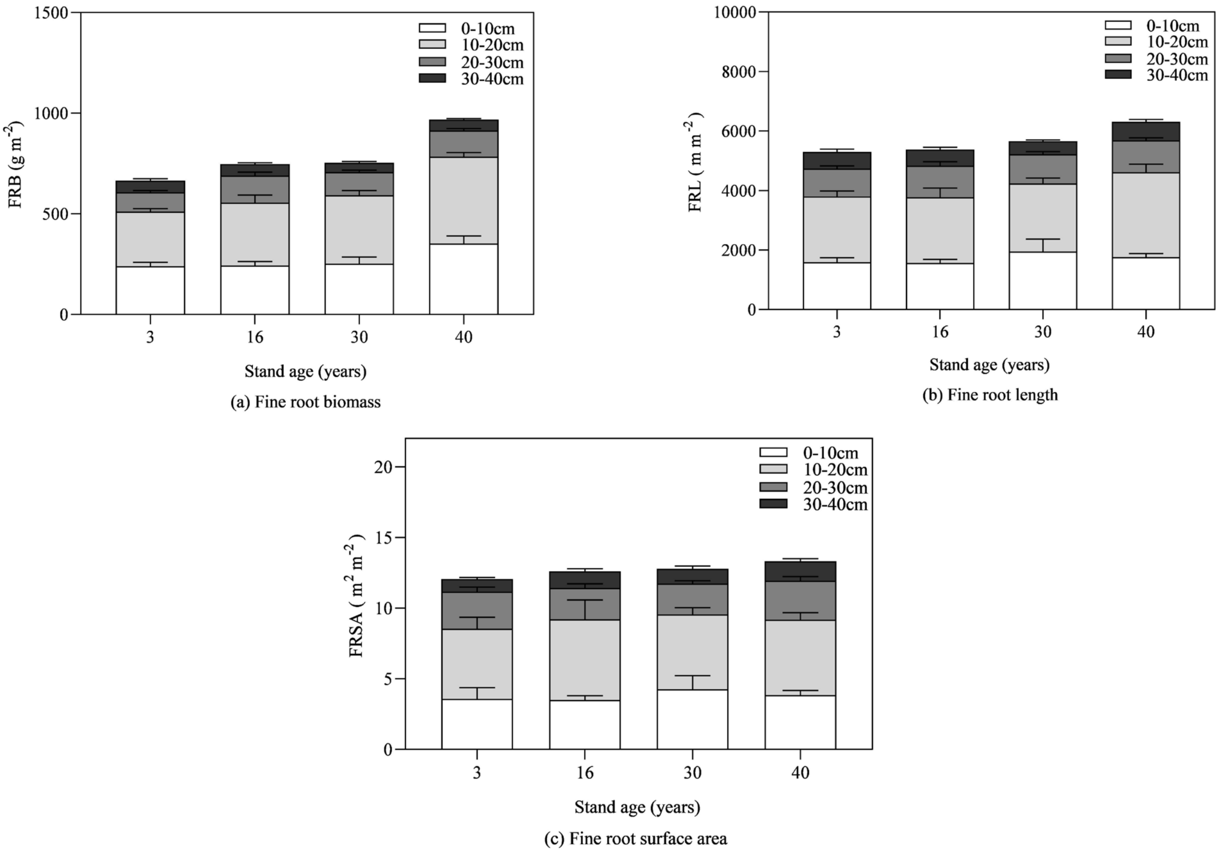

Figure 2. Fine root quantitative characteristics of 3-, 16-, 30- and 40-year-old *R. pseudoacacia* stands. Error bars represent the SE of the mean. FRB: fine root biomass; FRL: fine root length; FRSA: fine root surface area. (a) Fine root biomass. (b) Fine root length. (c) Fine root surface area.

OM increased from March to May, then decreased to a minimum in July, and increased thereafter (Figures 9a and 9d). However, the seasonal patterns of HN and AK were typically bimodal, which reached the maximum in May or September (Figures 9b and 9c).

3.5. Correlation analysis between fine roots and soil properties

According to the results of correlation analysis (Table 5), FRB, FRL and FRSA (fine root quantitative characteristics) had no significant correlation with temperature and precipitation (climatic factors) ($p > 0.05$, Table 5). Besides, FRB, FRL and FRSA were negatively correlated with SWC and SSC ($p < 0.01$, Table 5). Moreover, FRB, FRL and FRSA displayed significantly positive correlations with HN and AK (available nutrient parameters) ($p < 0.01$, Table 5), while had no significant correlation with TN and OM (total nutrient parameters) ($p > 0.05$, Table 5).

Inconsistent with fine root quantitative characteristics, SRL and SRA showed significantly positive correlations with temperature and precipitation (climatic factors) ($p < 0.01$, Table 5). SRL was positively correlated with SWC and SSC, while negatively correlated with TN ($p < 0.01$, Table 5).

Abiotic factors, including climatic factors and soil properties of *R. pseudoacacia* stands, were analyzed by PCA (principal component analysis). According to the results of PCA (Table 6), the first, the second and the third principal components together represented 79.95%. The first principal component (38.60%) included temperature and precipitation (climatic factors) and HN. The second principal component (28.24%) included and AK, TN and OM (soil nutrients). The third principal component (13.11%) included SWC and SSC. The results of PCA showed that climatic factors and HN were key abiotic factors in the coastal saline-alkali land of the Yellow River Delta.

4. Discussion

4.1. Effects of stand age, soil depth and growth month on fine roots

4.1.1. Effects of stand age on fine roots

Wang et al. (2017) had reported that mean values of FRB in China's forests were 278 g m^{-2}. Taking into account the four aged stands we studied, the mean value of FRB, FRL and FRSA was 205 g m^{-2}, 1415.62 mm^{-2} and 3.14 m^2

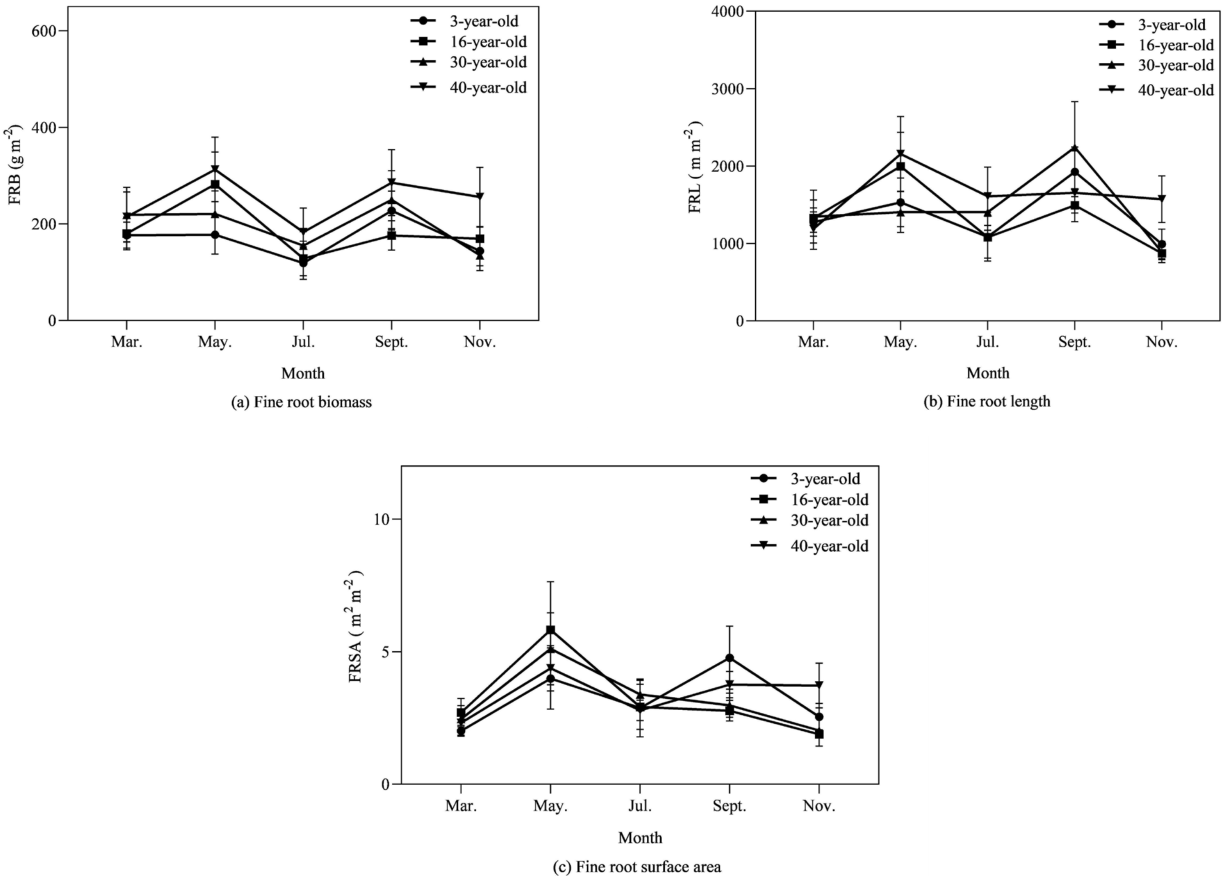

Figure 3. Seasonal variations of fine root quantitative characteristics of 3-, 16-, 30- and 40-year-old *R. pseudoacacia* stands. Error bars represent SE of the mean. FRB: fine root biomass; FRL: fine root length; FRSA: fine root surface area. (a) Fine root biomass. (b) Fine root length. (c) Fine root surface area.

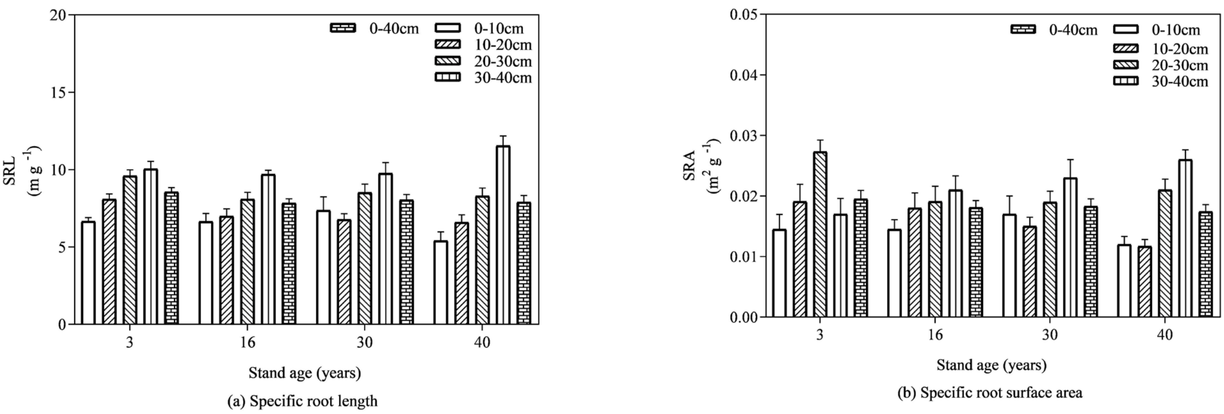

Figure 4. Fine root morphological characteristics of 3-, 16-, 30- and 40-year-old *R. pseudoacacia* stands. Error bars represent the SE of the mean. SRL: specific root length; SRA: specific root surface area. (a) Specific root length. (b) Specific root surface area.

m^{-2}, respectively, which were all much lower than other temperate deciduous forests reported in China and other foreign countries. There are several possible reasons for the considerable differences between the estimates of FRB, FRL and FRSA of *R. pseudoacacia* stands in coastal saline-alkali land versus other forests. First, the harsh climate and soil conditions in coastal saline-alkali land inhibited fine root growth. Second, differences in sampling and calculating methods may also contribute to the discrepancy in estimations for FRB between our study and other forests.

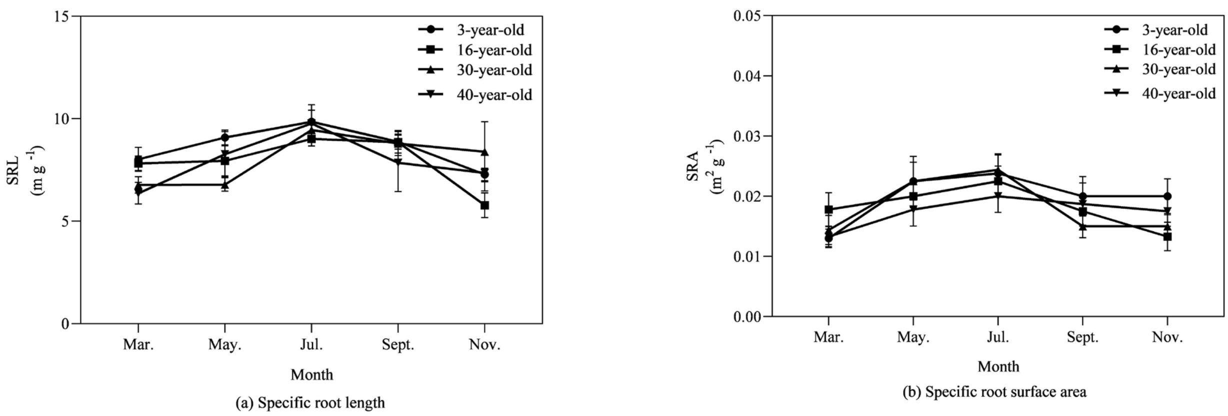

Figure 5. Seasonal variations of fine root morphological characteristics of 3-, 16-, 30- and 40-year-old *R. pseudoacacia* stands. Error bars represent SE of the mean. SRL: specific root length; SRA: specific root surface area. (a) Specific root length. (b) Specific root surface area.

Our results demonstrated that stand age is a critical influencing factor for *R. pseudoacacia* in coastal saline-alkali. The underlying mechanisms are supposed to be related to both physiological and ecological effects, though the exact mechanisms for the age-related patterns of these trees have not been published yet. In our study, FRB increased with stand age, which was consistent with the results reported (Pei et al., 2018).

Previous studies showed that morphological parameters of roots vary with stand age (Jagodzinski et al., 2016). In the *R. pseudoacacia* stands, the SRL of 3-year-old *R. pseudoacacia* was significantly larger than that in 16-, 30- and 40-year-old stands, which was in agreement with the conclusion drawn by Jagodzinski et al. (2016). Higher SRL during early phases of stand development increases the explorative ability of fine roots in soil volume, while lower SRL in older stands may indicate the acquisitive difficulties of nutrients and water and slow proliferation of fine roots. In this study, with larger SRL, 3-year-old *R. pseudoacacia* could improve the explorative ability for more soil resources, thus achieving the aim of fast growth and salt resistance.

4.1.2. Effects of soil depth and grow month on fine roots

Soil depth and growth month had a significant influence on FRB, FRL and FRSA. In these four different aged *R. pseudoacacia* stands, FRB, FRL and FRSA in the top soil layer (0–20 cm) was significantly higher than that in the deeper layer (20–40 cm). Besides, 77.82% of FRB was concentrated in the top 20 cm of soil, which was similar to previous results drawn from other forests (Yuan and Chen, 2010). In terms of the seasonal pattern of FRB, the peak value usually appears in spring and autumn, most of the patterns are bimodal (Qin et al., 2013). However, in some forest ecosystems, the maximum fine root biomass appears only once within a year, which could be in spring, summer or autumn. On the whole, FRB of all aged stands we studied reached the maximum in May (later spring) and September (autumn), which was the typically bimodal type.

According to the results, soil depth and growth month had significant effects on both SRL and SRA. In vertical soil profile, SRL increased with increasing soil depth, which was consistent with the previous conclusion drawn by Mahgoub et al. (2017). Fine roots with lower SRL or SRA in the upper soil layers could be able to penetrate to deeper soil layers due to their improved elongation potential, which provides more opportunity for water and nutrient uptake from deeper soil layers under water-limited conditions. SRL and SRA also showed significant temporal patterns. In July (the rainy season), both SRL and SRA reached the maximum. The higher SRL and SRA of fine roots may act as a morphological compensation for the loss of FRB due to excessive SWC in the rainy season of the Yellow River Delta (Hill et al., 2013).

4.2. Effects of stand age, soil depth and growth month on soil properties

4.2.1. Effects of stand age on soil properties

Consistent with the research results of Jun et al. (2008)on SWC of *Pinus koraiensis* plantation and Dong et al. (2014) on SSC of *R. pseudoacacia* plantation, SWC increased and SSC decreased with increasing stand age in our study, indicating the positive effects of *R. pseudoacacia* plantation on the amelioration of saline-alkali land. Besides, the variable coefficients of SWC and SSC in older stands (30a and 40a) were gentler than those in younger ones (including 3a and 16a).

According to the results, soil nutrients increased with stand age, which was consistent with the conclusions drawn by Singha et al. (2020). There are several possible reasons for this age-related pattern. First, previous studies reported that as stand age increased, the aboveground and underground biomass of trees were rapidly accumulating,

Table 3. ANOVA analyses of the effects of stand age, soil depth and growth month on soil water content, soil salt content, soil total nitrogen, soil hydrolytic nitrogen, soil available potassium, soil organic matter.

Characteristic	Source	d.f.	p
Soil water content	Stand age	3	< 0.01
	Soil depth	3	< 0.01
	Growth month	4	< 0.01
	Stand age × Soil depth	9	< 0.01
	Stand age × Growth month	12	< 0.01
	Soil depth × Growth month	12	< 0.01
	Stand age × Soil depth × Growth month	36	< 0.01
Soil salt content	Stand age	3	< 0.01
	Soil depth	3	< 0.01
	Growth month	4	< 0.01
	Stand age × Soil depth	9	< 0.01
	Stand age × Growth month	12	< 0.01
	Soil depth × Growth month	12	< 0.01
	Stand age × Soil depth × Growth month	36	< 0.01
Soil total nitrogen	Stand age	3	< 0.01
	Soil depth	3	< 0.01
	Growth month	4	< 0.01
	Stand age × Soil depth	9	= 0.81
	Stand age × Growth month	12	< 0.01
	Soil depth × Growth month	12	= 0.24
	Stand age × Soil depth × Growth month	36	= 0.39
Soil hydrolytic nitrogen	Stand age	3	< 0.01
	Soil depth	3	< 0.01
	Growth month	4	< 0.01
	Stand age × Soil depth	9	< 0.01
	Stand age × Growth month	12	< 0.01
	Soil depth × Growth month	12	< 0.01
	Stand age × Soil depth × Growth month	36	< 0.01
Soil available potassium	Stand age	3	< 0.01
	Soil depth	3	< 0.01
	Growth month	4	< 0.01
	Stand age × Soil depth	9	< 0.01
	Stand age × Growth month	12	< 0.01
	Soil depth × Growth month	12	< 0.01
	Stand age × Soil depth × Growth month	36	< 0.01
Soil organic matter	Stand age	3	< 0.01
	Soil depth	3	< 0.01
	Growth month	4	< 0.01
	Stand age × Soil depth	9	0.13
	Stand age × Growth month	12	< 0.01
	Soil depth × Growth month	12	=0.89
	Stand age × Soil depth × Growth month	36	=0.69

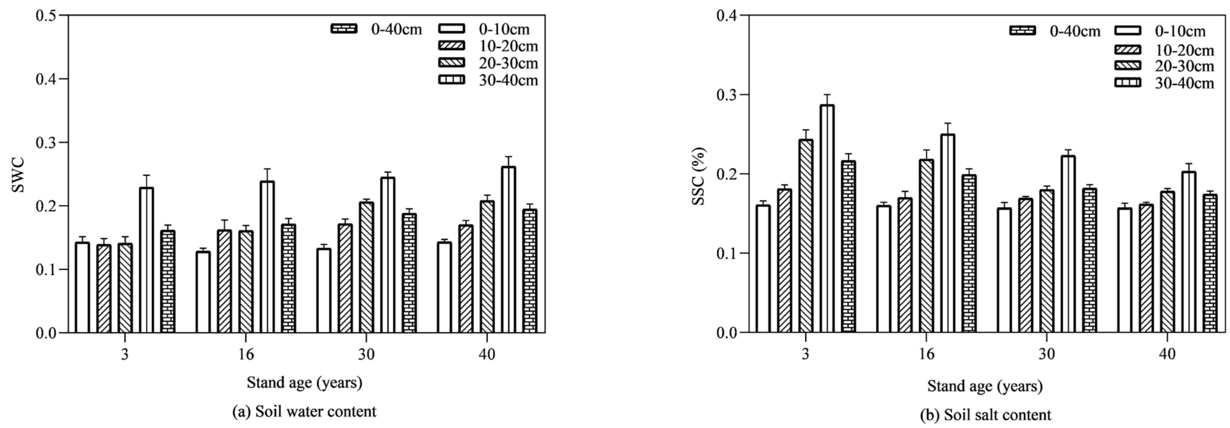

Figure 6. Soil water content and soil salt content of 3-, 16-, 30- and 40-year-old *R. pseudoacacia* stands. Error bars represent the SE of the mean. SWC: soil water content; SSC: soil salt content. (a) Soil water content. (b) Soil salt content.

Table 4. Variable coefficients (CV) of soil water content and soil salt content at different stand ages (a) and soil depth (b).

(a)	Stand age	Mean	S.D.	Minimum	Maximum	CV
SWC	3	0.16	0.05	0.08	0.30	0.31
	16	0.17	0.06	0.11	0.35	0.35
	30	0.19	0.05	0.1	0.28	0.26
	40	0.19	0.05	0.13	0.36	0.26
SSC (%)	3	0.22	0.06	0.14	0.36	0.27
	16	0.20	0.05	0.13	0.32	0.25
	30	0.18	0.03	0.12	0.27	0.17
	40	0.17	0.03	0.13	0.25	0.18

(a) at different stand ages.

(b)	Soil depth	Mean	S.D.	Minimum	Maximum	CV
SWC	0-10cm	0.14	0.05	0.1	0.18	0.14
	10-20cm	0.16	0.06	0.08	0.24	0.19
	20-30cm	0.18	0.05	0.08	0.26	0.22
	30-40cm	0.24	0.05	0.14	0.36	0.21
SSC (%)	0-10cm	0.16	0.02	0.12	0.19	0.13
	10-20cm	0.17	0.02	0.13	0.22	0.12
	20-30cm	0.21	0.04	0.16	0.30	0.19
	30-40cm	0.24	0.05	0.16	0.36	0.21

(b) at different soil depth.

and deciduous leaves increased soil nutrients in humus and the top mineral layer. Second, as salinity and water-deficiency could reduce microbial activity and biomass, older stands with relatively higher SWC and lower SSC may be more favorable for the soil microorganisms in decomposing plant residues and producing nutrients.

4.2.2. Effects of soil depth and growth month on soil properties

Vertically, both SWC and SSC increased with increasing soil depth, which may be resulted by the high level and mineralization of groundwater level in the Yellow River Delta (Ying et al., 2015). The variable coefficients of SWC

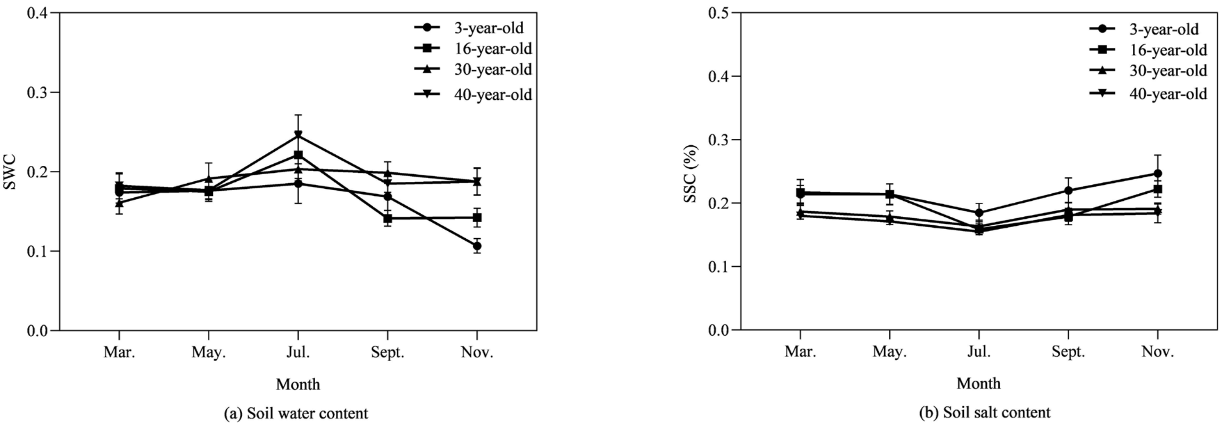

Figure 7. Seasonal variations of soil water content and soil salt content of 3-, 16-, 30- and 40-year-old *R. pseudoacacia* stands. Error bars represent the SE of the mean. SWC: soil water content; SSC: soil salt content. (a) Soil water content. (b) Soil salt content.

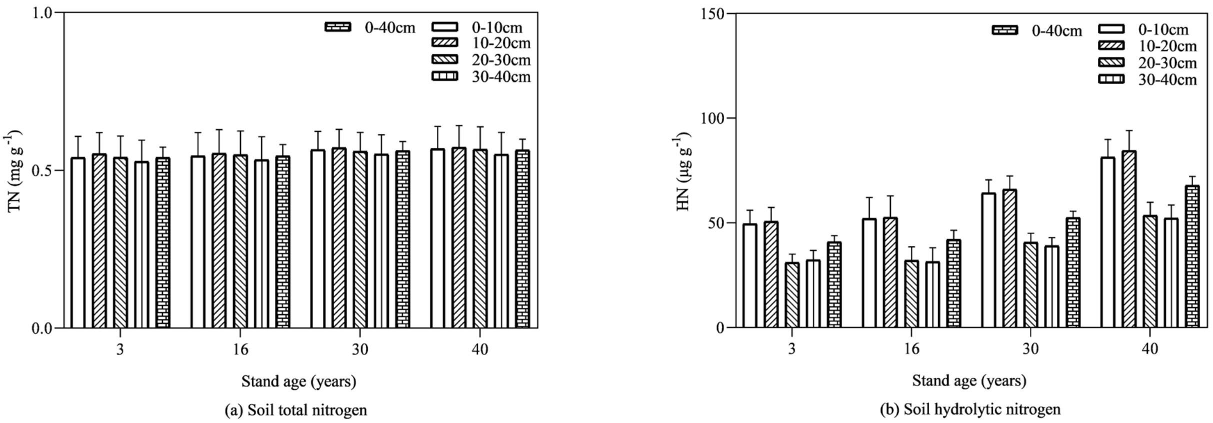

Figure 8. Soil nutrient parameters of 3-, 16-, 30- and 40-year-old *R. pseudoacacia* stands. The error bars represent the SE of the mean. TN: soil total nitrogen; HN: soil hydrolytic nitrogen; AK: soil available potassium; OM: soil organic matter. (a) Soil total nitrogen. (b) Soil hydrolytic nitrogen. (c) Soil available potassium. (d) Soil organic matter.

and SSC in the deeper soil layer (20–40 cm) were larger than those in the shallower layer (0–20 cm), indicating that the soil water-salt environment in 0–20 soil depth was more stable. Besides, SWC and SSC also showed obvious seasonal variations due to the continental monsoon climate types in the study region. Affected by the monsoon climate, the distribution of rainfall in the coastal area is extremely uneven in the year, showing obvious drought in early spring and flood in summer, and drought after the flood. As a result, the salt accumulation because of evaporation and the desalination due to eluviation occur alternately, thus SWC and SSC change frequently within a year. In early spring, autumn and winter, SWC was low while SSC was high under the effect of low precipitation and evaporation. In summer, however, a large amount of precipitation during this period increased SWC and diluted soil salinity. Based on the study conducted in *R. pseudoacacia* planting area in coastal saline-alkali land of Tianjin, China, Fu et al. (2015) found similar seasonal patterns of SWC and SSC.

Soil depth and growth month had significant effects on TN, HN, AK, OM. With the increase of soil depth, TN, HN, AK and OM decreased. Many previous studies also showed that soil nutrients decreased with increasing soil depth (Sharma and Singh, 2017), which may be due to the decomposition of deciduous leaves and other plant residues, and the favorable temperature for microbial activity and C and N mineralization in top soil. The temporal patterns of TN and OM, were different from those of HN and AK, indicating the discrepancies of temporal change between total and available nutrient parameters.

4.3. Effects of abiotic factors on fine roots

4.3.1. Effects of climate factors on fine roots

Although results of PCA showed that climatic factors were key abiotic factors in coastal saline-alkali land of the

Table 5. Correlation coefficients (CV) between fine root characteristics, climatic factors and soil properties of *R. pseudoacacia* stands FRB: fine root biomass; FRL: fine root length; FRSA: fine root surface area; SRL: specific root length; SRA: specific root surface area; SWC: soil water content; SSC: soil salt content; TN: soil total nitrogen; HN: soil hydrolytic nitrogen; AK: soil available potassium; OM: soil organic matter.

	Temperature	Precipitation	SWC	SSC	TN	HN	AK	OM
FRB	0.02	–0.11	–0.50**	–0.54**	0.16	0.57**	0.61**	0.17
FRL	0.19	0.03	–0.40**	–0.50**	0.03	0.57**	0.61**	0.13
FRSA	0.20	0.12	–0.38**	–0.45**	0.10	0.52**	0.59**	0.10
SRL	0.37**	0.35**	0.59**	0.35**	–0.34**	–0.13	–0.15	–0.14
SRA	0.34**	0.37**	0.31**	0.16	-0.15	–0.07	–0.03	-0.18

Notes: The values statistically significant were marked in bold. Levels of significance are indicated by asterisks: * p < 0.05; ** p < 0.01.

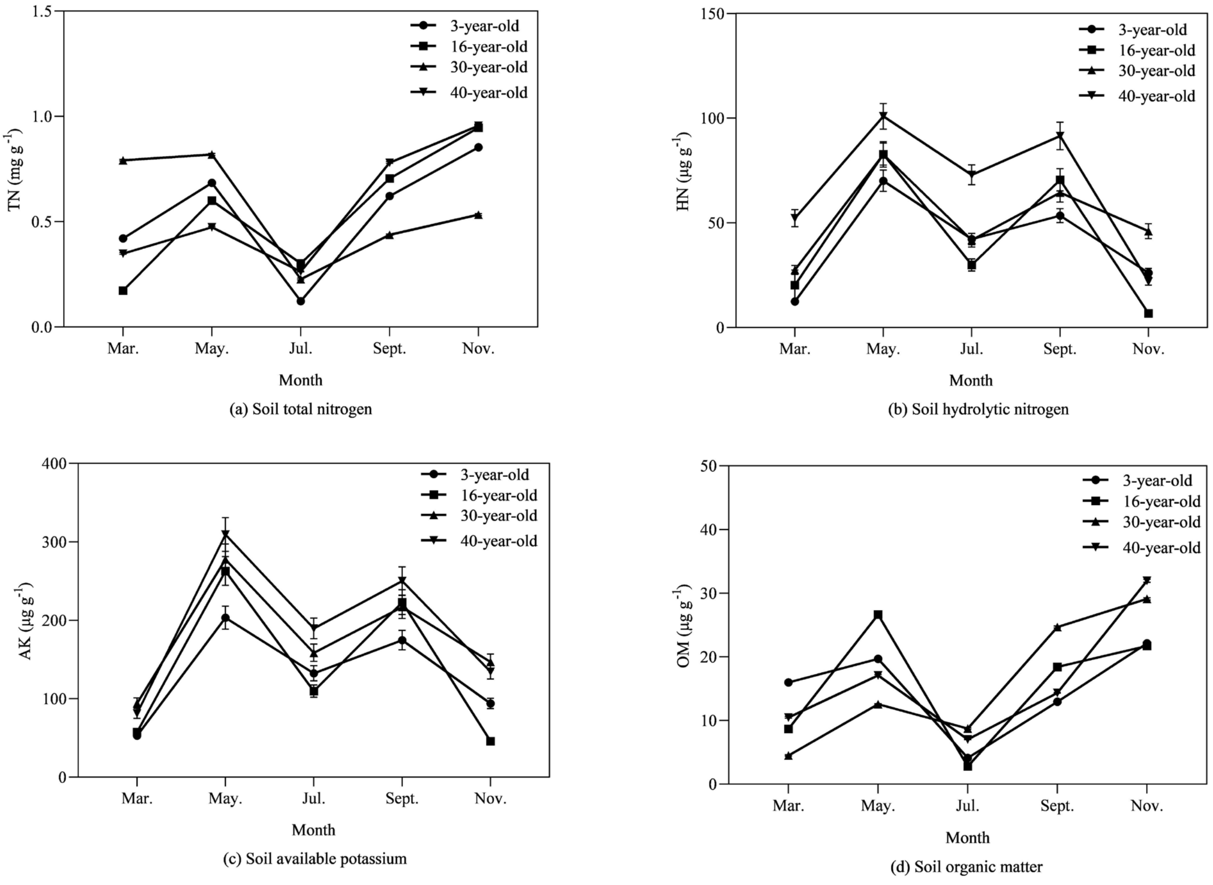

Figure 9. Seasonal variations of soil nutrient parameters of 3-, 16-, 30- and 40-year-old *R. pseudoacacia* stands. Error bars represent the SE of the mean. TN 1: soil total nitrogen; HN 1: soil hydrolytic nitrogen; AK 2: soil available potassium; OM (d): soil organic matter. (a) Soil total nitrogen. (b) Soil hydrolytic nitrogen. (c) Soil available potassium. (d) Soil organic matter.

Yellow River Delta, FRB, FRL and FRSA had no significant correlations with temperature and precipitation. In consideration of the direct contact of fine roots with the soil environment, climatic factors may indirectly influence fine roots by changing soil properties.

4.3.2. Effects of SWC on fine roots

We observed that FRB, FRL and FRSA were negatively correlated with SWC. Opposite to our results, increasing water shortage was considered to decrease fine root production (Joslin et al., 2000). Perhaps this apparent

Table 6. The coefficient, eigenvalue, variance contribution rate, and accumulated contribution rate of principal components of *R. pseudoacacia* stand. SWC: soil water content; SSC: soil salt content; TN: soil total nitrogen; HN: soil hydrolytic nitrogen; AK: soil available potassium; OM: soil organic matter.

Index	The first principle component	The second principle component	The third principle component
Temperature	0.90	–0.11	0.20
Precipitation	0.79	–0.34	0.11
HN	0.67	0.64	0.16
AK	0.64	0.72	0.20
TN	–0.50	0.62	0.20
OM	–0.46	0.61	0.39
SWC	0.16	–0.59	0.64
SSC	–0.56	–0.31	0.58
Eigenvalue	3.09	2.26	1.05
Variance contribute rate (%)	38.60	28.24	13.11
Accumulated contribute rate (%)	38.60	66.85	79.95

contradiction has resulted from both physiological and ecological effects. However, although water deficit restricts fine root growth, moderate drought stress could improve root growth, especially for drought-tolerant tree species under water-limited circumstances. Besides, as *R. pseudoacacia* is one kind of drought-tolerant and waterlogging-sensitive tree species, excessive SWC could have negative effects on the growth of roots and individuals.

Correlation analysis showed that SRL was positively correlated with SWC, indicating that SRL increases with increasing SWC. Compared with producing more fine roots, altering morphological traits of fine roots such as increasing SRL and SRA in soil with higher SWC helps trees obtain more water with less cost.

4.3.3. Effects of SSC on fine roots

According to the results, FRB, FRL and FRSA were negatively correlated with SSC. Imada et al. (2015) also found that salt stress has negative effects on fine roots and plant growth. Furthermore, in addition to the ionic effects of NaCl, salt stress decreases soil water potential and soil hydraulic conductivity thus induces water scarcity. Besides, since we found the coefficient of variation of SWC and SSC in younger stand and deeper soil layer was larger, the disturbance of water and salt fluctuation may be another key reason resulting in the less standing crops of fine roots in younger stand and deeper soil layer.

Results of correlation analysis showed that SRL was positively correlated with SSC, indicating SRL increase with increasing SSC. Under adversity, in order to obtain more soil resources for growth and survival, tolerant plants could adapt to adversity by expanding root distribution (Day et al., 2010). In fact, increasing SRL or SRA was one kind of inexpensive expanding strategy, which help *R. pseudoacacia* forage more resources under salt stress. Besides, by increasing the volume of soil exploited per unit biomass invested, increasing SRA and SRL may partially compensate for the loss in root biomass under salinity.

4.3.4. Effects of soil nutrients on fine roots

The amounts of fine roots are largely influenced by soil resource availability (Chang et al., 2012). In this study, FRB FRL and FRSA were positively correlated with HN and AK. Our findings show the importance of soil nutrients in increasing the amounts of fine roots. Fine root morphology had significant correlations with soil nutrients. Previous studies showed that nutrient deficiency induces variable root responses, among them a larger SRL was detected (Li et al., 2019). Studies on root morphological traits across soil nutrient gradients also indicated lower SRL was constructed under increasing soil nutrients (Ostonen et al., 2007). In this study, SRL was negatively correlated with TN, indicating that fine roots of *R. pseudoacacia* could improve uptake efficiency via larger SRL when soil nutrients decreasing.

5. Conclusion

This study investigated the fine root vertical-seasonal distributions of *R. pseudoacacia* in a chronosequence in coastal saline-alkali land of the Yellow River Delta, as well as how these root variables changed in relation to climatic factors and soil properties. The results presented here showed that stand age appears to be a contributing factor for quantitative and morphological characteristics of fine roots, SWC, SSC and soil nutrients. FRB, FRL and FRSA increased with stand age, with most of the fine roots distributed in the top 20 cm soil layer. SRL in 3-year-old were significantly highest, indicating the greater explorative ability of fine roots in soil volume of young tree individuals. With the increase of stand age, SWC and soil nutrients increased, SSC decreased, indicating the long-term cultivation of *R. pseudoacacia* plantation in coastal saline-alkali land can improve the soil condition to a certain extent. In addition to the stand age effect, fine roots exhibited highly vertical and temporal variations in *R. pseudoacacia* stands. Correlation analysis showed that there existed significant correlations between fine roots, climatic factors and soil parameters, indicating that variable root responses and adaptive strategies could be induced by environmental variations. As the investigations on the temporal variation of fine root biomass is essential for the evaluation of fine root production, our study also provides basic data for fine root and stand productivity estimation of *R. pseudoacacia* in coastal saline-alkali land. Further investigation should focus on both the aboveground and underground parts of trees, and clarify the relationship between roots and aboveground parts, roots and long-term maintenance of plantation productivity, which can provide a theoretical basis for productivity recovery of *R. pseudoacacia* plantation in coastal saline-alkali land.

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Conflict of interest

The authors declare no conflicts of interest.

Availability of data and material

All of the data and materials supporting our research findings are contained in the materials and methods section of the manuscript.

Contribution of authors

Conceptualization, B.C., P.M. and L.G.; funding acquisition, B.C.; methodology, B.C., P.M. and L.G.; investigation, L.G., Z.L., M.H., T.W. and F.J.; data collection and analysis, L.G.; writing original draft preparation, L.G.; writing, review and editing, B.C. and P.M.; All authors have read and agreed to the published version of the manuscript.

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