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# Root growth and spatio-temporal distribution of three common annual halophytes in a saline desert, northern Xinjiang

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**Abstract:** Root growth and spatial and temporal distribution in the 0–100 cm soil profiles of three common annual halophytes *Salsola subcrassa*, *Suaeda acuminata* and *Petrosimonia sibirica* distributed in a saline desert in northern Xinjiang, China were studied in 2009 and 2010. The results showed that the root systems of the three halophytes were of the taproot type, vertically distributed in the 90-cm soil profile, and were deepest in late July. Their taproots reached maximum depth rapidly, early in the growth period, but with rare lateral roots. They were then dug out in an orderly way, from bottom to top, exhibiting vertical development first and then horizontal development. The distribution of specific root length, which reflects the characteristics of the feeder root, was gradually increased from top to bottom, whereas root weight displayed an opposite distribution pattern. The root length distribution of the three halophytes was concentrated (62% to 76%) in the middle soil profile (20–60 cm), with less distribution in the surface (0–20 cm) and bottom (60–90 cm) soil profiles. The results indicated that the roots of the three annual halophytes grew rapidly into the deeper soil layer after germination, which ensured the plant survival and uptake of water and nutrition, and thus built up a strong tolerance to an arid, high-salt environment.

**Keywords:** northern Xinjiang; saline desert; root growth, root spatial and temporal distribution; *Salsola subcrassa*; *Suaeda acuminata*; *Petrosimonia sibirica*

Vegetation covers approximately 20% of the saline deserts in Xinjiang. The dominant life forms are perennial herbs, followed by annual herbs. Patches of annual halophytes are distributed among halophytic shrubs (Xi *et al.*, 2006). Annual halophytes not only have important eco-economical significance for saline soil reclamation, wind erosion prevention, oasis protection, and livestock grazing in winter and spring, but are also key model plants for salt tolerance research (Flowers and Colmer, 2008). Compared with succulent halophytic shrubs, annual halophytes confront more serious survival risks, for example, drought, saline, strong solar radiation, and high temperature. Perennial halophytes can cope with these stresses by taking advantages of the spatial distribution of their root systems, and nutrition accumulated in roots and

shoots from previous years. In contrast, annual halophytes have to grow a new root system each year, and the characteristics of their root development and distribution determine their growth and reproduction for the current year. In the natural succession of saline desert vegetation communities, few annual halophytes are able to accomplish generation succession and inhabit the desert environment for long. *Salsola subcrassa*, *Suaeda acuminata*, and *Petrosimonia sibirica* are three common annual halophytes found in the saline deserts of northern Xinjiang, and their characteristics of root growth and distribution are representative of their class.

Root ecology is an active field in current ecology

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research. As an important organ of plant growth, the root not only possesses many important physiological functions, such as absorption, fixation, storage, synthesis, and reproduction, but also deeply influences the plant's adaptation to the environment, interspecific competition, and ecological strategy (Rundell and Nobel, 1991; Ma *et al.*, 1996; Kroon and Visser, 2003; Liu *et al.*, 2008). In addition to the above functions, halophyte roots must adapt to an arid and saline environment; therefore, the ecological adaptation of halophyte roots is related mainly to water, salt, nutrition, and plant species (Ownbey and Mahall, 1983; Sun and Yu, 1992; Kong and Ma, 1995; Zhang *et al.*, 1995; Ma *et al.*, 1996; Sala and Smith, 1996; Xu and Li, 2006; Xu *et al.*, 2007; Chakraborty and Li, 2009; Gao *et al.*, 2010; Xu *et al.*, 2010). Most of the existing researches into the characteristics of halophyte root growth have focused on perennial halophytes, mainly involving their horizontal and vertical root distribution. However, research about the root development characteristics over time is lacking, and research into the root spatial and temporal distribution characteristics of annual halophytes is even less. Restricted as it is by growth time and shoot biomass, the space in which annual halophyte root can develop is very limited. The present study focused on annual halophyte root characteristics, growth and distribution, and the differences in root development and growth among annual halophytes under natural ecological conditions.

## 1 Materials and methods

### 1.1 Study area

The study area is located in the primitive saline desert region of Fukang National Field Scientific Observation and Research Station for Desert Ecosystem, Chinese Academy of Sciences. This area is at the northern pediment of Bogda Peak of the Tianshan Mountains, the oasis-desert ecotone of the south Gurbantungut Desert, belonging to the lower part of the Sangonghe alluvial plain, and geographically located at 87°56'E and 44°17'N, with an elevation of 475 m. It has a typical temperate desert climate, an annual precipitation of 100–200 mm, and an annual evaporation of 1,000–2,000 mm. Groundwater in the research area is 2.9–5.3 m (varying with seasons) deep and has a salin-

ity of approximately 2 g/L. Drought, high temperature, and strong solar radiation bring about seasonal surface-soil salt accumulation, fostering sulfate-dominant saline soil in which native succulent shrubs and herbs are sparsely scattered. This kind of habitat is commonly called a succulent halophytic desert. Total annual hours of sunshine are 2,532.5 h, and the frost-free period is 174 d (Xu and Li, 2006; Xu *et al.*, 2007).

### 1.2 Materials

Three native annual halophytes distributed in a saline desert of northern Xinjiang, i.e. *S. subcrassa*, *S. acuminata*, and *P. sibirica*, were chosen as the research materials (Fig. 1). Samples were collected in the primitive saline desert at the research station.

### 1.3 Sampling methods

Sampling sites about 100 m<sup>2</sup> in area were randomly chosen in the primitive saline desert where the three native halophytes were distributed. The sampling sites were far away from shrubs, flat, and without human disturbance, so there were enough materials for sampling at different time points during their whole growth period. The halophyte roots were obtained at different growth periods in 2009 and 2010, respectively. In 2009, a soil core method was used to obtain roots (Fig. 2, left): three 30 cm×30 cm quadrats were randomly excavated in the sampling spot as 3 replicates, with a total of 9 quadrats for 3 halophytes. Ditches 120 cm deep were dug, 50–60 cm around each quadrat, and the soil cores trimmed to cuboids of 30 cm×30 cm×100 cm, which were then carried back with board, then the whole root system linked was washed out with small water flow. Before the soil cores were trimmed well, soil samples for each 10-cm soil layer from bottom to top were collected for laboratory analysis. Plant counts were made for each quadrat: all plant shoots were cut and washed rapidly, blotted with absorbent paper, and freshly weighed, then bake-dried and weighed, crushed, and sieved for later use. Roots of all plants in each soil core were washed out carefully with water, scanned, and weighed.

In 2010, in order to reduce the workload, we used a stratified excavation method (Fig. 2, right): three 30 cm×30 cm quadrats were randomly chosen, with a total of 9 quadrats for 3 halophytes. After cutting all shoots, each 10-cm soil layer was excavated from top



**Fig. 1** Three native annual halophytes grown in northern Xinjiang. Photos were taken on 28 April 2010



**Fig. 2** Methods used for root sampling in 2009 (left) and 2010 (right)

to bottom (100 cm deep). The roots of each soil layer were picked out and brought back to the laboratory in freshness-protection bags and then washed clean. Part of the roots was used for a root-length scan; the rest were dried with absorbent paper and weighed freshly, bake-dried and weighed along with the shoots, and then crushed and sieved for later use. After the roots of each soil layer were picked out, the soil was mixed together, and part of the mixture was brought back to the laboratory in freshness-protection bags for determining its water content, pH, electrical conductivity, and organic matter, etc.

#### 1.4 Soil and plant sample analyses

Soil sample analyses included bulk density, organic matter, water content, pH, and electrical conductivity (EC). Plant analyses included fresh and dry weights of shoot and roots, and specific root length (SRL), which was the root length (m) per unit of root dry weight (g).

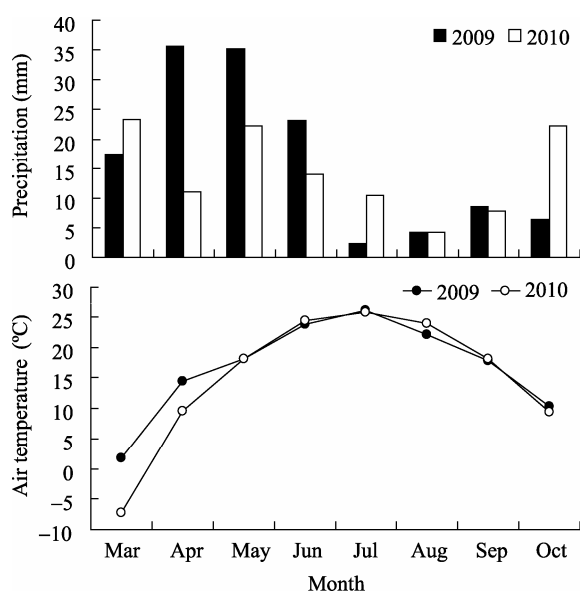
Test methods of soil indices were as follows: bulk density was measured by the cutting-ring method, organic matter by the digestion furnace heating-potassium dichromate volumetric method, water content by the weighing method, pH by the potential method, and total

salt by the EC method (soil/water ratio was 1:5). Fresh and dry weights of shoot and roots were measured using the weighing method (Bao, 2000).

#### 1.5 Meteorological data of the study area during growth season

The monthly precipitation and temperature data for the growth periods of 2009 and 2010 were collected from Fukang National Field Scientific Observation and Experiment Research Station for Desert Ecosystem. Figure 3 shows that total precipitation during the growth periods (March–October) for the two years was 133 mm and 115 mm, respectively. The precipitation was highest from March to June, accounting for 84% and 61% of the total precipitation during the growth periods of 2009 and 2010, respectively. Precipitation was lowest from July to September, accounting for only 11% and 19% of the total precipitation during the growth periods of 2009 and 2010, respectively. Precipitation for October accounted for 4.8% and 19.3% of the total precipitation during the 2009 and 2010 growth periods, respectively. The period of greatest stress for plant growth was July and August, which offered less precipitation and higher temperatures. The

average temperatures in the growth periods of 2009 and 2010 were 16.8°C and 15.2°C, respectively (the daily maximum temperatures occurred on 4 August 2009 and 18 July 2010, 30.4°C and 31.7°C, respectively). Both the temperature and precipitation were higher in 2009 than in 2010, and the precipitation during the 2009 growth period was more sufficient and beneficial to plant germination and growth. With early spring snowmelt in 2009 and 2010, annual halophytes successfully germinated and established seedlings in mid-to-late March. The precipitation was greatest and temperature most favorable from April to June during the growth period; afterwards, evaporation increased and salt and drought stress became severe owing to the increase in temperature.



**Fig. 3** Monthly precipitation and air temperature during 2009 and 2010 growth periods

### 1.6 Data analysis

After the roots were scanned by a scanner (Epson 4990, Indonesia), root parameters were analyzed by an analysis software (WinRhizo Pro Vision 5.0a). Data calculation and statistic analysis were performed by using Excel 2003 and SAS 8.1 one-way ANOVA.

## 2 Results

### 2.1 Soil properties

Soil property analysis of a 0–100 cm soil profile for

the two study years showed that water content, pH, and bulk density increased continuously from top to bottom. Organic matter content, on the contrary, decreased in a continuum from top to bottom; the ECs of soil solutions of each layer for the two years were high only in the surface soil layer and changed little in all the lower soil layers (Table 1). There was a little difference in the ECs of each soil layer between the two years. The interannual variations of EC were mainly influenced by precipitation and transpiration and often showed certain inconsistencies.

During the yearly growth period, along with the gradually increasing temperature and reduced precipitation, the soil water content declined continuously and increased again in autumn.

### 2.2 Comparison of plant growth characteristics

The growth periods of *P. sibirica* and *S. acuminata* were shorter than that of *S. subcrassa*. The former two halophytes had almost finished their life cycles in late August and then died, whereas *S. subcrassa* was still growing in September. *P. sibirica* germinated and became mature earlier. The three halophytes germinated on around 15 March 2009 and around 31 March 2010 (Table 2).

Root dry weight increased along with the shoot biomass, and both changes were similar. In the course of growth, the dry weight of shoot and root increased continuously until the last sampling in 2009, as shown in Table 2. After germination, the roots reached maximum depth in a relatively short period and stopped growing downward thereafter. For example, on 26 April 2009, the root depth of *S. acuminata* and *P. sibirica* approached their maximum; because spring arrived late in 2010, halophytes germinated about 15 days later than in 2009 and reached the maximum root depth later than in 2009. Comparison of the three halophytes showed that *S. subcrassa* attained the maximum root depth, followed by *P. sibirica* and *S. acuminata* in order.

Total root length and root dry weight exhibited a similar tendency toward change. The total root length of *P. sibirica* and *S. acuminata* started to decline one month earlier in 2009 than in 2010, possibly related to early germination and growth. The root/shoot ratios declined with growth time and tended to be stable during the mid

**Table 1** Soil properties at 0–100 cm depth during the growth periods of 2009 and 2010

Soil layer (cm)	Water content (g/g)		pH (1:5)		EC (ms/cm) (1:5)		Bulk density (g/cm <sup>3</sup> )	SOM (g/kg)	
	2009	2010	2009	2010	2009	2010		2009	2010
0–10	0.084 <sup>e</sup>	0.054 <sup>d</sup>	8.5 <sup>f</sup>	8.6 <sup>d</sup>	6.3 <sup>a</sup>	4.5 <sup>ab</sup>	1.0 <sup>h</sup>	8.0 <sup>a</sup>	8.0 <sup>a</sup>
10–20	0.111 <sup>ef</sup>	0.069 <sup>dc</sup>	8.7 <sup>e</sup>	8.9 <sup>e</sup>	5.1 <sup>b</sup>	3.6 <sup>c</sup>	1.0 <sup>h</sup>	4.6 <sup>b</sup>	4.7 <sup>b</sup>
20–30	0.113 <sup>ef</sup>	0.103 <sup>ab</sup>	8.8 <sup>d</sup>	9.0 <sup>bc</sup>	5.0 <sup>bc</sup>	4.2 <sup>bc</sup>	1.0 <sup>h</sup>	4.4 <sup>bc</sup>	4.1 <sup>bc</sup>
30–40	0.107 <sup>f</sup>	0.089 <sup>bc</sup>	8.8 <sup>d</sup>	9.0 <sup>abc</sup>	4.9 <sup>bc</sup>	4.5 <sup>ab</sup>	1.1 <sup>g</sup>	4.3 <sup>bc</sup>	3.5 <sup>cd</sup>
40–50	0.110 <sup>ef</sup>	0.094 <sup>b</sup>	8.8 <sup>d</sup>	9.0 <sup>abc</sup>	4.8 <sup>bc</sup>	4.8 <sup>ab</sup>	1.1 <sup>f</sup>	3.8 <sup>cd</sup>	3.1 <sup>de</sup>
50–60	0.117 <sup>de</sup>	0.096 <sup>b</sup>	9.0 <sup>c</sup>	9.0 <sup>bc</sup>	4.7 <sup>bc</sup>	4.9 <sup>a</sup>	1.2 <sup>e</sup>	3.4 <sup>de</sup>	2.8 <sup>def</sup>
60–70	0.123 <sup>cd</sup>	0.104 <sup>ab</sup>	9.1 <sup>b</sup>	9.0 <sup>bc</sup>	4.6 <sup>bc</sup>	5.0 <sup>a</sup>	1.3 <sup>d</sup>	3.3 <sup>def</sup>	2.5 <sup>ef</sup>
70–80	0.131 <sup>c</sup>	0.108 <sup>ab</sup>	9.0 <sup>b</sup>	9.0 <sup>abc</sup>	4.6 <sup>bc</sup>	4.7 <sup>ab</sup>	1.3 <sup>c</sup>	3.1 <sup>ef</sup>	2.1 <sup>f</sup>
80–90	0.149 <sup>b</sup>	0.125 <sup>a</sup>	9.0 <sup>b</sup>	9.1 <sup>ab</sup>	4.8 <sup>bc</sup>	4.6 <sup>ab</sup>	1.4 <sup>b</sup>	2.7 <sup>f</sup>	2.2 <sup>f</sup>
90–100	0.163 <sup>a</sup>	0.127 <sup>a</sup>	9.1 <sup>a</sup>	9.2 <sup>a</sup>	4.5 <sup>c</sup>	4.4 <sup>ab</sup>	1.5 <sup>a</sup>	3.1 <sup>def</sup>	2.3 <sup>f</sup>

Note: Each value in the table was the mean for different sampling dates during the growth period. Values in column followed by different letters represent significant difference among soil layers ( $P < 0.05$ ). SOM, soil organic matter.

**Table 2** Comparison of the growth parameters of the three annual halophytes in 2009 and 2010

Indices	Plant species	Sampling date in 2009								
		31 Mar	9 Apr	12 Apr	26 Apr	6 May	23 May	5 Jun	15 Jul	25 Aug
Shoot DW (g/10 plants)	<i>S. subcrassa</i>	0.03 <sup>a</sup>	0.05 <sup>a</sup>	0.08 <sup>b</sup>	0.08 <sup>c</sup>	0.13 <sup>b</sup>	0.3 <sup>c</sup>	0.68 <sup>c</sup>	4.41 <sup>c</sup>	26.01 <sup>b</sup>
	<i>S. acuminata</i>	0.01 <sup>a</sup>	0.07 <sup>a</sup>	0.06 <sup>b</sup>	0.26 <sup>a</sup>	1.45 <sup>a</sup>	17.79 <sup>a</sup>	22.12 <sup>a</sup>	103.75 <sup>a</sup>	174.03 <sup>a</sup>
	<i>P. sibirica</i>	0.02 <sup>a</sup>	0.05 <sup>a</sup>	0.11 <sup>a</sup>	0.12 <sup>b</sup>	0.10 <sup>b</sup>	3.65 <sup>b</sup>	8.24 <sup>b</sup>	66.26 <sup>b</sup>	11.25 <sup>c</sup>
Root DW (g/10 plants)	<i>S. subcrassa</i>	0.02 <sup>a</sup>	0.02 <sup>a</sup>	0.03 <sup>b</sup>	0.02 <sup>b</sup>	0.03 <sup>b</sup>	0.07 <sup>b</sup>	0.09 <sup>c</sup>	0.39 <sup>c</sup>	1.72 <sup>b</sup>
	<i>S. acuminata</i>	0.01 <sup>a</sup>	0.03 <sup>a</sup>	0.02 <sup>b</sup>	0.08 <sup>a</sup>	0.19 <sup>a</sup>	0.41 <sup>a</sup>	1.61 <sup>a</sup>	15.30 <sup>a</sup>	11.93 <sup>a</sup>
	<i>P. sibirica</i>	0.01 <sup>a</sup>	0.02 <sup>a</sup>	0.05 <sup>a</sup>	0.03 <sup>b</sup>	0.02 <sup>b</sup>	0.43 <sup>a</sup>	1.02 <sup>b</sup>	8.51 <sup>b</sup>	0.79 <sup>c</sup>
Root/shoot ratio	<i>S. subcrassa</i>	0.59 <sup>a</sup>	0.35 <sup>a</sup>	0.32 <sup>b</sup>	0.29 <sup>a</sup>	0.22 <sup>a</sup>	0.22 <sup>a</sup>	0.13 <sup>a</sup>	0.09 <sup>a</sup>	0.07 <sup>a</sup>
	<i>S. acuminata</i>	0.56 <sup>a</sup>	0.34 <sup>a</sup>	0.34 <sup>b</sup>	0.31 <sup>a</sup>	0.13 <sup>b</sup>	0.02 <sup>c</sup>	0.07 <sup>b</sup>	0.15 <sup>a</sup>	0.07 <sup>a</sup>
	<i>P. sibirica</i>	0.57 <sup>a</sup>	0.30 <sup>a</sup>	0.42 <sup>a</sup>	0.20 <sup>b</sup>	0.23 <sup>a</sup>	0.12 <sup>b</sup>	0.12 <sup>a</sup>	0.13 <sup>a</sup>	0.07 <sup>a</sup>
Total root length (m/plant)	<i>S. subcrassa</i>	0.11 <sup>a</sup>	0.15 <sup>b</sup>	0.17 <sup>c</sup>	0.20 <sup>b</sup>	0.26 <sup>c</sup>	0.64 <sup>c</sup>	1.03 <sup>b</sup>	1.29 <sup>c</sup>	3.56 <sup>b</sup>
	<i>S. acuminata</i>	0.07 <sup>b</sup>	0.39 <sup>a</sup>	0.57 <sup>a</sup>	0.76 <sup>a</sup>	1.91 <sup>a</sup>	2.42 <sup>a</sup>	3.11 <sup>a</sup>	30.43 <sup>a</sup>	22.05 <sup>a</sup>
	<i>P. sibirica</i>	0.08 <sup>b</sup>	0.16 <sup>b</sup>	0.39 <sup>b</sup>	0.67 <sup>a</sup>	0.71 <sup>b</sup>	1.48 <sup>b</sup>	3.12 <sup>a</sup>	22.27 <sup>b</sup>	3.12 <sup>b</sup>
Root depth (cm)	<i>S. subcrassa</i>		8.6 <sup>b</sup>		14.8 <sup>b</sup>		16.4 <sup>b</sup>	55.0 <sup>b</sup>	65.0 <sup>b</sup>	80.0 <sup>a</sup>
	<i>S. acuminata</i>		13.8 <sup>a</sup>		71.0 <sup>a</sup>		77.0 <sup>a</sup>	76.7 <sup>a</sup>	80.0 <sup>a</sup>	80.7 <sup>a</sup>
	<i>P. sibirica</i>		13.1 <sup>a</sup>		77.0 <sup>a</sup>		80.0 <sup>a</sup>	80.0 <sup>a</sup>	80.0 <sup>a</sup>	54.5 <sup>b</sup>
		Sampling date in 2010								
		25 May	17 Jun	27 Jul	4 Sep	30 Oct				
Shoot DW (g/10 plants)	<i>S. subcrassa</i>	0.38 <sup>b</sup>	2.44 <sup>b</sup>	21.19 <sup>b</sup>	185.45 <sup>a</sup>	333.89 <sup>a</sup>				
	<i>S. acuminata</i>	0.78 <sup>a</sup>	6.53 <sup>a</sup>	16.10 <sup>b</sup>	47.49 <sup>c</sup>	12.26 <sup>c</sup>				
	<i>P. sibirica</i>	0.79 <sup>a</sup>	5.29 <sup>a</sup>	31.01 <sup>a</sup>	75.38 <sup>b</sup>	23.46 <sup>b</sup>				
Root DW (g/10 plants)	<i>S. subcrassa</i>	0.06 <sup>a</sup>	0.33 <sup>b</sup>	1.78 <sup>a</sup>	5.25 <sup>a</sup>	10.61 <sup>a</sup>				
	<i>S. acuminata</i>	0.05 <sup>a</sup>	0.51 <sup>a</sup>	0.97 <sup>b</sup>	1.98 <sup>c</sup>	0.72 <sup>c</sup>				
	<i>P. sibirica</i>	0.08 <sup>a</sup>	0.32 <sup>b</sup>	1.70 <sup>a</sup>	3.54 <sup>b</sup>	1.69 <sup>b</sup>				
Root/shoot ratio	<i>S. subcrassa</i>	0.14 <sup>a</sup>	0.13 <sup>a</sup>	0.09 <sup>a</sup>	0.03 <sup>b</sup>	0.03 <sup>c</sup>				
	<i>S. acuminata</i>	0.06 <sup>b</sup>	0.07 <sup>b</sup>	0.06 <sup>b</sup>	0.04 <sup>a</sup>	0.06 <sup>b</sup>				
	<i>P. sibirica</i>	0.11 <sup>ab</sup>	0.05 <sup>b</sup>	0.06 <sup>b</sup>	0.05 <sup>a</sup>	0.07 <sup>a</sup>				
Total root length (m/plant)	<i>S. subcrassa</i>	0.62 <sup>a</sup>	1.72 <sup>a</sup>	5.13 <sup>a</sup>	12.45 <sup>a</sup>	3.18 <sup>a</sup>				
	<i>S. acuminata</i>	0.52 <sup>c</sup>	1.83 <sup>a</sup>	3.91 <sup>c</sup>	4.33 <sup>b</sup>	2.06 <sup>c</sup>				
	<i>P. sibirica</i>	0.58 <sup>b</sup>	1.14 <sup>b</sup>	4.72 <sup>b</sup>	12.37 <sup>a</sup>	2.59 <sup>b</sup>				
Root depth (cm)	<i>S. subcrassa</i>	40.0 <sup>a</sup>	80.0 <sup>a</sup>	87.0 <sup>a</sup>	90.0 <sup>a</sup>	60.0 <sup>b</sup>				
	<i>S. acuminata</i>	37.0 <sup>a</sup>	78.0 <sup>a</sup>	83.0 <sup>b</sup>	80.0 <sup>b</sup>	70.0 <sup>a</sup>				
	<i>P. sibirica</i>	40.0 <sup>a</sup>	80.0 <sup>a</sup>	85.0 <sup>b</sup>	80.0 <sup>b</sup>	60.0 <sup>b</sup>				

Note: Letters a, b, and c represent significant differences among plant species ( $P < 0.05$ ). DW, dry weight.

to late growth period. During the same period of each year, the root/shoot ratio of *S. subcrassa* was higher and decreased more rapidly, while the root/shoot ratios of *S. acuminata* and *P. sibirica* changed slowly.

### 2.3 Characteristics of root spatial and temporal distribution of the three halophytes

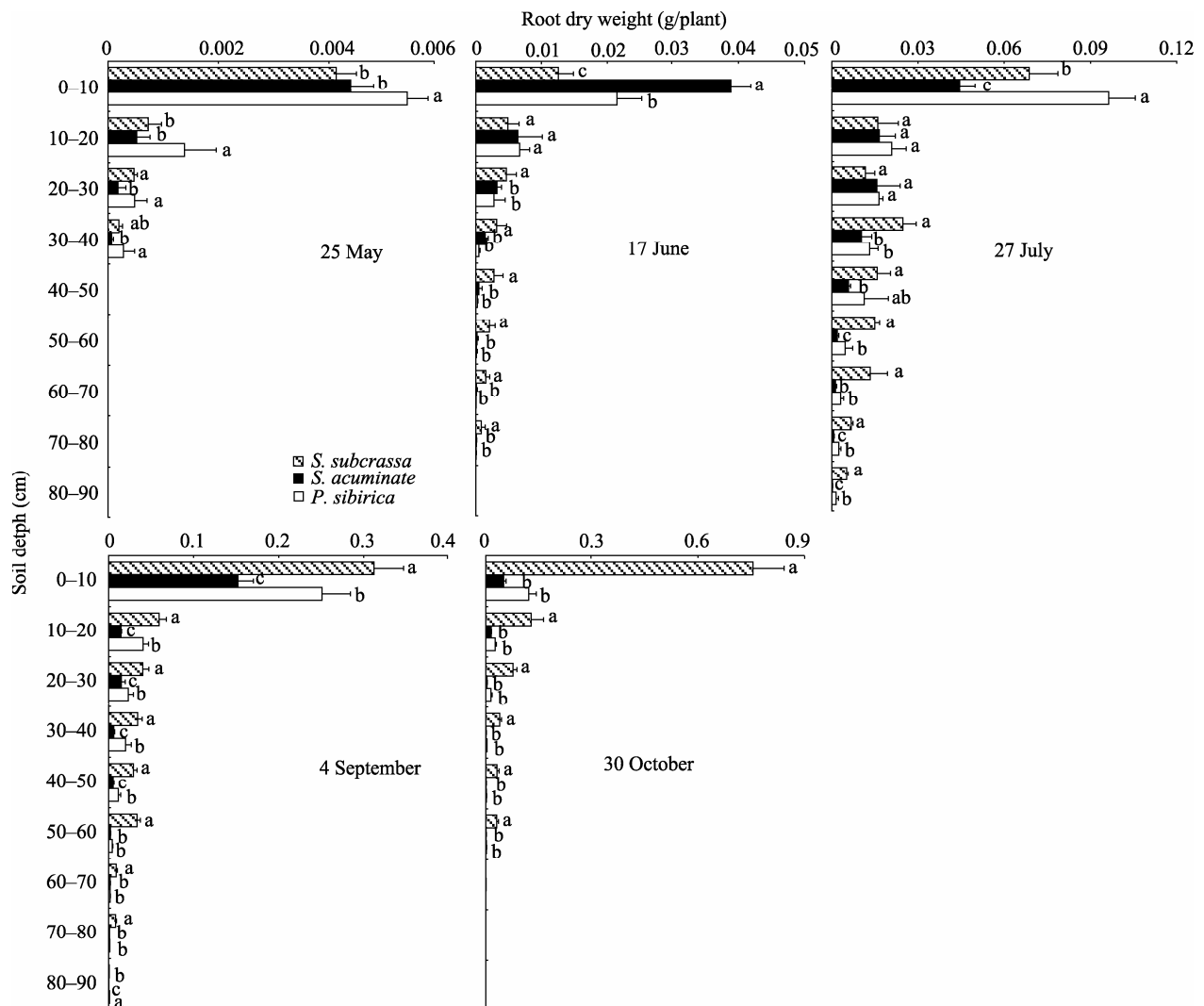
In 2010, the characteristics of root spatial and temporal distribution of the three halophytes were compared, including changes in root dry weight, root length, and specific root length (SRL, which refers to the ratio of root length to root dry weight).

#### 2.3.1 Distribution of root dry weight

The root dry weights of the three halophytes decreased

along with an increase in soil layer depth (Fig. 4). The distribution percentage of root dry weight in the surface soil layer (0–10 cm) was the largest, accounting for 70% of the total. As the growth period progressed, however, the distribution of root dry weight moved downward gradually: the percentage of root distributed in the surface soil layer decreased from 72%–85% during the early growth period to 39%–57% on 27 July. Until the late growth period, the root weight percentage in the surface soil layer increased again owing to accelerating aging and decomposition of low-layer roots.

A comparison of the three halophytes reveals that during the early growth period (25 May 2010),



**Fig. 4** Root dry weight distribution of three native annual halophytes in 0–100 cm soil profiles in 2010. Different letters at the end of columns in each soil layer represent significant differences among plant species ( $P < 0.05$ ). Means  $\pm$  SE;  $n = 3$ .

*P. sibirica* exhibited the most extensive root dry weight distribution in each soil layer, followed by *S. subcrassa* and *S. acuminata*. During the extended growth time, since *S. acuminata* had the highest root growth rate (from 22 May to 17 June, 2010), its root dry weight was the highest in the 0–20 cm soil layer, although the distribution in the middle-to-lower soil layer was far smaller than that of *S. subcrassa*. From 27 July to 4 September 2010, the root dry weight of *S. acuminata* decreased rapidly, while the roots of the other two halophytes were still growing rapidly, making the root dry weight of *S. acuminata* the lowest in each soil layer. With the extension of growth time, the root weight of *S. acuminata* and *P. sibirica* decreased in the deep soil layer while their root weight was still increasing in the shallow soil layer. In contrast, the root weight of *S. subcrassa* was still increasing in each soil layer until 4 September 2010, when the root dry weight of this plant reached its peak in the surface soil layer, while both the deep and shallow roots of *S. acuminata* and *P. sibirica* had already rotted rapidly.

### 2.3.2 Distribution of root length

The root length distribution of the three halophytes differed markedly from their root dry weight distribution, i.e. the distribution of root length was notably lower down the profile than the root dry weight found in the surface soil layer. As the growth period continued, the root length distribution center moved noticeably downward (Fig. 5). As of 4 September, the total root lengths of the three halophytes had reached their respective peaks, distributed mainly in the 10–80 cm soil layer, but their root length distribution centers differed from each other. The taproot length distribution of *S. acuminata*, *P. sibirica*, and *S. subcrassa* was found in 10–50 cm, 10–60 cm, and 10–80 cm soil layers, respectively, with maximum root lengths present in 20–30 cm, 30–40 cm, and 30–40 cm soil layers, respectively.

Vertically, the roots of the three halophytes reached the 90-cm deep soil layer on 27 July, and their root depth and length decreased rapidly after 4 September, suggesting that the roots were dying rapidly. In contrast, the death rate of *S. acuminata* root was lower than that of *S. subcrassa* and *P. sibirica*. It was observed at the sampling time that the root of *S. acumi-*

*nata* was black, crisp, and easy to break.

### 2.3.3 Changes of specific root length (SRL)

SRL refers to the ratio of root length to root dry weight. It could be seen from Fig. 6 that the SRL distribution of the three halophytes in different soil layers differed from what is for root dry weight (Fig. 4) and root length (Fig. 5). The results in Figs. 4 and 5 and Table 2 showed that on the sampling date of 4 September 2010, the total root length and root dry weight of all three halophytes reached their peaks, whereas the maximum SRL in the deep soil layer took place during the early period of root growth (on 17 June), although the taproot had not yet reached the maximum root depth. On each sampling date, the root systems of all three halophytes showed the same tendency, that is, the SRL was the highest in the lower soil layer (except for 17 June, when the highest SRL of *S. subcrassa* was present in the middle soil layer), and the SRL was the lowest in the upper layer, suggesting thinner roots in lower soil layer. The SRLs of the three halophytes decreased with growth time.

## 3 Discussion

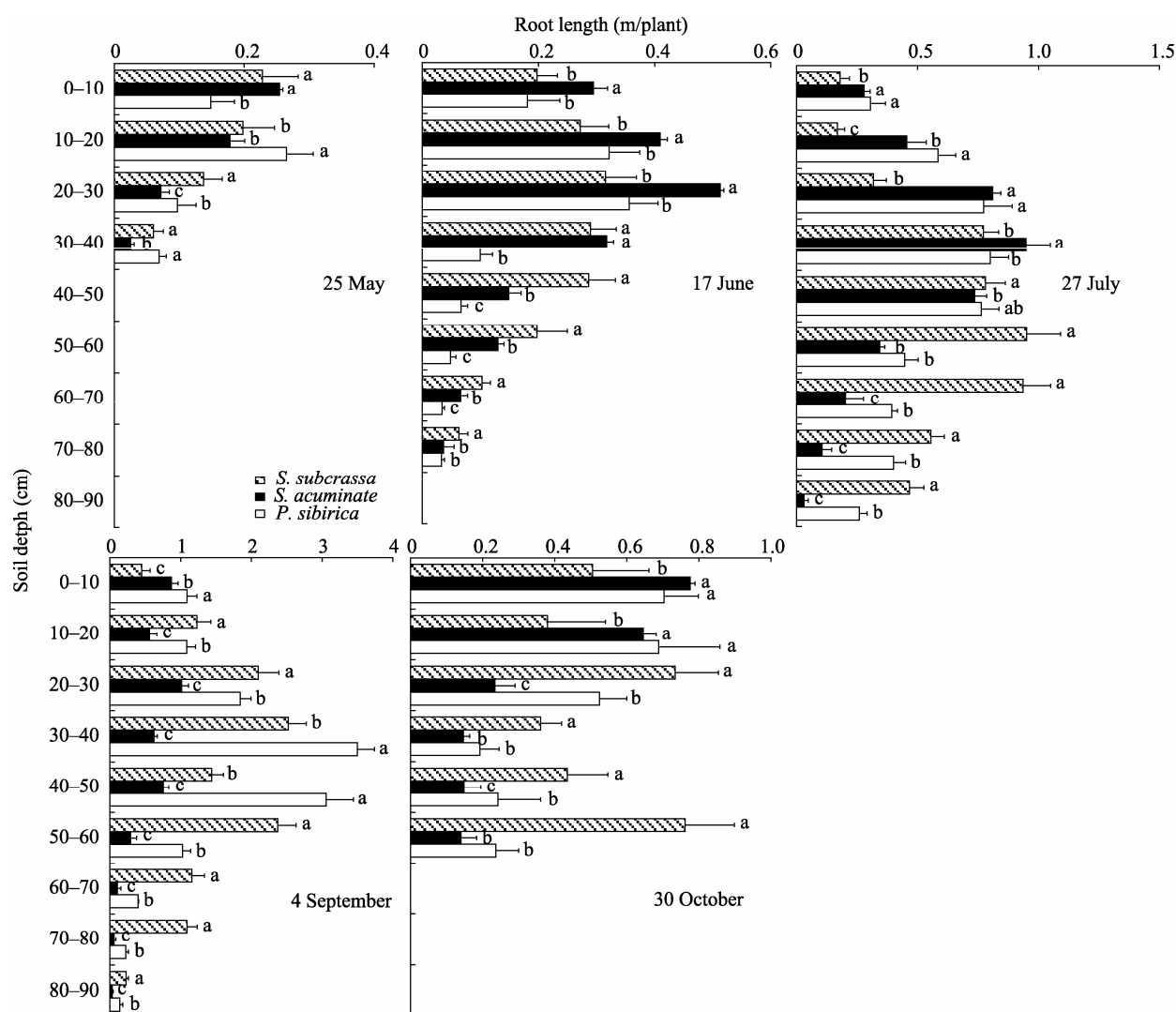
### 3.1 Root growth characteristics and environmental adaptability of annual halophytes

The three annual halophytes investigated in the present study have well-developed taproots, and their root depth characteristics show habitat similarity. Although the organic matter content was the highest in the surface soil layer, the salt concentration was also high (see EC data, Table 1) in the surface soil. Also, the water content was low, indicating relatively severe drought and salt damage in the surface soil layer. To adapt to such environmental stresses, the three annual halophytes developed root rapidly after germination, giving priority to root development and a relatively high root/shoot ratio, which can reach 0.6 during the early growth period. The results implied that assimilates synthesized in shoot in the early growth period were mainly used for downward growth of roots. This growth pattern is beneficial to the halophyte's survival within the arid environment (with recurrent water shortage that does not allow the plants to absorb sufficient water), and reflects the ecological adaptation of

these species. As the growth season proceeded, the plant growth changed from vegetative to reproductive stage, and the growth center of plants moved from roots to shoot. After prior distribution of their root systems, the annual halophytes started to allocate more dry matter to shoot production so as to maximize reproductive allocation.

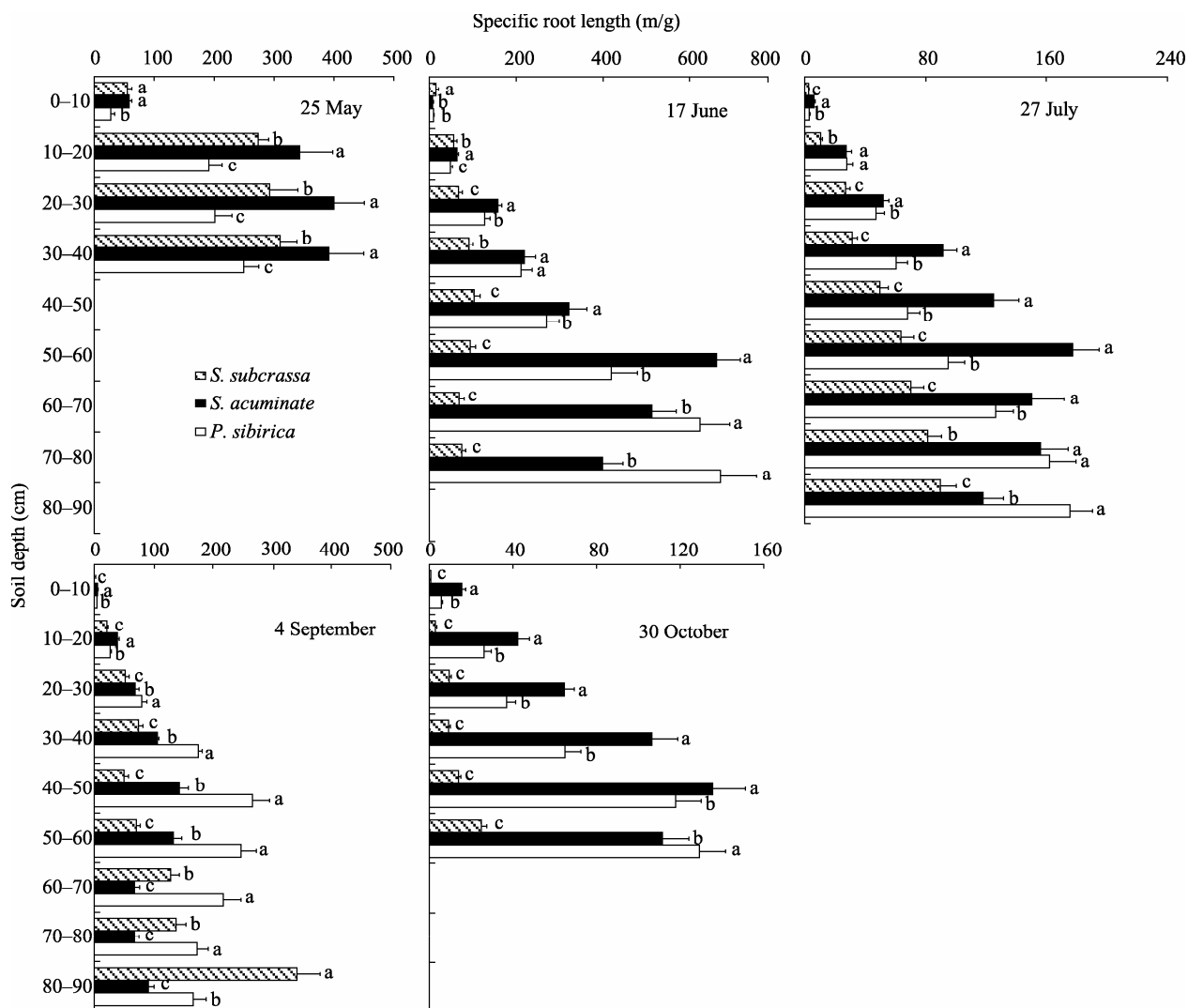
There are two main sources of water in the saline deserts in Xinjiang, i.e. precipitation (Fig. 3) and groundwater/phreatic water supply. At the time of germination, snowmelt and low temperatures established favorable conditions for the

early growth of halophytes (Fig. 3); May–June was a period of aridity during which halophytes grew slowly. Later in the season, there was more precipitation and rising groundwater level due to spring snowmelt flooding in mid to late March in Tianshan Mountains and autumn icemelt flooding during June–August (Wang *et al.*, 2002). Then, the roots in the deep soil layer, developed during the early growth period, played their role, and the halophytes started to grow rapidly. The growth of annual halophytes was sensitive not only to precipitation but also to seasonal changes in groundwater depth, which determined the plants' success to a large extent (Su *et al.*, 2005).



**Fig. 5** Root length distribution of three native annual halophytes in 0–100 cm soil profiles in 2010. Different letters at the end of columns in each soil layer represent significant differences among plant species ( $P < 0.05$ ). Means  $\pm$  SE;  $n = 3$ .





**Fig. 6** Distribution of specific root length of the three native annual halophytes in 0–100 cm soil profiles in 2010. Different letters at the end of columns in each soil layer represent significant differences among plant species ( $P < 0.05$ ). Means  $\pm$  SE;  $n = 3$ .

### 3.2 Root spatial and temporal distribution of annual halophytes

The root is the plant organ that comes into direct contact with soil. It is the goal of root evolution to pursue advantages and avoid detriments, and to efficiently absorb soil resources, such as water and nutrients. The spatial and temporal changes of root distribution of annual halophytes in the course of their growth, as well as the relation between such changes and soil factors and shoot growth, help us to understand the adaptive behavior of the root system of halophytes (Hartlea *et al.*, 2006). This adaptive distribution is the result of the evolution of halophytes within their environment.

The discussion about root distribution characteristics often focuses on root length distribution. The root distribution of halophytes varies with species and habitat. For example, the root of *Nitraria tangutorum*, affected by soil moisture and compaction, is distributed mainly in the 0–40 cm soil profile, in a well-developed horizontal, lateral manner (Sun and Yu, 1992). The root of perennial Tamaricaceae is deep and, to avoid salt absorption, its feeder root is distributed mainly near groundwater table (Xu and Li, 2006; Xu *et al.*, 2007). The water absorption efficiency of deeply rooted plants is hardly affected by water shortages in shallow soil layers (Sala and Smith, 1996). The vertical root of *Halocnemum strobilaceum* and

*Kalidium foliatum* (succulent halophytic shrubs) is distributed mainly in 30–60 cm and 20–50 cm soil profiles, respectively (Gao *et al.*, 2010), similar to the root length distribution of annual halophytes observed in this research.

In contrast with crops, whose root distribution converges near soil surface (Liu *et al.*, 2009; Lu *et al.*, 2010; Wang *et al.*, 2010), the root systems of annual halophytes in the 1-m soil profile exhibited a downward distribution. They were sensitive to and made good use of precipitation, and benefited from the supply of groundwater (Table 1). The root distribution of annual halophytes was similar to that of high salt-tolerant shrubs such as *Halocnemum strobilaceum* and *Kalidium foliatum* (Xu and Li, 2006; Gao *et al.*, 2010), and especially the SRL, which represents the root absorption capacity, was distributed in the lower soil layer. Compared with the feeder root of perennial *Tamarix chinensis* (Xu and Li, 2006; Xu *et al.*, 2007), the root systems of annual halophytes may have a stronger ability to tolerate salt damage. In this research, the salt distribution in the habitat soil (Table 1) showed that the EC of soil solution in each layer was greater than 4 ms/cm, and the average was 4.5 ms/cm (on the basis of 1 ms/cm approximates 0.6% NaCl, the soil NaCl content was 2.7%). The root distributed in the 0–10 cm soil layer had been lignified and browned, being salt-tolerant, and the root distributed in the 30–70 cm soil layer accounted for the largest proportion, most of which consisted of feeder root. This distribution suggests that the halophyte root systems can tolerate high salt stress. The saline soil in this arid area is characteristic of salt aggregation. Thus, the root distribution behavior of annual halophytes was water/salt oriented, nutrition oriented, and salt-tolerant.

The range of horizontal root distribution in soil was relatively small (30 cm), and the vertical root distribution was characterized by the majority of roots residing in the middle-lower soil layer, while few roots present in the surface and bottom soil layers. Because of the lack of precipitation, the surface soil layer was characteristic of drought and high salinity (Table 1); hence, there was no root surface convergence phenomenon, as exhibited by hygrophytes (Lai *et al.*, 2010) and crops (Liu *et al.*, 2009; Lu *et al.*, 2010;

Wang *et al.*, 2010). The following stresses existed in the bottom soil layer: oxygen deficiency (bulk density was higher, Table 1), nutrition shortage (SOM was lower, Table 1), and high salt content. Hence, it was impossible for the roots of the annual halophytes to aggregate near groundwater, which was in the deep soil layer. The same is true with the feeder roots of perennial halophytes such as *Tamarix chinensis* and *Alhagi sparsifolia* (Zhang *et al.*, 1995; Xu and Li, 2006; Xu *et al.*, 2007). Limited by short growth period and low biomass, annual halophytes distributed their roots mainly in the middle and lower soil layers (30–60 cm), with few roots found in surface (0–30 cm) and bottom (60–90 cm) soil layers. Such spatial distribution ensured plant survival, guaranteed the uptake of water and nutrition, and imparted a relatively strong tolerance to high salt content. This root distribution of annual halophytes differed from the feeder root distribution of *T. chinensis* and *A. sparsifolia*, near groundwater.

The SRL (representing the feeder root) of annual halophytes gradually increased from soil top to bottom (Fig. 6), opposite to the distribution of root weight. However, some plants have an SRL distribution pattern similar to their root dry weight distribution (Wei and Shangguan, 2006; Zhu *et al.*, 2009), in which root dry weight decreases vertically from top to bottom. Many factors affected the SRL vertical distribution, for example, nutrition (Ma, 2007; Schippers and Olff, 2000), salt stress (Eissenstat, 2000), and plant species (Wei and Shangguan, 2006). The distribution of the halophyte's root weight and SRL in different soil layers reflected the relationship between root growth competition and aging rate.

## 4 Conclusions

The results for 2009 and 2010 showed that the growth of annual halophytes in the saline desert in northern Xinjiang was sensitive to precipitation, of which the plants can take advantage. The root dry weight was the highest in the 0–10 cm soil layer and gradually decreased from surface soil layer to bottom layer.

The root systems of the three annual halophytes developed downward rapidly after germination, char-

acteristic of concentrated root length in the middle soil layer and less in the surface and bottom soil layers. The distribution of SRL, which characterized the feeder root, was opposite to the plant's root weight distribution, which gradually increased from top to bottom soil layers.

The root developmental characteristics of annual halophytes in different soil layers can be summarized as follows: the root reached the maximum depth rapidly during the early growth (vegetative–flowering) period, and afterwards, declined from bottom to top (from lower-layer root to middle-layer root and then to upper-layer root); the roots grew vertically first, and then horizontally. These patterns of root development are long-term interactions of annual halophytes with arid-saline desert environment.

As can be seen from the soil pH, EC, and root distribution (Table 1, Fig. 5), it was difficult to discharge

salt from soil because the alkali and total salt were distributed evenly. According to the root distribution characteristics of annual halophytes, it is possible to biologically reclaim saline soil by planting annual halophytes, which can be cultivated and harvested annually on a large scale as crops. In this way, annual halophytes could be a key alternative in the biological reclamation of saline soil.

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