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RESEARCH ARTICLE

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Response of root distribution of *Haloxylon ammodendron* seedlings to irrigation amounts in the hinterlands of the Taklimakan Desert, China

Abstract We excavated soil to study root distribution in *Haloxylon ammodendron* seedlings grown with different amounts of irrigation (35, 24.5 and 14 kg water for each plant each time) in the hinterland of the Taklimakan Desert. The results indicated that: 1) With decreasing irrigation amounts, the root biomass tended to be distributed in deeper soil layers. Underground biomass had a significantly negative logarithmic relationship with soil depth under different irrigation amounts. 2) Maximum horizontal spread of roots was twice that of vertical root spread, and horizontal distribution of root biomass was similar under all irrigation amounts. 3) Vertical distribution of fine roots was nearly consistent with vertical changes in soil moisture, and all had a unimodal curve; but peak values of fine root biomass in different soil layers varied with different irrigation amounts. The smaller the amount of irrigation, the deeper were the fine roots concentrated in soil layers. 4) Root length, root surface area and root volume all exhibited a unimodal curve under different irrigation amounts; the less the irrigation amount, the deeper the peak values appeared in soil layers. 5) Root-shoot ratio and ratio of vertical root depth to plant height both increased as irrigation amounts decreased.

Keywords root system, root surface area, underground biomass, root-shoot ratio

1 Introduction

Water is a major limiting factor which affects the existence and growth of plants. The soil water change also commonly affects water balance and morphogenesis of plants. Most plants have large root systems in arid regions. Even though only a fraction of roots are distributed in deep soil, they play a very important role in plants for the maintenance of life activities and in the adaptation to adverse environments (Gale and Grigal, 1987; Jackson et al., 1996). Scientists from the former Soviet Union have comparatively researched the root systems of the same species between humid and drought conditions in the Yili-Alataou mountain range. The results revealed that plant root systems have poor ramification in moist environments, with only 2–3 orders; on the contrary, in arid areas of the southern range of the mountain, root systems of the same species can reach 5-order branches (Baitulin and Meri, 1995). Some studies have shown that light water stress would help root systems grow toward deeper soil (Yang et al., 1993; Zhang and Miao, 1997). These suggested that water plays an important role in the regulation and distribution of root morphological structure in arid regions.

After the afforestation of the protection forest along the Taklimakan Desert highway, the sustainability of protection forests has become the focus of attention. It was hypothesized in some studies that some areas in the protection forest along the desert highway could directly make use of deep soil water by changing the management

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model in the future. According to Sheng (2004) and Li (1995), naturally distributed *H. ammodendron* in Inner Mongolia could use groundwater to maintain its life activities. There is no naturally distributed *H. ammodendron* in the hinterlands of the Taklimakan Desert. Artificial protection forests of *H. ammodendron* in this desert always depend on drip irrigation to maintain life. For the purpose of saving water resources and maintaining stability of the protection forest, we studied root systems of *H. ammodendron* seedlings under different irrigation conditions in the spring of 2005 in the hinterlands of the Taklimakan Desert.

H. ammodendron, belonging to family Chenopodiaceae, is a perennial small tree or shrub-like plant in some regions. It is the major afforestation species in protection forests along the Tarim desert highway. In recent years, many scientists have studied the physiological and ecological characteristics of *H. ammodendron* under different watering regimes, but they focused mainly on the aboveground physiological process of drought resistance (Li, 1992; Ma et al., 2003; Wu and Zhang, 2005). *H. ammodendron* has developed its own special ways in drought conditions for adapting to such an adverse environment. Its roots are distributed very widely due to the loose sand and arid environment, so it is rather difficult to dig it out. So far, few papers have reported on the response of root distribution characteristics of *H. ammodendron* to different water conditions. In this study, we investigated root distribution and canopy structure characteristics of *H. ammodendron* seedlings under different irrigation amounts in the hinterlands of the Taklimakan Desert. Then we discussed the response of individual characteristics of *H. ammodendron* to changes in water condition.

2 Methods

2.1 Natural conditions of the study area

The experiment was performed in a lowland dune which is located 8 km southeast of the Taklimakan Desert Botanical Garden of the Xinjiang Ecology and Geography Institute, Chinese Academy of Sciences. According to data from the Tazhong Meteorological Station and the Auto-Meteorological Station of the Botanical Garden, the annual average temperature of this area is 12.4°C. The highest temperature occurs in July, with a monthly average temperature of 28.2°C, and the coldest in December, with a monthly average temperature of −8.1°C. The recorded highest temperature is 45.6°C and the lowest −22.2°C. The annual sunlight time is 2571.3 h. The mean annual precipitation is 36.6 mm. The relative humidity is 29.4% on average. The potential evapotranspiration rate is 3638.6 mm. The wind speed is 2.5 m/s on average and the highest instantaneous speed is 24.0 m/s. From April to August is the windy season, and the average wind velocity is 3.2 m/s. Sandstorms often occur. On average, in a year there are 60 d with heavy wind, 74 d with floating dust, and 45 d of sand raised by wind. Soil type varies in different physiognomies, and is mainly mobile wind sandy soil. The salt content is 1.26–1.63 g/kg. In the low soil layers, 20–60 cm thick semi-clay occurs occasionally, existing amid the wind sandy soils.

2.2 Methods

2.2.1 Plot design and management

In March 2005, *H. ammodendron* seedlings were planted in the study area, with row spacing of 4 m × 4 m. The irrigative water was local underground saline water and the irrigation model was drip irrigation. The irrigation interval was consistent with that of the Tarim desert highway protection forest, i.e., 10 d from March to August, 15 d from September to November. To prevent sand burying and shearing, we set up mechanical sand barriers between rows. We adopted three watering treatments. Treatment 1 was 35 kg water per plant each time, which is the same as the current irrigation amount for the protection forest; treatment 2 and treatment 3 were 24.5 and 14 kg water per plant each time, respectively. After planting for a month, the survival ratio of plants under different irrigation amounts all reached about 90%.

2.2.2 Experimental methods

We excavated soil to investigate root distribution characteristics of *H. ammodendron* seedlings in October 2005. Four plants from each treatment were selected randomly. The sample was excavated out of soil to study root distribution. We took the plant as the center, and in a horizontal direction, every 30 cm was considered as a section, while in the vertical direction every 20 cm was a layer. Roots in each section and layer were dug out and sieved with a 2 mm sieve until no roots existed in both directions. At the same time, the aboveground growth indexes (individual plant height, crown diameter, basal stem diameter) of samples were measured. Root samples were washed in the laboratory. According to whether the stem diameter was $\leqslant 1$ mm or > 1 mm, the samples were separated manually. Five root samples were randomly selected to measure root diameter; their average value was considered as the average diameters of the roots at the layer and the section. Root volume (V) was measured by the Archimedes method. Root length (L) and root surface area (S) were calculated using the formula $L = 4V/\pi d^2$ and $S = 4V/d$, where d is the root diameter. The samples from underground were dried at 105°C until the weights of the samples became constant when weighed.

3 Results

3.1 Vertical distribution of root biomass under different irrigation amounts

As shown in Figs. 1–3, the vertical distribution of the root biomass of *H. ammodendron* seedlings presented the same tendencies under different irrigation amounts. The results showed that root biomass of *H. ammodendron* seedlings gradually decreased with soil layer depth. However, root biomass appeared to have a rising tendency with the decrease in irrigation amounts in the deepest soil layer. Correlation analysis between the depth of vertical sampling layer and the root biomass of each layer showed that a negative logarithm relationship existed under different irrigation amounts (Table 1). At 60–80 cm and at 80–100 cm depths, the biomass was 29.77 and 8.36 g in treatment 3, accounting for 21.41% and 6.01% of the total root biomass, respectively; at the same, in the same two layers of treatment 2, the biomass was 3.60 and 0.28 g, accounting for 3.10% and 0.24% of the total, respectively; while in the same two layers of treatment 1, the biomass was 5.54 and 0 g, accounting for 5.45% and 0% of the total, respectively. Analysis of variance showed that the underground biomass in treatment 3 was significantly higher than that in treatments 1 and 2 at the depths of 60–80 cm and 80–100 cm ($p < 0.05$, $df = 3$); whereas the underground biomass at the depth of 0–60 cm had no significant difference under each irrigation amount.

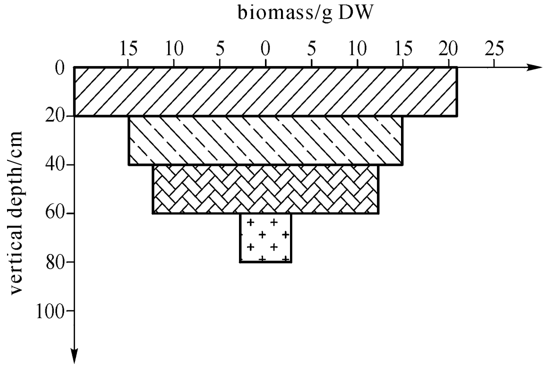

Fig. 1 Vertical distribution of underground biomass in each layer for treatment 1

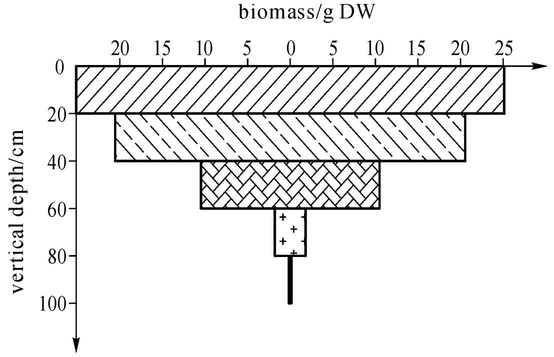

Fig. 2 Vertical distribution of underground biomass in each layer for treatment 2

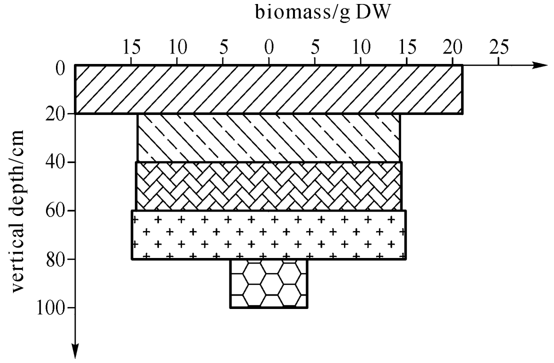

Fig. 3 Vertical distribution of underground biomass in each layer for treatment 3

3.2 Horizontal distribution of root biomass under different irrigation amounts

Root biomass of each section in the horizontal direction decreased gradually with increasing distance from plants under different irrigation amounts (Fig. 4). However, in the 60–90 cm section, the root biomass had little increase in each irrigation amount. The reason was that, although root density in the 60–90 cm section was slightly smaller than that of the 30–60 cm section, soil volume of the section was two times as large as that of the 30–60 cm section, which made root biomass increase in this section. A correlation analysis between each horizontal sampling section and root biomass in each section showed that there was no significant difference between the two factors under each

Table 1 Vertical distribution curve equation of underground biomass under different irrigation amounts (the relationships between depth and biomass of sampling layers)

treatments	fitting equation	determination coefficient
treatment 1	$Y = -25.94\ln X + 122.86$	$R^2 = 0.9112$
treatment 2	$Y = -33.61\ln X + 156.12$	$R^2 = 0.9280$
treatment 3	$Y = -16.65\ln X + 93.63$	$R^2 = 0.7116$

irrigation amount, and the data were −0.9607, −0.9670, −0.9602, respectively. The result of variance analysis showed that there was no significant difference at each horizontal section within the same irrigation amount; the total root biomass had no significant difference under each irrigation amount ($p < 0.05$, $df = 3$). Analysis from cumulative percentage of horizontal root biomass showed that the biomass in a circle with a radius of 90 cm accounted for almost 80% of the total biomass under each irrigation amount. However, maximum horizontal root spread had some differences among different irrigation amounts, 210 cm in treatment 3, 180 cm in treatments 1 and 2.

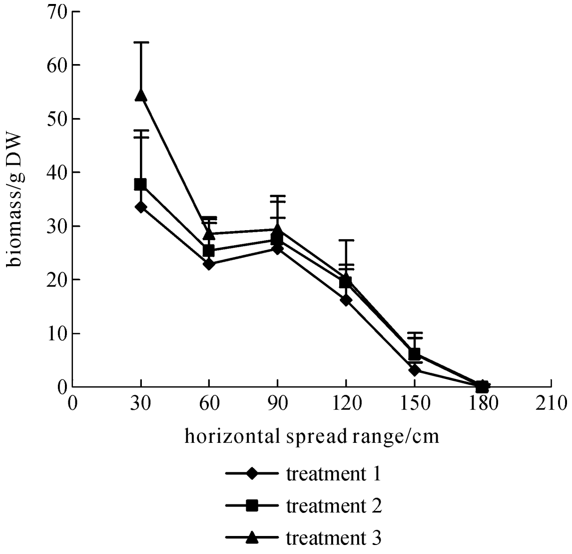

Fig. 4 Horizontal distribution of underground biomass under different irrigation amounts

3.3 Relationships between vertical distribution of fine roots (absorptive roots) and soil moisture under different irrigation amounts

In the root distribution range, though soil moisture showed a unimodal curve with soil depth (Figs. 5 and 6), it presented two peaks in treatment 3 (Fig. 7). Analysis of variance showed that soil moisture in treatment 3 was significantly lower than in treatments 1 and 2 ($p < 0.05$, $df = 3$), but there was no significant difference between treatment 1 and treatment 2 ($p < 0.05$, $df = 3$). We also examined the ANOVA of the soil moisture of the same layer under different irrigation amounts. The results showed that the top layer (0–20 cm) had no significant difference under each irrigation amount. It was perhaps because under the extremely arid conditions of the Taklimakan desert, soil humidity of the top layer was quite low due to strong evaporation, so there was no significant difference under each irrigation amount ($p < 0.05$, $df = 3$). In the meantime, at depths of 60–80 and 80–100 cm, the soil moisture also had no significant difference under each irrigation amount ($p < 0.05$, $df = 3$). It was probably because irrigation water could not reach these two layers and the soil moisture of the layers did not change significantly under the same site conditions. However, at 20–40 cm depth, the soil moisture of treatment 3 was significantly lower than that of treatment 1 ($p < 0.05$, $df = 3$), and at 40–60 cm depth the soil moisture of treatment 3 was also significantly lower than those of treatment 1 and treatment 2 ($p < 0.05$, $df = 3$).

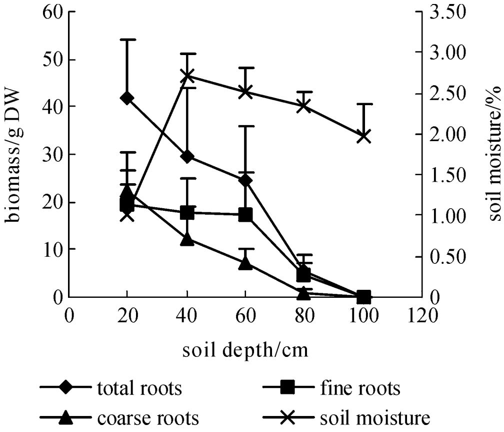

Fig. 5 Relationship between soil moisture and root distribution of treatment 1

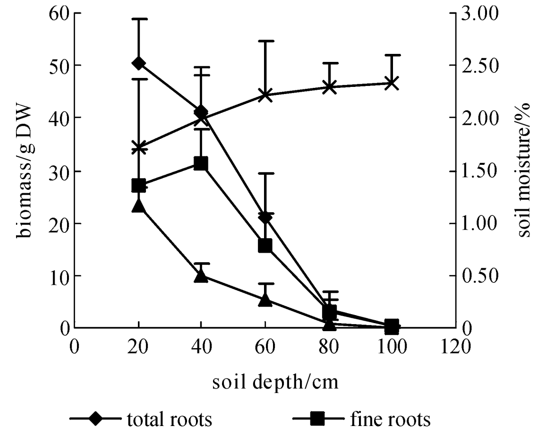

Fig. 6 Relationship between soil moisture and root distribution of treatment 2

The vertical distribution of fine roots was nearly consistent with vertical changes in soil moisture, and all had a unimodal curve, but in different soil layers the peak values of fine root biomass varied with different irrigation amounts. This is exemplified in treatment 1, where the peak value was 19.45 g at 0–20 cm depth; in treatment 2 the peak value was 31.26 g at 20–40 cm depth and in treatment 3 the peak value was 21.17 g at 60–80 cm. This result showed that fine roots tended to be concentrated in deeper soil

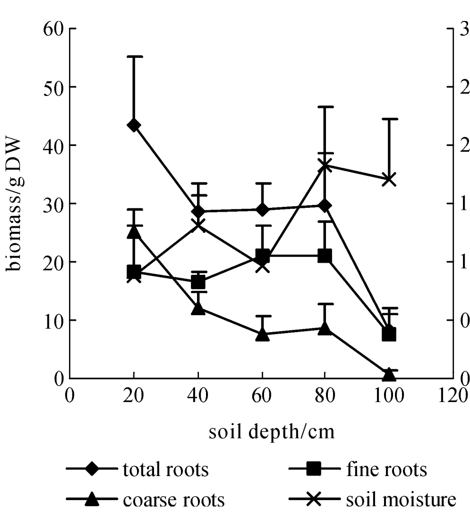

Fig. 7 Relationship between soil moisture and root distribution of treatment 3

layers in response to decreasing irrigation amount. However, the total root biomass and coarse root biomass decreased gradually with the increase in soil depth under different irrigation amounts.

3.4 Change of root volume, root length and root surface area under different irrigation amounts

As shown in Figs. 8–10, root volume, root length and root surface area of *H. ammodendron* seedlings all exhibited a unimodal curve in response to increasing soil depth under different irrigation amounts. However, their peak values were seen at different soil depths under different irrigation amounts. In treatment 1 the peak values of root volume and root surface area appeared at 20–40 cm depth, but the maximum root length presented at 0–20 cm; in treatment 2 the peak values of root volume, root surface area and root length all presented at 20–40 cm; whereas in treatment 3 the peak values of root volume, root length and root surface area all presented at 60–80 cm. At same time, the root volume, root length and root surface area in treatment 3 were all smaller than those in treatment 1 and treatment 2 at 0–60 cm; whereas the values in treatment 3 were all larger than in treatment 1 and treatment 2 at 60–100 cm (Figs. 8–10). The analysis of proportion of each index in each layer showed that the percentages of root volume, root length and root surface area in treatment 3 were 62.38%, 62.39%, and 61.17% at 0–60 cm, respectively, while those in treatment 1 were 92.51%, 90.50%, and 91.78%, and those in treatment 2 were 95.63%, 94.46%, and 95.31%, respectively. The ANOVA revealed that there was no significant difference at 0–60 cm among the different irrigation amounts ($p < 0.05$, $df = 3$); but at 60–100 cm, the root volume, root length and root surface area in treatment 3 were significantly larger than those in treatment 1 and treatment 2 ($p < 0.05$, $df = 3$).

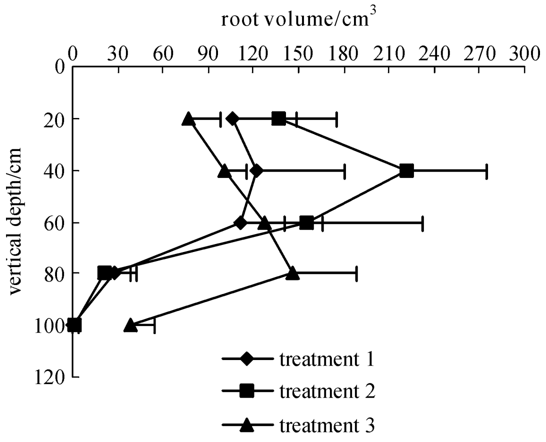

Fig. 8 Vertical distribution of root volume at different irrigation amounts

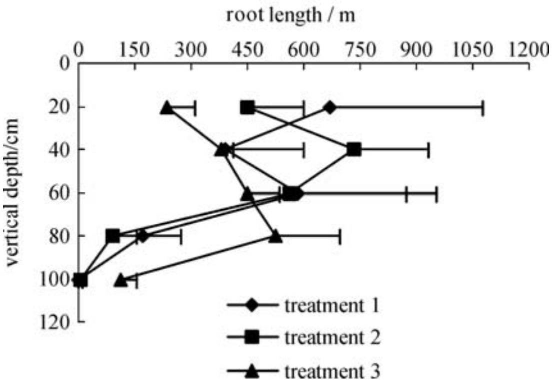

Fig. 9 Vertical distribution of root length at different irrigation amounts

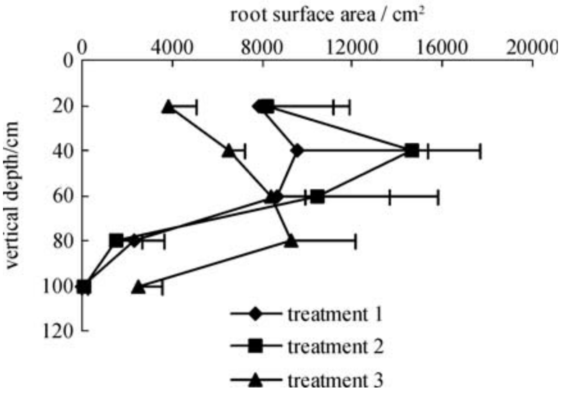

Fig. 10 Vertical distribution of root surface area at different irrigation amounts

3.5 Ratio of above/under ground growth indices and regressive prediction model of underground biomass

Root-shoot ratio and ratio of vertical root depth to plant height increased with the decrease in irrigation amounts; the ratios of root spread range to crown diameter of in

Table 2 Proportion between under- and aboveground growth indices under different irrigation amounts (mean ± *SE*)

treatment	root-shoot ratio	ratio of root depth to individual plant height	ratio of root spread range to crown diameter
treatment 1	0.88 ± 0.11	0.95 ± 0.16	12.70 ± 1.54
treatment 2	0.90 ± 0.12	1.06 ± 0.15	17.16 ± 3.41
treatment 3	0.92 ± 0.20	1.37 ± 0.12	14.85 ± 3.61

treatment 2 and treatment 3 were larger than that of treatment 1 (Table 2). Correlation analysis between the aboveground indices and underground biomass showed that underground biomass had an extremely significant correlation with aboveground biomass and basal stem diameter, and had a significant correlation with crown diameter. A stepwise regression of the aboveground growth indices showed that only the partial regression coefficient of stem diameter was significant ($p < 0.05$). The best regression prediction model underground was $y = 10.76x - 21.93$, $r = 0.806$, where y is the underground biomass and x is stem diameter.

4 Discussion

Studies on responses of plant morphogenesis to changes in ecological factors have recently become a focus of attention. In extremely arid environments, water is a dominant factor which restricts the development and growth of plants. Differences in soil moisture induce the variant morphological structures of plants, which not only appear as structural traits of the aboveground canopy, but also show in the morphological characteristics of their root systems.

4.1 Effect of different irrigation amounts on vertical distribution of root system

Under different irrigation amounts, vertical distribution of the root biomass of *H. ammodendron* seedlings decreased gradually with soil depth. This result agreed with the general rule of vertical distribution of plant root biomass and was consistent with other researches which focused on vertical distribution of plant roots (Bai, 1999; Zhang, 1999; Zhang et al., 1999; Wang et al., 2003; Li and Zhao, 2004; Li et al., 2005). However, nearly 86% of the root biomass of *H. ammodendron* seedlings was concentrated at the 0–60 cm soil depth under drip irrigation conditions, which indicated that the root tended to concentrate in the soil surface. This was caused by hydrotropism of roots in drip irrigation. There was a negative logarithmic relationship between the vertical sampling depth and the root biomass in the corresponding depth under different irrigation amounts, which was consistent with findings of Li et al. (2005) about *H. ammodendron* under various site conditions in the hinterlands of the Taklimakan Desert. ANOVA revealed that root biomass at 0–60 cm had no significant difference in the same layer under different irrigation amounts ($p < 0.05$, $df = 3$), but in the 60–100 cm layer the root biomass of treatment 3 was obviously larger than that of treatment 1 and treatment 2 ($p < 0.05$, $df = 3$). This result indicated that a sufficient irrigation amount satisfied the water requirement of the plants, and reduced the tendency of roots to grow toward deeper soil layers, which resulted in having the root biomass concentrated in the surface layer, and the root system occupying a relatively small space. On the contrary, when irrigation amount was insufficient, more roots spread toward the deeper soil layer and occupied a relatively larger space in order to obtain more water resources for growth. This was similar to *Sabina vulgaris*, which adapted to a water-deficit environment by increasing the depth of roots (He, 2000). There is intensive evaporation and rare precipitation in the hinterlands of the Taklimakan Desert. In order to offset soil moisture deficit, *H. ammodendron* seedlings have to keep their water balance by the downward growth of roots to absorb water in deep soil if the irrigation amount decreases.

4.2 Effect of different irrigation amounts on the horizontal distribution of the root system

Under different irrigation amounts, the horizontal distribution range of the root system (0–210 cm) of *H. ammodendron* seedlings was twice as large as the vertical distribution depth of the root system (0–100 cm), which indicated that the growth of horizontal roots developed very well under drip irrigation. This agreed with Ren et al. (2001), who found the same root distribution pattern in *Salix gordejevii* under artificial cultivation. The correlation coefficients between root biomass of every section and the corresponding horizontal distance under different irrigation amounts were close, that is to say, the horizontal distribution of the root systems of *H. ammodendron* seedlings had the same tendency under each irrigation amount. The horizontal roots of seedlings grew circuitously under drip irrigation, which was likely because water distributed near plants after irrigation, and root hydrotropism resulted in a circuitous growth. It was also similar to the root distribution of natural *H. ammodendron* in the Alasha region of Inner Mongolia where the soil moisture is controlled largely by rainfall (Shen et al., 2004).

4.3 Effect of different irrigation amounts on root length, root surface area and root volume of seedlings

Under the same irrigation amounts, vertical changes in root length, root surface area and root volume of the seedlings had the same tendency, whereas under different irrigation amounts the vertical changes of roots varied. However, all the vertical distributions presented a unimodal curve. This agreed with He (2000) who found that vertical distribution of *Sabina vulgaris* roots had shown a unimodal curve under different sandy sites, but it differed from Sun and Yu (1992) who found that vertical distribution of root volume, root length and root surface area decreased with soil depth in the Alasha region of Inner Mongolia. This was probably because in the extremely arid environment in the hinterlands of the Taklimakan Desert, the strong evaporation usually makes the surface layer (0–20 cm) quite dry even under drip irrigation conditions, and the amount of drip irrigation could not satisfy the water demand of roots. So there were a few roots distributed in this layer, and the vertical distribution of root volume, root length and root surface area all followed a unimodal curve. In the hinterlands of the Taklimakan Desert, the peak value distribution of root volume, root length and root surface area tended to appear in deeper layers when the irrigation amount reduced. Meanwhile, on the top layers (0–60 cm), the root volume, root length and root surface had no significant differences under each irrigation amount ($p < 0.05$, $df = 3$), but in deep layers (60–80 cm), the root volume, root length and root surface area of treatment 3 were obviously larger than those of treatment 1 and treatment 2.

4.4 Relationship between vertical change of soil moisture and fine root distribution

Roots can be divided into fine roots and coarse roots in view of their functions. For herbs and shrubs, roots with a diameter larger than 1 mm are considered as coarse roots, and their primary function is for water uptake and nutrient delivery; roots with diameters smaller than 1 mm are fine roots, and their main function is water transportation and nutrient absorption (Zhao et al., 1997). The sandy soil moisture of highway protection forests in the Tarim desert was mainly affected by the amount of drip irrigation, evaporation and root water uptake, but sandy land physical evaporation was obstructed due to the loose structure of the sandy land, the weak absorptive ability of soil capillary and a dry soil surface. The soil moisture of sandy land was thus mainly affected by water absorption of the protection forest under drip irrigation; because the relationship between the root system and soil moisture was determined by root hydrotropism and fine roots were the main organ of water absorption for plants, the sand soil moisture had a close relationship with the space distribution of fine roots. The vertical distribution of fine roots of *H. ammodendron* seedlings basically matched the change in sandy soil moisture under drip irrigation in the hinterlands of the Taklimakan Desert. This agreed with the findings of Alamusa et al. (2003) who found that the fine root distribution of *Caragana icrophylla* had a close relationship with soil moisture, both presenting a unimodal curve. The peak values of fine root biomass in different soil layers under different irrigation amounts showed a pattern wherein the lesser the irrigation amount there was, the deeper the peak value.

4.5 Effect of different irrigation amounts on root-shoot ratio

Root-shoot ratio is a comprehensive index of plants based on many internal changes and the process of self-adaptation and self-adjustment under the effect of environmental factors (Li et al., 1999). It is also a main index which reflects the relationship between the root system and the aboveground parts of plants. It is commonly regarded that desert plants have a larger and deeper root system which can absorb water and nutrients from soil for aboveground evaporation. In the present study, root-shoot ratio and the ratio of vertical root depth to plant height of *H. ammodendron* seedlings increased with the decrease in irrigation amounts in the hinterlands of the Taklimakan Desert. The results suggested that plants keep water balance to adapt to drought environments under light water stress by downward growth of roots or by increasing ramification to expand its available water resources.

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