

Spatial and temporal distribution of mung bean (*Vigna radiata*) and soybean (*Glycine max*) roots

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Abstract

Spatial and temporal distribution of roots of mung bean and soybean originated from different geographical backgrounds is an important scientific issue. The aim of this study was to research the spatial and temporal distribution of roots system of soybean cultivar 'Hefeng55' and mung bean cultivar 'Jily7' which can elucidate differences between soybean roots and mung bean roots in the key spatial and temporal locations. The roots at V6, R2, R4, R5, R6, and R7 stages were collected to acquire data of root length, root surface area, root volume and root dry weight. 49.8%, 11.7%, 13.2%, 14.7% and 10.6% of soybean roots and 57.8%, 10.7%, 11.2%, 11.9% and 8.4% of mung bean roots were in 0-5, 5-10, 10-15, 15-20 and 20-25 cm horizontal soil layers, respectively; 79.2%, 11.5%, 4.3%, 1.8%, 1.1%, 1.0% and 1.1% of soybean roots and 70.0%, 12.3%, 8.0%, 3.0%, 1.6%, 1.7% and 3.4% of mung bean roots were in 0-20, 20-40, 40-60, 60-80, 80-100, 100-120 and 120-140 cm vertical soil layers, respectively. Compared with mung bean, soybean had a much larger root system during development. In horizontal direction, soybean root tended to be more laterally developed, but the distribution of mung bean root was more uniform in vertical direction. With a greater root surface area to weight ratio (AWR), mung bean had a finer root system than soybean. These findings can help to clarify the four-dimensional spatial and temporal distribution characteristics of legumes and may provide reference for production practice of soybean and mung bean in the future.

Keywords: mung bean; root length; root surface area; root volume; root dry weight; soybean

Introduction

Roots are an important organ of plants (Fang, 2011) which determines the ability of plants to absorb water and nutrients (Vamerali *et al.*, 2003; Ehdaie *et al.*, 2010). Roots of different crops have different distribution characteristics (Lynch, 1995; Benjamin and Nielsen, 2006). Comparing the temporal and spatial distribution characteristics of different crops' roots is beneficial to research the root structure differences and the adaptability of root systems to the soil environment among different crops (Gan, 2009; Fan *et al.*, 2016).

The distribution characteristic of roots is the basic attribute during plant development (Atta *et al.*, 2013). Pulses tend to have larger root volumes; this may better facilitate moisture absorption and transport to

other plant parts (Eissenstat and Yanai, 2002; Waisel and Eshel, 2002). Liu *et al.* (2011) studied the distribution of pulses and found that surface area was mainly distributed in 0-60 cm soil layer. Benjamin and Nielsen (2006) reported 97% of the root dry weight of soybean and about 80% of the root dry weight of chickpea and field pea were in the surface 23 cm. Mitchell and Russell (1971) found that 90% or more of the root dry weight of soybean was concentrated in the upper 7.5 cm early in the season and in the upper 15 cm during the remainder of the season.

Both soybean and mung bean are leguminous crops, which originated from different geographical backgrounds. Various workers have studied the root distribution of soybean in the last few years (Calonego *et al.*, 2010; Farmaha *et al.*, 2012), but the difference between these two crops' root distribution at different time and space points is still unclear. In this study, we used innovative horizontal and vertical devices to study the root distribution of soybean and mung bean in 0-5, 5-10, 10-15, 15-20 and 20-25 cm horizontal soil layers and in 0-20, 20-40, 40-60, 60-80, 80-100, 100-120 and 120-140 cm vertical soil layers, respectively. We hypothesized that the root system of soybean and mung bean have different trends in temporal distribution and different pattern in spatial distribution. It can give a deeper understanding of the four-dimensional spatial and temporal distribution characteristics of legume roots and may provide reference for breeding new cultivars of soybean and mung bean in the future.

Materials and Methods

Experimental site

The experiment was carried out at outdoor test site in National Coarse Cereals Engineering Research Centre, Daqing, China on June 5, 2015 (soybean) and June 5, 2016 (mung bean). The annual precipitation at the experimental site was 508.7 mm, the average annual temperature was 5.60 °C, the effective accumulated temperature was 2900-3000 °C, and the sunshine duration was 1158 h (Collected from Daqing Weather Station).

Experimental devices

There were two kinds of devices: horizontal device and vertical device (Figure 1). The horizontal device was a cylindrical metal barrel with a diameter of 50 cm and a height of 50 cm, which was fixed with a cross steel frame with a length of 54 cm on both sides of the metal barrel. The inside of the metal barrel was equipped with a diameter of 10 cm, 20 cm, 30 cm and 40 cm of metal net. The distance between the metal net was 5 cm and the metal net were fixed on the cross-steel frame by nylon straps (Figure 2). The vertical device was a cylindrical plastic barrel with a diameter of 30 cm and a height of 150 cm (Figure 3). In order to facilitate sampling, inside the vertical device was a plastic water belt of 30 cm in diameter and the soil was filled in the plastic water belt (Figure 4). The lower end of the plastic water belt was sealed and four round holes were cut using scissors.

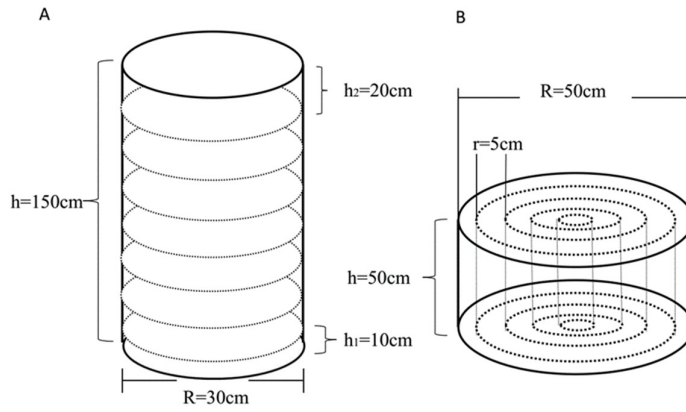


Figure 1. A: Vertical device, which was a cylindrical plastic barrel with a diameter of 30 cm and a height of 150 cm; B: Horizontal device, which was a cylindrical metal barrel with a diameter of 50 cm and a height of 50 cm.



Figure 2. Horizontal device entity



Figure 3. Vertical device entity



Figure 4. The plastic water belt of 30 cm in diameter inside the vertical device and the soil was filled in the plastic water belt

Soil characteristics

The soil was chernozem, with physical and chemical properties characterized by a pH of 7.8, effective phosphorus of 13.69 mg·kg⁻¹, alkali-hydrolyzed nitrogen of 134 mg·kg⁻¹, available potassium of 204 mg·kg⁻¹, and organic matter of 32.8 g·kg⁻¹. The soil was screened before pouring into the devices to remove grass root, tree root and large granular clods and stones. Then the soil was filled into the vertical device and horizontal device, respectively (1.15×102 kg·m⁻³ in density).

Experiment design, species and seeding

Soybean cultivar ‘Hefeng55’ and mung bean cultivar ‘Jilv7’ were planted at five seeds per barrel separately in 48 barrels which included 24 horizontal devices and 24 vertical devices. Two seedlings were retained, and grown with four replications per growth stage and type of device.

Root sample collection

Soil samples were collected from the devices at V6, R2, R4, R5, R6 and R7 stage (Pedersen *et al.*, 2004). In horizontal devices, the centre of the cross section of the column was taken as the starting point to obtain root samples in the horizontal direction i.e. 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm and 20-25 cm layers. In vertical devices, the upper soil surface was taken as the starting point to obtain soil samples with root in 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm, 100-120 cm and 120-140 cm soil layers in vertical direction. The plants were clipped at cotyledons by scissors before sampling. Soil samples containing root were soaked in a plastic bucket filled with water until the soil became soft and then filtered. The obtained root samples were washed with clean tap water and then placed in a plastic, sealable bag, and the bag was placed in a refrigerator for further use.

Data collection

The harvested root samples were placed in a clear glass tray filled with water. The roots were washed to remove soil particles and other dirt that could hamper efficient scanning of root samples. The glass tray was placed on a scanner (Epson V700) and digital images were generated at 400 dpi. Digital image analysis of root samples was conducted using WinRHIZO (version 2014a, Reagent Instruments Inc., Quebec, Canada) and the data included root length, root surface area and root volume, from which root length density (RLD), root surface area density (RSAD) and root volume density (RVD) were estimated as follows:

$$RLD = L/V_0$$

$$RSAD = S/V_0$$

$$RVD = V/V_0$$

$$V_0 = \pi r^2 h$$

where V is the root volume, L is root length, S is root surface area, V₀ is the soil volume, r is the radius, and h is the height.

After scanning, the roots were removed from glass tray and subsequently were placed in an oven at 105 °C for 2 hours, then drying to constant weight in 75 °C oven. The dry weight of roots was obtained by analytical balance and the root dry weight density (RDWD) was estimated as:

$$RDWD = M/V_0$$

$$V_0 = \pi r^2 h$$

where M is the root dry weight.

Statistical analysis

Differences between soybean and mung bean roots were determined by LSD test by SPSS 22. Figure preparation was carried out by MicroCal Origin software 2017 (Origin Lab).

Results

Temporal distribution of total root length

The growth stage needed to reach the maximum total root length for ‘Hefeng55’ was R5. The greatest total root length of ‘Jilv7’ were found at R4 in vertical devices and R5 in horizontal devices. In vertical devices, the total root length of ‘Jilv7’ were greater than ‘Hefeng55’ at V6 and R2, but ‘Hefeng55’ had significantly greater total root length than ‘Jilv7’ by 87.8%, 106.6% and 104.2% at R5, R6 and R7, respectively. In horizontal devices, ‘Hefeng55’ had greater total root length than ‘Jilv7’ from V6 to R2. Total root length of ‘Hefeng55’ were 59.4% and 75.1% significantly more than ‘Jilv7’ at R2 and R6, respectively (Figure 5).

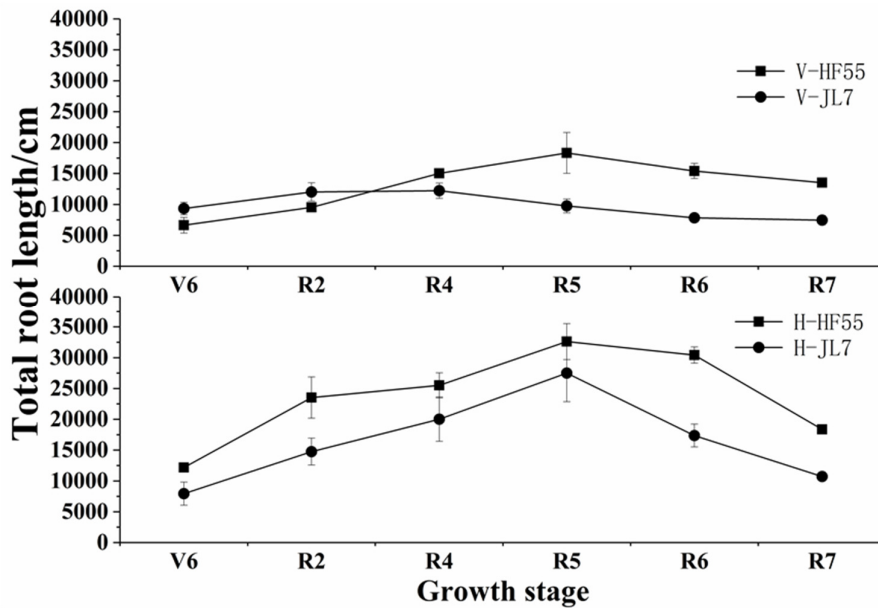


Figure 5. Changes of total root length of soybean and mung bean in vertical device and horizontal device at different growth stages (V-JL7 (mung bean cultivar ‘Jilv7’ in vertical device), V-HF55 (soybean cultivar ‘Hefeng55’ in vertical device), H-JL7 (mung bean cultivar ‘Jilv7’ in horizontal device), H-HF55 (soybean cultivar ‘Hefeng55’ in horizontal device)); Data represent average ± standard error. Significant at the 0.05 probability level

The spatial distribution of root length density

Root length density as estimated by horizontal device: In horizontal devices, the root length density of 'Hefeng55' in different soil layers at R2, R4 and R6 were greater than 'Jilv7', and 'Hefeng55' had significantly greater root length density than 'Jilv7' by 42.5% in 0-5 cm soil layer at R6. At V6, R5, and R7, 'Jilv7' had significantly greater root length density than 'Hefeng55' by 57.1%, 45.1% and 32.9% respectively in 0-5 cm soil layer. The percentage of root length in 0-5, 5-10, 10-15, 15-20 and 20-25 cm horizontal soil layers to total root length of 'Hefeng55' were 8.8%, 15.6%, 23.8%, 28.9% and 22.9%, respectively, and the percentage of root length in 0-5, 5-10, 10-15, 15-20 and 20-25 cm horizontal soil layers to total root length of 'Jilv7' were 13.6%, 16.8%, 21.7%, 27.4% and 20.5%, respectively (Table 1).

Root length density as estimated by vertical device: 'Hefeng55' and 'Jilv7' had the largest root length density in 0-20 cm soil layer in vertical devices. 'Hefeng55' had significantly greater root length density than 'Jilv7' in 0-20 cm soil layer at R5, R6 and R7 by 88.0%, 314.4% and 141.5% respectively. The root length density of 'Jilv7' was significantly greater than 'Hefeng55' by 75.9% in 0-20 cm soil layer at V6. At R2, 'Jilv7' had significantly greater root length density than 'Hefeng55' in 20-40 cm soil layer by 119.0%. At R5 and R7, total root length of 'Hefeng55' were 131.2% and 159.8% respectively significantly more than 'Jilv7' in 20-40 cm soil layer. At R6, total root length of 'Jilv7' was 46.1% significantly more than 'Hefeng55' in 40-60 cm soil layer. The percentage of root length in 0-20, 20-40, 40-60, 60-80, 80-100, 100-120 and 120-140 cm vertical soil layers to total root length of 'Hefeng55' were 56.8%, 23.2%, 8.6%, 4.3%, 2.5%, 2.1% and 2.5%, respectively, and the percentage of root length in 0-20, 20-40, 40-60, 60-80, 80-100, 100-120 and 120-140 cm vertical soil layers to total root length of 'Jilv7' were 51.2%, 22.9%, 13.7%, 5.0%, 2.2%, 2.8% and 2.2%, respectively (Table 2).

Table 1. Root length density ($\text{cm}\cdot\text{cm}^{-3}$) of soybean cultivar 'Hefeng55' and mung bean cultivar 'Jilv7' in different horizontal soil layers at V6, R2, R4, R5, R6 and R7 growth stages

Growth stages	Cultivars	Soil layers (cm)				
		0 - 5	5 - 10	10 - 15	15 - 20	20 - 25
V6	'Hefeng55'	0.296 ± 0.033a	0.121 ± 0.023a	0.115 ± 0.013a	0.124 ± 0.010a	0.111 ± 0.009a
	'Jilv7'	0.465 ± 0.080b	0.104 ± 0.019a	0.078 ± 0.015a	0.072 ± 0.036a	0.039 ± 0.022a
R2	'Hefeng55'	0.599 ± 0.083a	0.340 ± 0.041a	0.313 ± 0.077a	0.226 ± 0.040a	0.136 ± 0.015a
	'Jilv7'	0.463 ± 0.043a	0.258 ± 0.024a	0.231 ± 0.045a	0.118 ± 0.036a	0.060 ± 0.017a
R4	'Hefeng55'	0.615 ± 0.115a	0.319 ± 0.036a	0.317 ± 0.039a	0.270 ± 0.014a	0.161 ± 0.013a
	'Jilv7'	0.545 ± 0.142a	0.304 ± 0.092a	0.178 ± 0.026a	0.150 ± 0.037a	0.116 ± 0.024a
R5	'Hefeng55'	0.643 ± 0.027a	0.513 ± 0.021a	0.441 ± 0.052a	0.312 ± 0.041a	0.193 ± 0.033a
	'Jilv7'	0.933 ± 0.270b	0.398 ± 0.089a	0.293 ± 0.033a	0.315 ± 0.092a	0.168 ± 0.023a
R6	'Hefeng55'	0.724 ± 0.174a	0.356 ± 0.040a	0.350 ± 0.033a	0.353 ± 0.044a	0.193 ± 0.032a
	'Jilv7'	0.508 ± 0.023b	0.198 ± 0.031a	0.184 ± 0.028a	0.190 ± 0.021a	0.119 ± 0.020a
R7	'Hefeng55'	0.334 ± 0.061a	0.230 ± 0.047a	0.195 ± 0.024a	0.214 ± 0.015a	0.132 ± 0.017a
	'Jilv7'	0.444 ± 0.069b	0.124 ± 0.013a	0.109 ± 0.009a	0.118 ± 0.012a	0.061 ± 0.005a

Data represent average ± standard error. Distinct letters in the row indicate significant differences. Significant at the 0.05 probability level

Table 2. Root length density ($\text{cm}\cdot\text{cm}^{-3}$) of soybean cultivar 'Hefeng55' and mung bean cultivar 'Jilv7' in different vertical soil layers at V6, R2, R4, R5, R6 and R7 growth stages

Growth stages	Cultivars	Soil layers (cm)						
		0 - 20	20 - 40	40 - 60	60 - 80	80 - 100	100 - 120	120 - 140
V6	'Hefeng55'	0.270 ± 0.074a	0.098 ± 0.012a	0.040 ± 0.030a	0.035 ± 0.012a	0.016 ± 0.002	0.011 ± 0.006	0
	'Jilv7'	0.475 ± 0.047b	0.115 ± 0.046a	0.051 ± 0.028a	0.026 ± 0.014a	0	0	0
R2	'Hefeng55'	0.361 ± 0.057a	0.126 ± 0.009a	0.082 ± 0.006a	0.056 ± 0.015a	0.028 ± 0.006a	0.015 ± 0.004	0.006 ± 0.003
	'Jilv7'	0.392 ± 0.081a	0.276 ± 0.146b	0.154 ± 0.059a	0.026 ± 0.011a	0.003 ± 0.001a	0	0
R4	'Hefeng55'	0.730 ± 0.170a	0.270 ± 0.068a	0.116 ± 0.022a	0.058 ± 0.009a	0.034 ± 0.006a	0.031 ± 0.007a	0.053 ± 0.011
	'Jilv7'	0.593 ± 0.132a	0.167 ± 0.025a	0.085 ± 0.031a	0.016 ± 0.006a	0.004 ± 0.002a	4.68 × 10 ⁻⁴ ± 1.96 × 10 ⁻⁴ a	0
R5	'Hefeng55'	0.594 ± 0.063a	0.259 ± 0.047a	0.093 ± 0.023a	0.034 ± 0.007a	0.023 ± 0.002a	0.033 ± 0.009a	0.030 ± 0.004a
	'Jilv7'	0.316 ± 0.093b	0.112 ± 0.019b	0.074 ± 0.012a	0.059 ± 0.006a	0.049 ± 0.005a	0.058 ± 0.024a	0.022 ± 0.012a
R6	'Hefeng55'	0.750 ± 0.080a	0.226 ± 0.031a	0.041 ± 0.005a	0.019 ± 0.002a	0.011 ± 0.002a	0.013 ± 0.001a	0.022 ± 0.005a
	'Jilv7'	0.181 ± 0.007b	0.168 ± 0.040a	0.130 ± 0.003b	0.036 ± 0.010a	0.0118 ± 0.0002a	0.026 ± 0.014a	0.002 ± 7.68 × 10 ⁻⁶ a
R7	'Hefeng55'	0.442 ± 0.076a	0.304 ± 0.044a	0.106 ± 0.026a	0.037 ± 0.007a	0.026 ± 0.008a	0.016 ± 0.004a	0.026 ± 0.010a
	'Jilv7'	0.183 ± 0.031b	0.117 ± 0.016b	0.080 ± 0.011a	0.044 ± 0.012a	0.023 ± 0.010a	0.034 ± 0.025a	0.069 ± 0.037a

Data represent average ± standard error. Distinct letters in the row indicate significant differences. Significant at the 0.05 probability level.

Temporal distribution of total root surface area

The greatest total root surface area of 'Hefeng55' was found at R5. The greatest total root surface of 'Jilv7' were found at R2 in vertical devices and R5 in horizontal devices. In vertical devices, the total root surface of 'Hefeng55' were greater than 'Jilv7' except for V6, and 'Hefeng55' were 132.5%, 226.1%, 225.7% and 247.7% respectively significantly more than 'Jilv7' at R4, R5, R6 and R7. In horizontal devices, the total root surface of 'Hefeng55' were greater than 'Jilv7' during all growth stages. In addition to V6, 'Hefeng55' had significantly greater total root surface than 'Jilv7' by 93.9%, 104.7%, 90.6%, 145.5% and 141.8%, respectively (Figure 6).

The spatial distribution of root surface area density

Root surface area density as estimated by horizontal device: The greatest root surface area density of 'Hefeng55' and 'Jilv7' were found in 0-5 cm soil layers in horizontal devices. During all growth stages, the root surface area density of 'Hefeng55' in different soil layers were greater than 'Jilv7' except for the 0-5 cm soil layer at V6. 'Hefeng55' had significantly greater root surface area density than 'Jilv7' by 64.3%, 55.7%, and 81.1% respectively at R2, R4, and R6 in 0-5 cm soil layer. In addition, the root surface area density of 'Hefeng55' were respectively significantly greater than 'Jilv7' by 68.8%, 114.9%, 156.9%, and 157.6 in 5-10 cm soil layer at R2, R5, R6, and R7. Significant differences also were in 10-15 cm soil layer at R4, R5, R6 and R7 and root surface area density of 'Hefeng55' were 144.5%, 150.4%, 173.2%, and 161.8% respectively more than 'Jilv7'. In 15-20 cm soil layer at R6 and R7, 'Hefeng55' had significantly greater root surface area density than 'Jilv7' by 162.8% and 168.4% respectively. The percentage of root surface area in 0-5, 5-10, 10-15, 15-20 and 20-25 cm horizontal soil layers to total root surface area of 'Hefeng55' were 10.6%, 16.0%, 23.6%, 28.0% and 21.8%,

respectively, and the percentage of root surface area in 0-5, 5-10, 10-15, 15-20 and 20-25 cm horizontal soil layers to total root surface area of 'Jilv7' were 15.8%, 16.7%, 21.2%, 26.3% and 20.0%, respectively (Table 3).

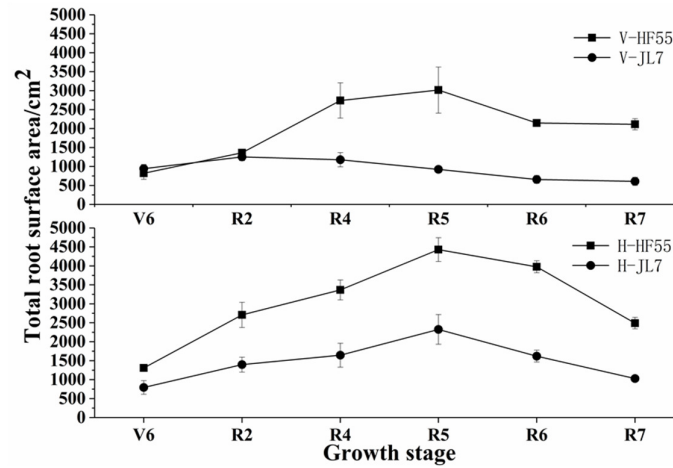


Figure 6. Changes of total root surface area of soybean and mung bean in vertical device and horizontal device at different growth stages V-JL7 (mung bean cultivar 'Jilv7' in vertical device), V-HF55 (soybean cultivar 'Hefeng55' in vertical device), H-JL7 (mung bean cultivar 'Jilv7' in horizontal device), H-HF55 (soybean cultivar 'Hefeng55' in horizontal device); Data represent average \pm standard error. Significant at the 0.05 probability level

Table 3. Root surface area density ($\text{cm}^2\text{-cm}^{-3}$) of soybean cultivar 'Hefeng55' and mung bean cultivar 'Jilv7' in different horizontal soil layers at V6, R2, R4, R5, R6 and R7 growth stages

Growth stages	Cultivars	Soil layers (cm)				
		0 - 5	5 - 10	10 - 15	15 - 20	20 - 25
V6	'Hefeng55'	42.24 \pm 4.82a	13.41 \pm 1.86a	12.72 \pm 1.11a	12.49 \pm 0.70a	11.10 \pm 1.01a
	'Jilv7'	49.98 \pm 7.63a	9.64 \pm 1.71a	7.57 \pm 1.35a	7.16 \pm 3.51a	3.93 \pm 2.11a
R2	'Hefeng55'	84.55 \pm 9.51a	39.93 \pm 4.63a	34.91 \pm 7.69a	24.62 \pm 3.82a	15.42 \pm 1.80a
	'Jilv7'	51.47 \pm 3.83b	23.65 \pm 1.52b	21.28 \pm 4.09a	10.96 \pm 3.45a	5.58 \pm 1.47a
R4	'Hefeng55'	94.06 \pm 13.73a	42.57 \pm 4.40a	40.57 \pm 4.61a	35.20 \pm 2.48a	20.75 \pm 1.89a
	'Jilv7'	60.41 \pm 12.41b	28.15 \pm 7.98a	16.59 \pm 2.29b	13.68 \pm 3.28a	10.61 \pm 2.10a
R5	'Hefeng55'	105.41 \pm 4.48a	71.27 \pm 3.95a	59.70 \pm 6.24a	41.79 \pm 4.68a	24.28 \pm 3.99a
	'Jilv7'	85.97 \pm 3.12a	33.16 \pm 7.47b	23.84 \pm 2.75b	26.26 \pm 7.16a	14.29 \pm 2.01a
R6	'Hefeng55'	107.87 \pm 19.43a	48.99 \pm 4.99a	45.80 \pm 3.97a	44.20 \pm 4.86a	24.44 \pm 4.53a
	'Jilv7'	59.57 \pm 3.35b	19.07 \pm 2.78b	16.76 \pm 2.41b	16.82 \pm 1.90b	10.49 \pm 1.71a
R7	'Hefeng55'	58.62 \pm 9.24a	32.77 \pm 7.20a	26.28 \pm 3.74a	27.78 \pm 1.35a	16.87 \pm 1.37a
	'Jilv7'	54.13 \pm 7.43a	12.72 \pm 0.93b	10.04 \pm 0.59b	10.35 \pm 0.84b	5.27 \pm 0.36a

Data represent average \pm standard error. Distinct letters in the row indicate significant differences. Significant at the 0.05 probability level

Root surface area density as estimated by vertical device: The greatest root surface density of 'Hefeng55' and 'Jilv7' were found in 0-20 cm soil layer. At R4, R5, R6, and R7, the root surface density of 'Hefeng55' were respectively significantly greater than 'Jilv7' by 126.1%, 217.3%, 273.3% and 456.7% in 0-20 cm soil layer. In 20-40 cm soil layer, the root surface density of 'Hefeng55' were 167.7%, 275.8%, 345.5% and 222.6% respectively significantly more than 'Jilv7' at R4, R5, R6 and R7. The percentage of root surface area in 0-20, 20-40, 40-60, 60-80, 80-100, 100-120 and 120-140 cm vertical soil layers to total root surface area of 'Hefeng55' were 53.9%, 22.6%, 8.3%, 8.6%, 2.3%, 2.0% and 2.3%, respectively, and the percentage of root surface area in 0-20, 20-40, 40-60, 60-80, 80-100, 100-120 and 120-140 cm vertical soil layers to total root surface area of 'Jilv7' were 55.7%, 19.3%, 13.7%, 4.8%, 2.1%, 2.7% and 1.7%, respectively (Table 4).

Table 4. Root surface area density ($\text{cm}^2\cdot\text{cm}^{-3}$) of soybean cultivar 'Hefeng55' and mung bean cultivar 'Jilv7' in different vertical soil layers at V6, R2, R4, R5, R6 and R7 growth stages

Growth stages	Cultivars	Soil layers (cm)						
		0 - 20	20 - 40	40 - 60	60 - 80	80 - 100	100 - 120	120 - 140
V6	'Hefeng55'	41.81 ± 1.88a	12.65 ± 2.03a	5.09 ± 0.35a	4.38 ± 1.35a	1.98 ± 0.26	0.72 ± 0.14	0
	'Jilv7'	47.79 ± 4.36a	11.53 ± 4.55a	5.29 ± 2.63a	2.13 ± 1.39a	0	0	0
R2	'Hefeng55'	52.98 ± 6.83a	16.81 ± 0.84a	11.97 ± 1.24a	7.70 ± 1.86a	3.91 ± 0.82a	2.22 ± 0.60	1.25 ± 0.44
	'Jilv7'	60.33 ± 11.79a	17.23 ± 2.47a	9.07 ± 3.29a	1.78 ± 0.62a	0.36 ± 0.18a	0	0
R4	'Hefeng55'	107.13 ± 21.61a	43.56 ± 10.14a	17.70 ± 2.85a	8.48 ± 0.99a	4.82 ± 0.62a	4.74 ± 0.79a	7.48 ± 1.31
	'Jilv7'	47.39 ± 5.16b	16.27 ± 3.97b	16.52 ± 5.42a	2.98 ± 1.04a	0.24 ± 0.20a	0.06 ± 0.03a	0
R5	'Hefeng55'	96.10 ± 12.24a	43.89 ± 7.64a	15.20 ± 3.89a	45.27 ± 9.86a	3.39 ± 0.26a	5.00 ± 1.23a	4.61 ± 0.71a
	'Jilv7'	30.29 ± 7.61b	11.68 ± 3.47b	9.00 ± 1.61a	5.65 ± 0.33a	4.73 ± 0.40a	5.67 ± 2.36a	2.26 ± 1.08a
R6	'Hefeng55'	70.86 ± 10.75a	48.51 ± 4.97a	16.40 ± 4.23a	5.82 ± 0.99a	3.85 ± 1.02a	2.42 ± 0.58a	4.15 ± 1.51a
	'Jilv7'	18.98 ± 2.68b	10.89 ± 1.70b	7.76 ± 1.19a	4.52 ± 1.08a	2.49 ± 0.96a	3.50 ± 2.40a	4.21 ± 3.97a
R7	'Hefeng55'	100.88 ± 9.25a	31.55 ± 4.31a	6.33 ± 0.77a	2.96 ± 0.40a	1.90 ± 0.28a	2.02 ± 0.14a	2.96 ± 0.67a
	'Jilv7'	18.12 ± 1.48b	9.78 ± 1.55b	7.09 ± 0.97a	2.13 ± 1.18a	0.77 ± 0.38a	1.50 ± 1.44a	0.16 ± 0.08a

Data represent average ± standard error. Distinct letters in the row indicate significant differences. Significant at the 0.05 probability level.

Temporal distribution of total root volume

During all growth stages, 'Hefeng55' had greater total root volume than 'Jilv7'. In vertical devices, 'Hefeng55' had significantly greater total root volume than 'Jilv7' by 224.4%, 472.8%, 444.4% and 374.1% at R4, R5, R6, and R7, respectively. In horizontal devices, 'Hefeng55' had significantly greater total root volume than 'Jilv7' by 151.0%, 184.1%, 215.3%, 224.1% and 200.6% at R2, R4, R5, R6 and R7, respectively. The greatest total root volume of Hefeng55 was found at R5, and the greatest total root volume of 'Jilv7' was at R4 in vertical devices and at R5 in horizontal devices (Figure 7).

The spatial distribution of root volume density

Root volume density as estimated by horizontal device: During all growth stages, 'Hefeng55' had greater root volume density than 'Jilv7' in different soil layer in horizontal devices. 'Hefeng55' had significantly greater root volume density than 'Jilv7' in 0-5 cm soil layer at V6 and 5-10 cm soil layer at R7 by 37.2% and 236.4%, respectively. In addition, at R2, R4, R5, and R6, the root volume density of 'Hefeng55' were significantly greater than that of 'Jilv7' in 0-5, 5-10, 10-15 and 15-20 cm soil layer. The percentage of root volume in 0-5, 5-10, 10-15, 15-20 and 20-25 cm horizontal soil layers to total root volume of 'Hefeng55' were 15.0%, 16.0%, 22.4%, 26.6% and 20.0%, respectively, and the percentage of root volume in 0-5, 5-10, 10-15, 15-20 and 20-25 cm horizontal soil layers to total root volume of 'Jilv7' were 22.4%, 15.9%, 19.6%, 23.9% and 18.2%, respectively (Table 5).

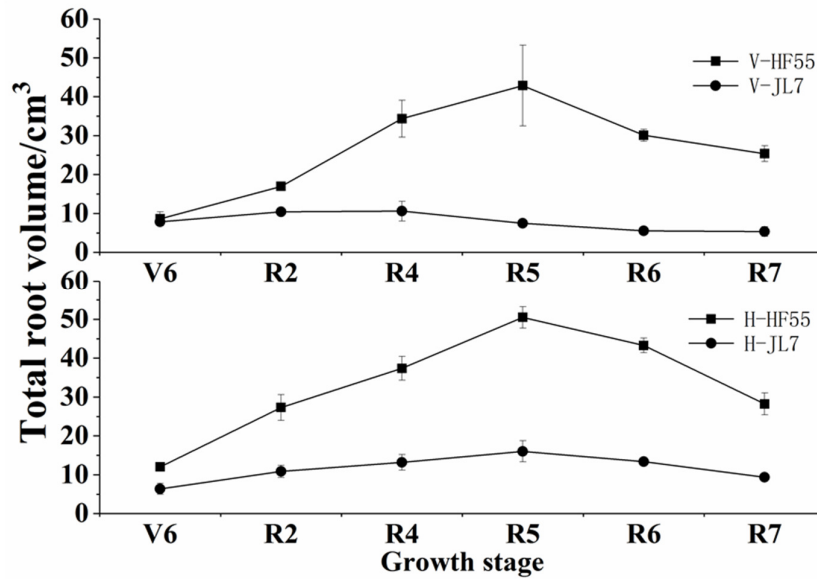


Figure 7. Changes of total root volume of soybean and mung bean in vertical device and horizontal device at different growth stages

V-JL7 (mung bean cultivar ‘Jilv7’ in vertical device), V-HF55 (soybean cultivar ‘Hefeng55’ in vertical device), H-JL7 (mung bean cultivar ‘Jilv7’ in horizontal device), H-HF55 (soybean cultivar ‘Hefeng55’ in horizontal device); Data represent average \pm standard error. Significant at the 0.05 probability level

Table 5. Root volume density ($\text{cm}^3\cdot\text{cm}^{-3}$) of soybean cultivar ‘Hefeng55’ and mung bean cultivar ‘Jilv7’ in different horizontal soil layers at V 6, R2, R4, R5, R6 and R7

Growth stages	Cultivars	Soil layers (cm)				
		0 - 5	5 - 10	10 - 15	15 - 20	20 - 25
V6	‘Hefeng55’	0.598 \pm 0.073a	0.121 \pm 0.011a	0.114 \pm 0.008a	0.102 \pm 0.006a	0.090 \pm 0.010a
	‘Jilv7’	0.436 \pm 0.057b	0.071 \pm 0.013a	0.059 \pm 0.010a	0.057 \pm 0.027a	0.031 \pm 0.016a
R2	‘Hefeng55’	1.145 \pm 0.098a	0.379 \pm 0.043a	0.313 \pm 0.061a	0.264 \pm 0.060a	0.140 \pm 0.017a
	‘Jilv7’	0.511 \pm 0.010b	0.175 \pm 0.014b	0.158 \pm 0.032b	0.082 \pm 0.027b	0.042 \pm 0.010a
R4	‘Hefeng55’	1.509 \pm 0.132a	0.463 \pm 0.046a	0.418 \pm 0.049a	0.369 \pm 0.035a	0.217 \pm 0.024a
	‘Jilv7’	0.704 \pm 0.083b	0.210 \pm 0.054b	0.125 \pm 0.016b	0.100 \pm 0.023b	0.078 \pm 0.015a
R5	‘Hefeng55’	1.756 \pm 0.090a	0.805 \pm 0.068a	0.652 \pm 0.063a	0.454 \pm 0.043a	0.250 \pm 0.040a
	‘Jilv7’	0.694 \pm 0.179b	0.222 \pm 0.050b	0.156 \pm 0.018b	0.176 \pm 0.045b	0.097 \pm 0.014a
R6	‘Hefeng55’	1.610 \pm 0.145a	0.544 \pm 0.050a	0.483 \pm 0.039a	0.446 \pm 0.043a	0.249 \pm 0.051a
	‘Jilv7’	0.819 \pm 0.075b	0.153 \pm 0.021b	0.124 \pm 0.017b	0.120 \pm 0.014b	0.074 \pm 0.012a
R7	‘Hefeng55’	0.994 \pm 0.166a	0.378 \pm 0.090a	0.285 \pm 0.046a	0.293 \pm 0.018a	0.176 \pm 0.013a
	‘Jilv7’	0.818 \pm 0.109a	0.112 \pm 0.008b	0.077 \pm 0.003a	0.074 \pm 0.006a	0.037 \pm 0.004a

Data represent average \pm standard error. Distinct letters in the row indicate significant differences. Significant at the 0.05 probability level

Root volume density as estimated by vertical device: In vertical devices, the root volume density of ‘Hefeng55’ was greater than that of ‘Jilv7’ in different soil layers during all growth stages except for the 0-20 cm soil layer at V6. They differed significantly in 0-20 cm soil layers at R2, R4, R5, R6 and R7, and in 20-40 cm soil layers at R4, R5, R6, and R7. The root volume density in 0-20 cm soil layers at R2, R4, R5, R6 and R7 of ‘Hefeng55’ were 41.6%, 194.6%, 429.2%, 528.3% and 564.5% significantly more than these of ‘Jilv7’, respectively. In 20-40 cm soil layers at R4, R5, R6, and R7, ‘Hefeng55’ had significantly greater root volume density than ‘Jilv7’ by 362.2%, 752.2%, 523.2% and 340.3%. The greatest proportion of root volume density of ‘Hefeng55’ and ‘Jilv7’ was found in 0-20 cm soil layer. The percentage of root volume in 0-20, 20-40, 40-60, 60-80, 80-100, 100-120 and 120-140 cm vertical soil layers to total root volume of ‘Hefeng55’ were 57.4%, 23.5%, 8.6%, 3.9%, 2.2%, 2.1% and 2.3%, respectively, and the percentage of root volume in 0-20, 20-40, 40-

60, 60-80, 80-100, 100-120 and 120-140 cm vertical soil layers to total root volume of 'Jilv7' were 57.8%, 18.6%, 12.9%, 4.6%, 2.1%, 2.5% and 1.5%, respectively (Table 6).

Table 6. Root volume density ($\text{cm}^3\cdot\text{cm}^{-3}$) of soybean cultivar 'Hefeng55' and mung bean cultivar 'Jilv7' in different vertical soil layers at V6, R2, R4, R5, R6 and R7 growth stages

Growth stages	Cultivars	Soil layers (cm)						
		0 - 20	20 - 40	40 - 60	60 - 80	80 - 100	100 - 120	120 - 140
V6	'Hefeng55'	0.344± 0.102a	0.132± 0.026a	0.054± 0.004a	0.044± 0.013a	0.020± 0.002	0.016± 0.008	0
	'Jilv7'	0.399± 0.038a	0.094± 0.037a	0.045± 0.020a	0.018± 0.011a	0	0	0
R2	'Hefeng55'	0.703± 0.064a	0.184± 0.006a	0.144± 0.021a	0.087± 0.018a	0.044± 0.009a	0.026± 0.007	0.015± 0.006
	'Jilv7'	0.497± 0.080b	0.142± 0.020a	0.077± 0.028a	0.016± 0.006a	0.006± 0.001a	0	0
R4	'Hefeng55'	1.382± 0.232a	0.598± 0.098a	0.205± 0.051a	0.070± 0.016a	0.041± 0.003a	0.063± 0.014a	0.056± 0.010
	'Jilv7'	0.454± 0.116b	0.123± 0.027b	0.142± 0.039a	0.028± 0.008a	0.010± 0.002a	0.005± 0.001a	0
R5	'Hefeng55'	1.338± 0.215a	0.568± 0.125a	0.222± 0.028a	0.102± 0.009a	0.057± 0.006a	0.059± 0.006a	0.085± 0.012a
	'Jilv7'	0.261± 0.043b	0.070± 0.012b	0.055± 0.006a	0.044± 0.001a	0.036± 0.003a	0.044± 0.019a	0.019± 0.008a
R6	'Hefeng55'	1.081± 0.124a	0.635± 0.067a	0.207± 0.057a	0.075± 0.013a	0.048± 0.011a	0.030± 0.007a	0.052± 0.020a
	'Jilv7'	0.172± 0.025b	0.121± 0.035b	0.061± 0.010a	0.037± 0.008a	0.021± 0.007a	0.029± 0.018a	0.031± 0.019a
R7	'Hefeng55'	1.220± 0.119a	0.358± 0.048a	0.080± 0.010a	0.038± 0.006a	0.026± 0.003a	0.026± 0.002a	0.033± 0.007a
	'Jilv7'	0.184± 0.014b	0.081± 0.014b	0.060± 0.009a	0.014± 0.008a	0.006± 0.003a	0.010± 0.006a	0.007± 0.001a

Data represent average \pm standard error. Distinct letters in the row indicate significant differences. Significant at the 0.05 probability level.

Temporal distribution of total root dry weight

The distribution of total root dry weight showed that 'Hefeng55' had significantly greater root dry weight than 'Jilv7' during all growth stages in horizontal devices, and total root dry weight of 'Hefeng55' were significantly greater than 'Jilv7' except for V6 in vertical devices (Figure 8).

The spatial distribution of root dry weight density

Root dry weight density as estimated by horizontal device: During all growth stages, the root dry weight density of 'Hefeng55' were significantly greater than 'Jilv7' in different layers in horizontal devices. The percentage of root dry weight in 0-5, 5-10, 10-15, 15-20 and 20-25 cm horizontal soil layers to total root dry weight of 'Hefeng55' were 49.8%, 11.7%, 13.2%, 14.7% and 10.6%, respectively, and the percentage of root dry weight in 0-5, 5-10, 10-15, 15-20 and 20-25 cm horizontal soil layers to total root dry weight of 'Jilv7' were 57.8%, 10.7%, 11.2%, 11.9% and 8.4%, respectively (Table 7).

Root dry weight density as estimated by vertical device: 'Hefeng55' had significantly greater root dry weight density than 'Jilv7' in 0-20 cm soil layer during all growth stages, in 20-40 cm soil layer at R2, R4, R5, R6, R7 and in 40-60 cm soil layer at R6. The percentage of root dry weight in 0-20, 20-40, 40-60, 60-80, 80-100, 100-120 and 120-140 cm vertical soil layers to total root dry weight of 'Hefeng55' were 79.2%, 11.5%, 4.3%, 1.8%, 1.1%, 1.0% and 1.1%, respectively, and the percentage of root dry weight in 0-20, 20-40, 40-60, 60-80, 80-100, 100-120 and 120-140 cm vertical soil layers to total root dry weight of 'Jilv7' were 70.0%, 12.3%, 8.0%, 3.0%, 1.6%, 1.7% and 3.4%, respectively (Table 8).

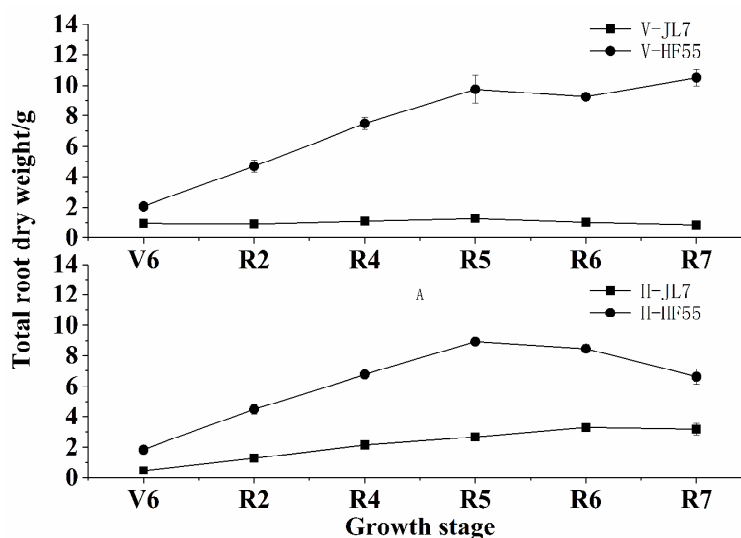


Figure 8. Changes of total root dry weight of soybean and mung bean in vertical device and horizontal device at different growth stages

V-JL7 (mung bean cultivar ‘Jilv7’ in vertical device), V-HF55 (soybean cultivar ‘Hefeng55’ in vertical device), H-JL7 (mung bean cultivar ‘Jilv7’ in horizontal device), H-HF55 (soybean cultivar ‘Hefeng55’ in horizontal device); Data represent average \pm standard error. Significant at the 0.05 probability level

Table 7. Root dry weight density ($\text{g} \cdot \text{m}^{-3}$) of soybean cultivar ‘Hefeng55’ and mung bean cultivar ‘Jilv7’ in different horizontal soil layers at V6, R2, R4, R5, R6 and R7 growth stages

Growth stages	Cultivars	Soil layers (cm)				
		0 - 5	5 - 10	10 - 15	15 - 20	20 - 25
V6	‘Hefeng55’	245.06 \pm 27.99a	15.19 \pm 1.17a	10.85 \pm 0.61a	9.53 \pm 0.74a	6.32 \pm 0.34a
	‘Jilv7’	77.67 \pm 10.99b	5.76 \pm 1.46b	2.53 \pm 0.59b	1.33 \pm 0.17b	0.50 \pm 0.10b
R2	‘Hefeng55’	636.82 \pm 31.53a	43.24 \pm 0.67a	28.99 \pm 4.14a	18.67 \pm 1.90a	11.43 \pm 1.29a
	‘Jilv7’	159.09 \pm 5.48b	12.74 \pm 1.40b	11.70 \pm 1.81b	6.28 \pm 1.00b	3.42 \pm 0.28b
R4	‘Hefeng55’	813.25 \pm 26.93a	70.03 \pm 5.98a	48.46 \pm 4.46a	38.59 \pm 1.02a	20.87 \pm 1.16a
	‘Jilv7’	309.31 \pm 2.91b	19.67 \pm 1.67b	11.99 \pm 1.33b	8.65 \pm 1.68b	6.22 \pm 1.08b
R5	‘Hefeng55’	1087.96 \pm 59.58a	99.99 \pm 5.56a	63.88 \pm 3.53a	47.39 \pm 4.54a	26.22 \pm 4.24a
	‘Jilv7’	359.25 \pm 32.01b	25.87 \pm 3.39b	14.89 \pm 0.76b	13.23 \pm 2.01b	7.80 \pm 0.91b
R6	‘Hefeng55’	1064.84 \pm 75.73a	77.76 \pm 7.77a	56.00 \pm 5.31a	48.32 \pm 2.87a	26.71 \pm 4.00a
	‘Jilv7’	506.16 \pm 30.21b	26.26 \pm 4.22b	17.56 \pm 1.77b	13.84 \pm 2.02b	7.41 \pm 1.56b
R7	‘Hefeng55’	856.87 \pm 75.52a	63.65 \pm 7.81a	41.51 \pm 4.94a	35.42 \pm 2.83a	20.28 \pm 1.08a
	‘Jilv7’	504.63 \pm 91.54b	28.13 \pm 2.72b	15.63 \pm 2.04b	12.99 \pm 1.82b	5.46 \pm 0.64b

Data represent average \pm standard error. Distinct letters in the row indicate significant differences. Significant at the 0.05 probability level.

Table 8. Root dry weight density ($\text{g} \cdot \text{m}^{-3}$) of soybean cultivar ‘Hefeng55’ and mung bean cultivar ‘Jilv7’ in different vertical soil layers at V6, R2, R4, R5, R6 and R7 growth stages

Growth stages	Cultivars	Soil layers (cm)						
		0 - 20	20 - 40	40 - 60	60 - 80	80 - 100	100 - 120	120 - 140
V6	‘Hefeng55’	121.58 ± 4.06a	13.12 ± 1.77a	5.18 ± 0.15a	3.25 ± 0.75a	1.46 ± 0.19	0.91 ± 0.50	0
	‘Jilv7’	52.04 ± 1.12b	8.98 ± 1.33a	4.68 ± 1.51a	1.26 ± 0.72a	0	0	0
R2	‘Hefeng55’	267.65 ± 20.36a	31.81 ± 5.95a	16.14 ± 2.35a	8.37 ± 0.98a	4.24 ± 1.02a	2.26 ± 0.84	1.83 ± 1.22
	‘Jilv7’	51.59 ± 1.05b	8.14 ± 0.73b	3.33 ± 0.52a	0.91 ± 0.33a	0.15 ± 0.08a	0	0
R4	‘Hefeng55’	409.74 ± 30.17a	58.98 ± 6.45a	26.89 ± 1.91a	13.03 ± 0.65a	7.76 ± 0.64a	6.12 ± 0.56a	7.18 ± 1.79
	‘Jilv7’	55.96 ± 5.08b	10.86 ± 1.36b	8.86 ± 1.64a	1.74 ± 0.62a	0.16 ± 0.03a	0.05 ± 0.01a	0
R5	‘Hefeng55’	544.01 ± 63.70a	82.47 ± 13.35a	28.52 ± 2.59a	10.08 ± 2.51a	6.98 ± 1.51a	9.67 ± 3.19a	8.95 ± 2.16a
	‘Jilv7’	60.41 ± 3.45b	9.11 ± 1.59b	6.60 ± 0.13a	4.56 ± 0.40a	3.56 ± 0.55a	3.81 ± 1.59a	1.27 ± 0.57a
R6	‘Hefeng55’	511.85 ± 18.36a	82.74 ± 5.11a	28.67 ± 7.34a	11.75 ± 1.81a	8.23 ± 2.17a	5.36 ± 1.08a	6.78 ± 1.11a
	‘Jilv7’	46.98 ± 2.64b	8.92 ± 1.41b	5.50 ± 0.60b	2.90 ± 1.04a	2.14 ± 0.71a	2.36 ± 1.20a	3.49 ± 1.30a
R7	‘Hefeng55’	598.09 ± 32.76a	87.89 ± 7.38a	27.42 ± 8.70a	8.83 ± 1.31a	5.90 ± 0.34a	5.81 ± 0.66a	10.17 ± 2.76a
	‘Jilv7’	40.84 ± 1.72b	8.20 ± 1.13b	6.09 ± 0.01a	1.85 ± 0.91a	1.17 ± 0.15a	1.63 ± 0.90a	1.42 ± 0.34a

Data represent average ± standard error. Distinct letters in the row indicate significant differences. Significant at the 0.05 probability level

Root surface area to root weight ratio

In horizontal devices, ‘Jilv7’ had greater root surface area to root weight ratio (AWR) except for R7, and a significantly greater AWR of Jilv7 was found at V6 than ‘Hefeng55’. In vertical devices, ‘Jilv7’ had significantly greater AWR than ‘Hefeng55’ during all growth stages (Figure 9).

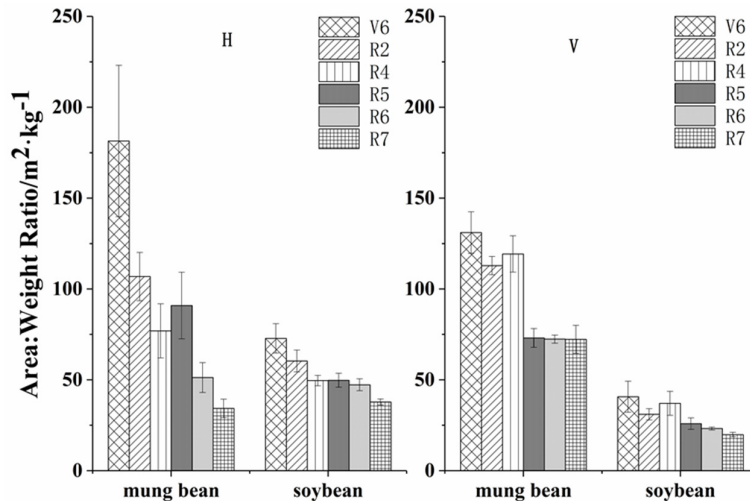


Figure 9. Root surface area to root weight ratio for soybean and mung bean roots in vertical devices and horizontal devices at different growth stages

V: the vertical device; H: the horizontal device; Data represent average ± standard error. Significant at the 0.05 probability level

Discussion

In this research, the variation and trend of horizontal distribution of total root length of soybean and mung bean were identical during all growth stages, but soybean had greater total root length than mung bean. In horizontal direction, both soybean and mung bean had the largest proportion of root length in 15-20 cm soil layer followed by 10-15, 20-25 and 5-10 cm soil layers, and the minimum proportion of root length was found in 0-5 cm soil layer. Root length of soybean in vertical 0-20 cm and 20-40 cm soil layers reached 56.8% and 23.2% of the total root length, respectively, which were higher than 51.2% and 22.9% of mung bean in the same soil layer. This is similar to the finding of Gao *et al.* (2010). However, both the ratio of root length to total root length of mung bean in vertical 40-60 and 60-80 cm soil were greater than those of soybean. In soil layers below 80 cm in vertical direction, the root length percentages of soybean and mung bean were similar. The root length of soybean and mung bean were mainly concentrated in 0-40 cm vertical soil layer, and root length of mung bean was more evenly distributed in the vertical direction compared with soybean.

The root length density of the crop could be used to reflect extension and distribution of crop root (Adiku *et al.*, 2001; Zhu, 2010; Liu *et al.*, 2011). With the deepening of the soil layer, root length density of soybean and mung bean decreased gradually. One possible explanation for this phenomenon is that mechanical impedance limited the extension of the root system (Logsdon *et al.*, 1987).

The distribution of crop root volume is critical to growth, development and yield formation of crop (Rao and Ito, 1998). The trend of total root volume of mung bean was more stable than that of soybean, but the total root volume of soybean was greater than that of mung bean during all growth stages. Spatial distribution of root showed that the root volume of mung bean was more concentrated in 0-5 cm horizontal soil layer compared with soybean, but soybean root volume tended to develop laterally. Both soybean (26.6%) and mung bean (23.9%) had the largest proportion of root volume in horizontal 15-20 cm soil layer. The ratio of root volume to total root volume in horizontal 0-5 cm soil layer of mung bean was greater than that of soybean, but the proportion of soybean in other horizontal soil layers were greater than those of mung bean. In vertical direction, soybean and mung bean were similar in root volume percentage in 0-20 cm vertical soil layer, and both of them had the greatest proportion in this layer. This is similar to the finding of Gan (2011). The root volume percentage of soybean in vertical 20-40 cm soil layer was higher than that of mung bean, but in the subsequent 40-80 cm vertical soil layer, mung bean had a larger root volume percentage compared with soybean. This showed that the difference of root volume distribution between soybean and mung bean was mainly concentrated in the upper middle soil layers in vertical direction. Compared with mung bean, soybean had a larger proportion of root volume in the upper soil layer, while proportion of mung bean root volume was higher than that of soybean in the middle soil layer.

In horizontal spatial distribution, the root surface area of soybean and mung bean were mainly distributed in the soil layer of 10-25 cm. Compared with soybean, mung bean had a larger percentage of root surface area in horizontal 0-10 cm soil layer. In vertical direction, soybean and mung bean had a similar distribution of root surface area in the upper, middle and lower layers. For root dry weight distribution, the dry root weight of soybean (49.8%) and mung bean (57.8%) were mainly distributed in 0-5 cm horizontal soil layer, and both dry weight of soybean and mung bean in vertical 0-20 cm soil layer reached more than 70% of the total dry weight, more than 82% of total root dry weight in vertical 0-40 cm soil layer. This is similar to the finding of Mitchell and Russell (1971) who found the highest proportion of root dry weight density in vertical 0.23 m soil layer.

A low AWR indicates either a thicker root system or roots with higher specific density (Benjamin and Nielsen, 2006). Mung bean had greater AWR than soybean during all growth stages. This showed mung bean had a finer root system or roots with lower specific density. From V6 to R7, soybean and mung bean AWR decreased indicating a thickening or densification of the root material.

In horizontal devices, we found that the maximum of total root length, total root surface area, and total root volume of soybean and mung bean were at R5. However, in vertical device, the maximum of total root

length, total root surface area, and total root volume of soybean were at R5. But for mung bean, the maximum of total root length and total root volume were found at R4 and the maximum total root surface was at R2. The reason may be that limiting the extension of roots in horizontal direction accelerated the aging process of mung bean roots, but soybean roots showed stronger adaptability than mung bean.

Conclusions

Compared with mung bean, soybean had a much larger root system during development; In horizontal direction, root system was mainly concentrated in the 0-5 cm soil layer, but soybean root tended to be more laterally developed compared with mung bean. In vertical direction, the distribution of mung bean root was more uniform than that of soybean; With a greater AWR, mung bean had a finer root system than soybean.

Authors' Contribution

HZ: Collection of samples, data collection and analysis, article writing; DZ and NF: Guidance on methods. All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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