

ROOT DISTRIBUTION VARIATION OF CROPS UNDER WALNUT-BASED INTERCROPPING SYSTEMS IN THE LOESS PLATEAU OF CHINA

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Efficient managing practices require an understanding of the root distribution of crop in walnut (*Juglans regia*)-crop intercropping systems, a field study was conducted in the Loess Plateau of China to examine the vertical distribution and horizontal variation of roots for soybean (*Glycine max*) and peanut (*Arachis hypogaea*) grown with walnut trees. Crop roots were sampled to 60 cm depth at five distances from the tree row using stratified digging method. The results showed that 72.7% of total root length density (RLD) for intercropped soybean distributed in the 0-10 cm soil layer and sole soybean roots in the first soil layer were determined to 54.3% of total RLD. The RLD of intercropped peanut primarily located in the 0-10 cm soil layer, reaching the average of 52.8 cm dm⁻³ for the five distances from the tree row. While the maximum RLD of 62.1 cm dm⁻³ for sole peanut was achieved in the 10-20 cm soil layer. The RLDs of both intercropped soybean and peanut increased with distance from the tree row, but the corresponding values at 1-1.5 m and 1.5-2 m from the tree row were significantly less than those at other distances. In addition, although the depths of root vertical barycenter (RVB) for both intercropped soybean and peanut tend to move downward with distance from the tree row, they were always shallower than sole soybean and peanut. Greater proximity to the tree row reduced crop roots and, furthermore, compelled crop roots to highly concentrate in the upper soil layer (0-10 cm), especially within the range of 1-2 m from the tree row.

Keywords: soybean, peanut, stratified digging method, root length density, root vertical barycenter, spatial distribution variation

INTRODUCTION

Crop cultivation is the traditional model of agricultural land use and the main source of income to farmers in the Loess Plateau of China, but it was limited badly by the water resources shortage and the unsound management (Zhu and Zhu, 2003). These directly resulted in farmers to replace the crops on their farmland with economic tree because it offers higher benefits than other farming practices and has stronger drought resistance and high adaptability to fragmented terrace ridge (Bi *et al.*, 2011; Yu *et al.*, 1979). But economic tree plantation is naturally long-term investments and may take several years until it generate a consumable output (Caviglia-Harris *et al.*, 2003), so agricultural crop was cultivated in alleyways between tree rows during the early years of tree production to provide the short-term profitability for the farming systems. And this practice also will buffer the effect of food insecurity in the region (Adisa and Balogun, 2013). During the intercropping period, if the income of intercrops is less than the investment, such intercropping will result in failure of the farming systems and not be adopted by farmers.

A drawback to combining tree with crop, however, is that tree roots extended to the crop alley where the tree and crop may compete for resources, in particularly where the

availability of resources are limited (Jose *et al.*, 2006; van Noordwijk *et al.*, 1996). The competition between tree and crop resulted in the reduction of crop roots and changed the root distribution of when exploitation of a resource by the tree (Neykova *et al.*, 2011; Zhang *et al.*, 2013), thus limiting growth and productivity of crop due to the suppression of the ability in resources acquirement (Yun *et al.*, 2012). Smith *et al.* (1999) found that the dominant root system of Silkoak (*Grevillea robusta*) tree and the high density of their roots at the top of the profile resulted in that maize (*Zea mays*) roots exhibited growth suppression in the upper region of the soil profile because of the low water availability. Livesley *et al.* (2000) also identified that maize root length decreased with greater proximity to the tree row, and potentially decreasing crop's ability to compete for soil resources. Those studies indicated that crop roots in spatial distribution had high plasticity to adapt to the competition and maximize access to soil resources in agroforestry systems (Lose *et al.*, 2003). However, Meng *et al.* (2002) found that the amount of crop roots was less in zones influenced by trees but there is no significant difference for vertical and temporal distribution of crop roots between the intercropping and the monoculture. Schroth and Zech (1995) even observed *Gliricidia sepium* hedgerows can improve

crop roots development through the favourable effect of mulch.

Knowledge of the rooting pattern of crop is necessary for better understanding the mechanisms of interspecific competition between tree and crop to take rational management and optimize structure configuration (Ong and Leakey, 1999; Schenk, 2006). Although many competitive vectors about crop roots in intercropping systems have been identified, the competitive effects of the tree on crop roots was inadequately quantified, specifically in quantity and spatial distribution variation of intercrop roots compared to sole crop. With that background, soybean (*Glycine max*) and peanut (*Arachis hypogaea*) under walnut (*Juglans regia*)-based intercropping systems were selected in this study because they are major cash crops in the Loess Plateau of China. Our study was carried out to analyze and quantify spatial distribution variation of intercrops roots and to test the hypothesis that crop roots were adversely affected by the competition from trees.

MATERIALS AND METHODS

Experimental site: The experimental site located in Jixian County (35°53'-36°21' N, 110°27'-111°07' E), Shanxi Province, China. Jixian County is a typical fragmented and gully area in the Loess Plateau. Climate in this area is of temperate continental monsoon nature with four distinct seasons, rainfall and heat in the same period, adequate illumination. The average annual precipitation is 571 mm and unevenly distribute throughout the year. The average annual temperature and the average annual accumulative temperature above 10°C is 9.9°C and 3357.9°C, respectively. The daylight hours are 2563.8 hr., and frost free period is 172 d. During the growing season from April to October, it has the accumulative temperature above 10°C of 3050°C, with daylight hours of 1498 hr., and rainfall is

521 mm accounting for more than 90% of the total annual precipitation. The soil is loess parent material, thick soil layer with uniform properties. The bulk density, organic C, total N, available P and available K, pH, cation exchange capacity, and Ca of the 0-100 cm soil layer is 1.32 g cm⁻³, 12.3 g kg⁻¹, 0.79 g kg⁻¹, 19.2 mg kg⁻¹ and 225.7 mg kg⁻¹, 7.92, 18.43 cmol kg⁻¹, 9.2 mg kg⁻¹ respectively. The major species of economic tree planted for agroforestry are walnut, apple (*Malus pumila*), apricot (*Prunus armeniaca*). The major crop species cultivated in agroforestry systems are soybean, peanut, maize. Since no irrigation practiced in the experimental area in the experimental area, the tree and crop mostly depend on the rainfall received.

Plant materials: The experiment was conducted in a provincial demonstration zone of walnut-crop intercropping systems in August 2011. Walnut trees were planted at a spacing of 7.0 m×7.0 m in 2006. The average tree crown width and tree height was 2.1 m and 4.1 m respectively in August 2011. Intercropped soybean and peanut were cultivated at a spacing of 0.45 m×0.15 m and 100 cm away from the tree row. Sole soybean and peanut were also cultivated at a spacing of 0.45 m×0.15 m.

Experimental design and procedure: The area within a distance of 1.0 m to 3.5 m from the tree row was used as experimental area in the walnut-crop intercropping systems. In this area, we designed a plot (2.5 m in length perpendicular to the tree row, 0.5 m in width parallel to the tree row) with two replications, and we divided each plot into five equal size sections (parallel to the tree row) according to the distance from the tree row, which were denoted as 1-1.5 m, 1.5-2 m, 2-2.5 m, 2.5-3 m and 3-3.5 m from the tree row respectively (Fig. 1). Three sections (0.5 m in length and 0.5 m in width) were randomly selected as contrast in soybean and peanut monoculture systems respectively. Soybean and peanut roots were excavated and collected hierarchically in vertical soil profile at four depth

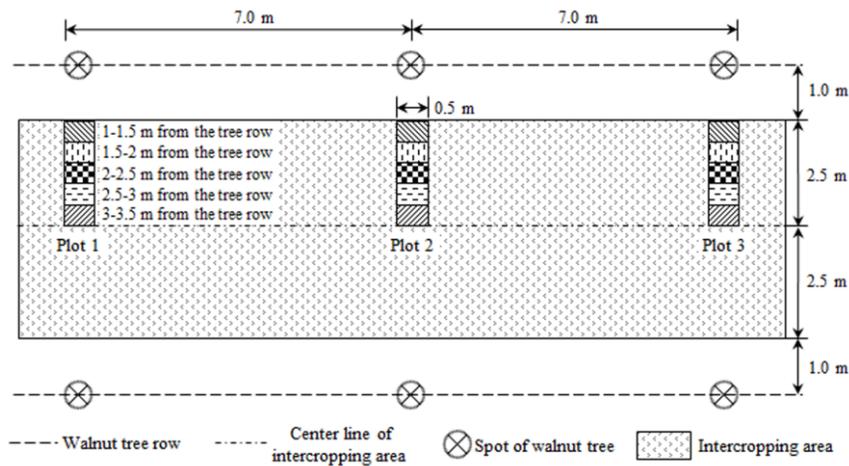


Figure 1. Location of sampling plots and sections in walnut-crop intercropping systems.

intervals of 0-10 cm, 10-20 cm, 20-40 cm and 40-60 cm in both intercropping and monoculture systems. This work was conducted based on Forestry Standards “Observation Methodology for Long-term Forest Ecosystem Research” of People’s Republic of China (LY/T 1952-2011).

Root processing and measurement: Root samples were individually collected and put into mesh bags (0.28 mm pores). After being soaked in water for 24 hours, samples were washed with tap water to remove soil particles adhering to the roots. Dead roots with dark color, or partly decomposed and brittle were removed with charcoal and other extraneous materials. Cleaned root samples were placed in 100 ml of 30% (v/v) methanol solution for storage at 4°C.

Data were expressed as root length density (RLD, cm dm⁻³). We identified root length of soybean and peanut root samples by WinRHIZO (Regent Instruments, Inc., Quebec, Canada) image analysis system, then the RLD was calculated as the ratio of the root length (L , cm) to the sample volume (V , dm³) (Merrill and Upchurch, 1994) and the formula was:

$$\text{RLD} = \frac{L}{V} \quad [1]$$

Calculations for root spatial distribution variation: Varignon’s theorem can be used for solving barycenter measuring in biomechanics for heterogeneous object (See Zatsiorsky *et al.* [2000] for a detail description). Since crop root system in whole vertical soil profile is heterogeneous and it can be regarded as homogeneous in each soil layer, the theorem was also applied to quantify vertical barycenter of crop roots to explore their spatial distribution variation (Wang *et al.*, 2011; Xu *et al.*, 2013). The root vertical barycenter (RVB, cm) in each sampling section was calculated as follows:

$$\text{RVB} = \sum_{i=1}^n D_i P_i \quad [2]$$

where i ($i \leq 5$) represents soil layer, D_i is the depth of the middle of i th soil layer and P_i is the proportion that the RLD of i th soil layer accounted for the total RLD in 0-60 cm soil layer.

Data analysis: Analysis of variance (ANOVA) test was performed using SPSS 20.0 (IBM Inc., Armonk, USA). Two-way ANOVAs were applied to assess differences of the RLD at different distances and depths for soybean and peanut, and the significance of their mean values ($n=3$) were compared by the least significant difference (LSD). We examined differences of the RVB at different distances from the tree row using two-way ANOVAs for soybean and peanut. Paired-samples T tests were conducted on RLD of crops to test the distribution difference between soil layers. Statistical results were showed with error bars and significance level (P), and differences at the $P \leq 0.05$ were considered statistically significant.

RESULTS

Vertical distribution of root length density: The vertical distribution of RLD for both intercropped soybean and sole soybean significantly declined ($P < 0.05$) with decreasing soil depth (Table 1). Moreover, the RLD of intercropped soybean concentrated in the surface soil layer (0-10 cm), where it accounted for 72.7% (the mean value at the five distances from the tree row) of total RLD in 0-60 cm soil layer. The RLD of intercropped soybean in the 10-20 cm soil layer was significantly 67.6% less than that in the surface soil layer ($P < 0.05$). However, only 4.4% of total RLD distributed in the subsoil (20–60 cm depth) for intercropped soybean. For sole soybean, the RLD in the 0-10 cm soil layer (RLD was 141.1 cm dm⁻³) accounted for 54.3% of total RLD and was greater than that for intercropped soybean. Meanwhile, the RLD difference between the first two soil layers for sole soybean was still significant ($P < 0.05$) although it was lower than intercropped soybean. In addition, 9.0% of total RLD located in the 20-60 cm soil layer for sole soybean, which was also higher than intercropped soybean.

Similarly, the RLD of intercropped peanut decreased significantly as soil depth declined ($P < 0.05$) (Table 1). And 62.2% of total RLD distributed in the surface layer (0-10 cm), which was 49.3% higher than that in the second soil layer. Only 6.6% of total RLD existed in the 20-60 cm soil layer for intercropped peanut, which was similar to intercropped soybean. Unlike those in intercropping system, the RLD of sole peanut increased with decreasing soil depth above 20 cm and achieved the maximum of 62.1 cm dm⁻³ in the 10-20 cm soil layer. However, still 15.4% of total RLD existed in the 20-60 cm soil layer for sole peanut, which was significantly greater than that for intercropped peanut ($P < 0.05$).

Horizontal distribution of root length density: The cumulative RLD (0-60 cm depth) for soybean and peanut significantly increased ($P < 0.05$) from 125.3 cm dm⁻³ and 56.5 cm dm⁻³ at 1-1.5 from the tree row to 122.3 cm dm⁻³ and 237.3 cm dm⁻³ at 3-3.5 from the tree row respectively (Table 1). However, the multiple comparisons analyses showed that no significant difference was found between 1-1.5 m and 1.5-2 m from the tree row ($P > 0.05$), while they had significant differences with the 2-2.5 m, 2.5-3 m and 3-3.5 m from the tree row respectively ($P < 0.05$). It’s worth noting that the RLDs at all distances from the tree row were lower than those at the contrast.

Spatial distribution variation of crop roots: The variation of RVB could reflect the combined differences in both horizontal and vertical distances. Significant increases ($P < 0.05$) with increasing distance from the tree row for the depths of the RVB were observed for intercropped soybean and peanut (Fig. 2), which indicated that the amount of roots in subsoil grew with the distance from the tree row. The

Table 1. Spatial distribution of root length density (cm dm⁻³) for crop in walnut-crop intercropping systems and crop monocropping systems

Planting types	Distances (m)	Soil depth (cm)				
		0-10	10-20	20-40	40-60	Total
Intercropped soybean	1-1.5	99.7±10.5 Aa	20.7±2.8 Ab	4.3±0.7 Ac	0.7±0.2 Ad	125.3±15.2 A
	1.5-2	105.2±10.7 Aa	22.1±3.2 Ab	4.6±0.3 Ac	1.0±0.2 Ad	132.9±14.4 A
	2-2.5	132.2±11.5 Ba	45.3±5.4 Bb	6.3±0.3 Bc	1.7±0.1 Bd	185.5±17.4 B
	2.5-3	149.6±13.4 Ca	58.7±5.0 Cb	7.7±0.9 Bc	2.1±0.2 Bc	218.1±19.6 C
	3-3.5	153.7±14.7 Ca	71.6±7.6 Db	8.4±1.3 Bc	3.7±0.2 Cc	237.3±23.8 C
	Average	128.1±12.2	43.7±5.0	6.3±0.7	1.8±0.2	179.8±18.1
Intercropped peanut	1-1.5	37.9±01.7 Aa	16.0±1.3 Ab	1.9±0.3 Ac	0.7±0.0 Ad	56.5±03.4 A
	1.5-2	40.1±02.2 Aa	16.5±1.3 Ab	2.4±0.2 Ac	1.1±0.1 Ac	60.1±03.8 A
	2-2.5	53.7±03.5 Ba	27.1±2.3 Bb	4.0±0.4 Bc	2.7±0.3 Bc	87.6±06.5 B
	2.5-3	62.4±04.9 Ca	36.9±1.7 Cb	4.7±0.5 Bc	3.0±0.4 Bc	106.9±07.5 B
	3-3.5	70.0±06.8 Da	42.6±3.4 Cb	5.8±0.7 Bc	3.9±0.5 Bc	122.3±11.5 B
	Average	52.8±03.8	27.8±2.0	3.8±0.4	2.3±0.3	86.7±06.6
Sole soybean		141.1±13.6 a	95.5±9.2 b	17.0±2.9 c	6.3±0.3 d	259.9±26.0
Sole peanut		51.6±50.7 a	62.1±6.4 a	14.0±1.7 b	6.6±0.9 c	134.3±14.7
Meaningful Orthogonal Contrasts						
Intercropped soybean vs. sole soybean		NS	*	*	*	*
Intercropped peanut vs. sole peanut		NS	*	*	NS	*

Values are means±SD; Means sharing similar letter in a row or in a column are statistically non-significant ($P>0.05$); Small letters represent comparison among soil layers and capital letters are used for distances from the tree row. * represents Significant, NS represents Non-significant.

depths of the RVB at 1.-1.5 m and 1.5-2 m from the tree row were significantly shallower than those at other distances from the tree row ($P<0.05$), which was similar to the horizontal variation of the RLD. In contrast, intercropped soybean and peanut had significantly lower ($P<0.05$) depths of the RVB than sole soybean and peanut, respectively.

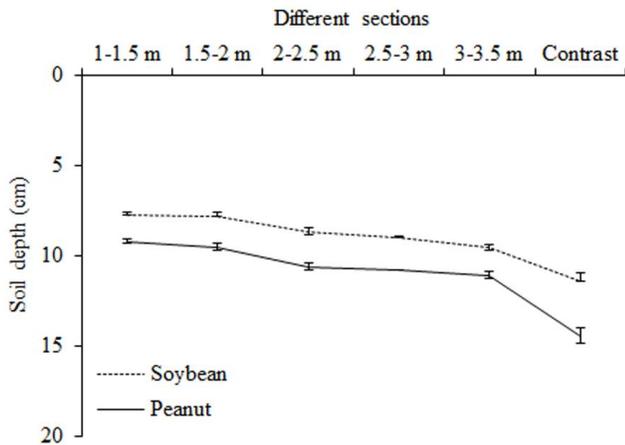


Figure 2. The depths of root vertical barycenter for soybean and peanut at five distances from the tree row in walnut-crop intercropping systems and crop monoculture systems. Bars represent standard deviations.

DISCUSSION

By means of layer-wise comparison, soybean and peanut grown with walnut trees all had intense coverage in soil depth of the uppermost 10 cm compared to sole soybean and peanut. Furthermore, the shallower root distribution for crop in intercropping systems may have experienced above- and below-ground competition because the canopy and root system of walnut developed simultaneously with that of the crop (Livesley *et al.*, 2005; Moreno *et al.*, 2005), which will directly lead to the decrease of crop yields (Yun *et al.*, 2012; Gao *et al.*, 2013). Meanwhile, the rapid decline of RLD and the shallower depth of RVB in vertical profile are indicative of more asymmetrical vertical distribution of intercrops roots. These results indicate that crop roots can plastically change their vertical distribution in response to spatial heterogeneous soil moisture and nutrient when concurrent growth occurs with other competitive root systems (Mou *et al.*, 1997; Farooq *et al.*, 2009). However, the relatively low fraction of RLD in the subsoil for intercrops implies their incapacity to grow into deep soil, which is of no avail to exploit more soil moisture and nutrient for sustainable growth of crops.

The roots of both intercropped soybean and peanut tended to thrive with distance from the tree row, which potentially increased their competitive uptake advantage for soil moisture and nutrient (Eastham and Rose, 1990) and also

was a positive response to the weaker competition from walnut trees (Yun, 2011). The RLDs and the depths of the RVB for soybean and peanut at five distances from the tree row all showed an obvious boundary between significant area (1-2 m from the tree row) and not significant area (2-3.5 m from the tree row). This phenomena illustrated that the interspecific competition effect of walnut trees on these crops was intense within the canopy edge than those beyond, which can be explained by the genetic characteristics of the walnut tree because the majority of its roots located within 1 times the canopy radius (Ma *et al.*, 2009; Xu *et al.*, 2013). However, the RLDs of intercrops were still less than those of sole crops and the depths of the RVB for intercrops concentrated in shallower soil layer compared to sole crops, since the influence area of walnut roots could spread horizontally to 4 m (Liu, 2004).

Agroforestry management practices aim to optimize the interspecific structure and improve the productivity in agroforestry systems. The key issue of agroforestry management is how to minimize interspecific competitions (Thevathasan and Gordon, 2004). Crop species and walnut trees coexist an entirely growing season of crop from April to September when they will be grown together in the Loess Plateau of China. So agronomic measures should be adopted to regulate the competition and promote the growth of crop (Ahmed *et al.*, 2013). The average RLD at five distance from the tree row for intercropped soybean was 30.8% lower than that for sole peanut. And the value of intercropped peanut reached to 35.4%. This difference between soybean and peanut showed that soybean roots had stronger adaptability than peanut in competitive situations under walnut-based intercropping systems. Therefore, soybean was suggested to be farmer's first choice for cultivated into the alleyways between walnut tree rows in this area. Expanding the spacing between tree rows and setting root barrier for trees are also rational methods to reduce the negative influence of trees on crop roots (Jose *et al.*, 2004; von Kiparski and Gillespie, 2008). According to the root distribution pattern of intercrops in our study, it was suggested to plant the crop in the area beyond the range of 2.0 m from the tree row or set root barrier (e.g. digging furrow along with tree row on both sides) at the 2.0 m from the tree row to avoid intercrop suffering from underground resources competition and light restrain resulted from walnut trees. In addition, more fertilizer should be applied in surface soil layer (0-10 cm) for the updated intercropping systems to ensure maximum contact of the fertilizer with crop roots and reduce the negative effect of walnut trees competing for nutrient. In a way, these agronomic measures could improve productivity and returns of the intercropping systems, and ultimately promote the high efficiency and sustainable utilization of natural resources.

Conclusions: Under the walnut-based intercropping systems, intercropped soybean and peanut had relatively lower RLD at all distances from the tree row than sole soybean and peanut respectively. This provides direct evidence for the hypothesis that the presence of walnut trees repaired the intercrop roots in the intercropping systems. The roots of intercropped soybean trended to have more shallow distribution in the soil profile than sole soybean. And the maximum RLD of intercropped peanut existed in the 0-10 cm soil layer whereas the vertical concentration area of the roots for sole peanut was in 10-20 cm depth. Additionally, the RVBs for intercropped soybean and peanut were all apt to move downward to deep soil as distance from tree row increased. All of those indicate that the competition from walnut trees reshaped the spatial distribution of crop roots in the intercropping systems, i.e., that tree forced crop roots to concentrate in the shallower soil layer. But this phenomenon would be relieved as the distance from the tree row increased. Further research is needed to determine the dynamic processes of interspecies interactions in tree-crop intercropping systems with crop of different growth stages and tree of different ages.

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