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Agroforestry Drives Root Plasticity and Increases Water Productivity for Roots in North China

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Abstract:

In tree-based agroforestry systems, plant would express trait plasticity to adapt the highly environmental heterogeneity and vary resource acquisition strategies. This poses a challenge for revealing the underlying relation between roots and soil water in agroforestry. Fieldwork was conducted in a 5 year old apple (*Malus pumila*) orchard in North China, including the apple-soybean (*Glycine max*) agroforestry, apple monoculture and sole soybean, to determine root distribution and water utilization. Root biomass density of apple and soybean were lower than those of monocultures, with averagely decrease of 39.7 g m^{-3} for apple and 185.0 g m^{-3} for soybean. The intercrop row adjacent to the tree row showed lower root biomass density than intercrop rows further away from the tree row, but apple trees represented an opposing distribution. Mean rooting depth of different components in agroforestry also showed an opposite growth trend in vertical soil profile. Introducing soybean into apple orchard obviously affected soil water compared to the sole stand, but water productivity for roots in agroforestry was higher than that in monocultures. Water equivalent ratio for root production was 1.33 when the partial water equivalent ratios were declined significantly 0.13 of soybean and slightly 0.04 of apple in agroforestry. The root biomass density expressed a significantly negative influence on soil moisture in the apple-soybean agroforestry and apple monoculture. In general, the competition and complementarity between apple and soybean with strong root plasticity can promote water utilization of root production in agroforestry.

Keywords*: Interspecific competition, Root distribution, Niche separate, Soil moisture, Water productivity.*

I. INTRODUCTION

Orchard is a traditional agricultural land use and important income source for farmers around the world, but it const rains the short-term benefits before the trees bear fruit. Thus, it is necessary to develop innovative agricultural systems to achieve more sustainable both economically and environmentally [1]. Realistically, there are very few conventional agricultural options that meet these imperatives [2]. Tree-crop agroforestry systems, however, are elegantly suited to do so. Apple (*Malus pumila*) shows strong climate adaptability, which motivated apple to become one of most productive economic tree species in China. Against the severe imbalance of input-output at the early stage of apple orchard, farmers generally growing crops, particularly like legumes, into the apple rows to access benefits [3]. The intercrop generated a greater system productivity and effective resource exploitation than the monoculture orchard.

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Consequently, introducing walnut trees into cropland systems has been widely promoted in China.

Crops may compete with trees for soil water when introducing crops into orchard and spreading into root zone of the trees [4]. As a result of the competition, tree roots exhibited morphological plasticity to acquire necessary soil resources and support the growth and productivity [5]. Agroforestry system produced more roots than monocultures to exploit more water [6]. But the agroforestry system generally decreased tree roots, especially in the upper soil layer [7]. In addition, intercrops produced lower root biomass in all soil depths than in crop monoculture, and this root plasticity of the tree and crop degraded with increasing distance from the trees [8].

Meanwhile, the combined root system also caused a greater heterogeneity of soil resources compared to the monocultures [9]. Soil water content in 0-80 cm soil layer of agroforestry systems were much lower than that of sole trees, indicated that the intercrop acquired shallow soil moisture that was not exploited by the tree, and increased above 30% of water use efficiency [10]. Greater root system was associated with soil resources, accompanied with high investment to plant roots, specific root length had the opposite variation [11]. Agroforestry reshaped the root traits and soil water distribution for plant production, but comparatively little information is available about the relationship between soil resources and plant roots.

Filling this gap would assist in understanding the interspecific competition between trees and crop in agroforestry systems. To reveal mechanisms underlying water moisture distribution and utilization based on root plasticity in agroforestry, here we study the intensive apple-soybean (*Glycine max*) agroforestry as a case study in North China. Specifically, the objectives of this study to (1) quantify tree root distribution in apple-soybean agroforestry; (2) evaluated soil water effect and water utilization in relation to root interaction between apple trees and soybean.

II. MATERIALS AND METHODS

2.1 Trial site and experimental design

The trial site was in Cangxian County (38.23 N, 116.76 E), Hebei Province, where has the typical soil type in the North China Plain. The annual mean air temperature is 12.5°C and the accumulative temperature is 4785°C. The average frost-free period is 181 days, and sunshine hours are 2483 hours. The annual precipitation is 581 mm and occurred in June to August. The soil in this site is classified as loam soil with a pH of 7.98, a bulk density of 1.35 g cm^{-3}, a SOM of 12.23 g kg^{-1}, a total N content of 0.13 g kg^{-1}, a total P content of 0.28 g kg^{-1}, and a total K content of 9.5 g kg^{-1}.

The experiment was conducted at a family farm of apple-crops agroforestry systems from August 2018. Three cropping systems were compared: apple monoculture, sole soybean, apple-soybean agroforestry. Apple trees were cultivated in 2013 with a spacing of 5 m between rows and a planting spacing of 4 m. The rows were oriented north-south. The average tree crown and height was 2.2 m and 4.3 m in August 2018, respectively. Soybean was intercropped at 0.5 m distance, with 1 m interspecific distance between the soybean and apple trees. Row distance and sown density in the crop monoculture were the same as in the

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agroforestry system.

2.2 Root biomass

The 1.0-2.5 m zone away the apple trees was used to experimental intercropping area in agroforestry system. Roots and soil water were sampled for both apple trees and soybean in this area. Soil samples of 20 cm × 20 cm in 0-100 cm soil profile were excavated at the 1.0 m, 1.5 m, 2.0 m and 2.5 m distance from the tree row. Every soil sample was split into five layers by 20 cm increment in the vertical profile. The mixed samples of soil and roots were separately collected into bags of 16 mesh and washed with tap water to obtain the pure roots. The fine roots of apple trees and soybean roots were manually picked out. Root biomass density was calculated for each soil volume. To quantify morphological variation of roots, mean rooting depth was determined by weighted mean of root biomass per strata for each plot at different distance.

2.3 Soil moisture content

The samples of soil water were taken in each section (including intercropping and monoculture) down to 100 cm soil profile by 20 cm increment. The soil moisture content which represented soil water was determined gravimetrically. To quantify the difference of agroforestry and monocultures, the soil water effect in each crop row in intercropping area of agroforestry was calculated by the equation: $E = [(M-M_{mono}) / M_{mono}] \times 100$. The E was soil water effect, M was average soil water content of agroforestry in 0-100 cm, M_{mono} was average soil water content of monoculture in 0-100 cm.

Water utilization (WU) in 0-100 soil profile during the soybean growth was determined by the water balance method by Bai et al. [10]. Water use efficiency (WUE) was evaluated as the ratio between the root biomass density and WU. Water equivalent ratio (WER) was applied to express the WUE of root production in agroforestry [12].

2.4 Statistical analysis

Two-way ANOVAs of root biomass density, mean rooting depth, soil effect, and one-way ANOVAs of WU, WUE were analyzed by the software of SPSS 25.0 (IBM, USA). 5% level was applied to evaluate statistical differences among treatments.

III. CONCLUSION

3.1 Root horizontal distribution

Root biomass density of apple along the horizontal distance away from the trees were significantly decreased in monoculture and agroforestry (Fig 1, P<0.05). The root biomass density of intercropped apple was 405.44 g m^{-3} at the nearest intercrop row, 263.19 g m^{-3} at the 1.5 m distance, 167.68 g m^{-3} at the 2.0 m distance and 97.60 g m^{-3} 90.2% at the 2.5 m distance. But not significant differences did occur in between agroforestry and apple monoculture (P>0.05). The root production ratio of intercropped apple compared

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with sole apple ranged from 86.7% at the 1.0 m distance, 82.8% at the 1.5 m distance, 84.4% at the 2.0 m distance and 90.2% at the 2.5 m distance.

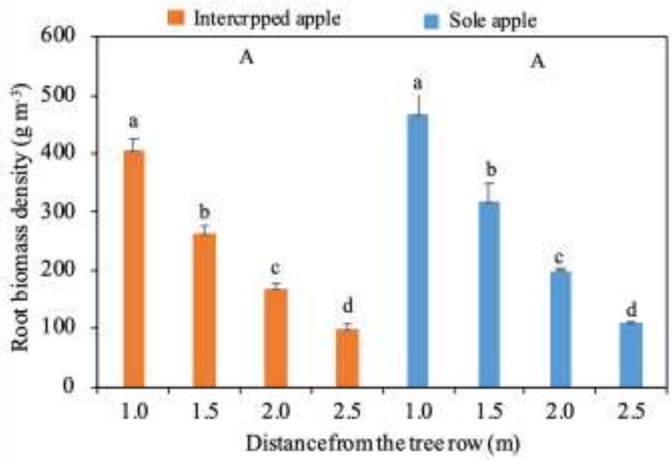

Fig 1: Root biomass density of apple in agroforestry and monoculture

Apple trees significantly decreased the root biomass density of soybean in agroforestry (Fig 2, $P<0.05$). Root biomass density at the 1.0 m distance was 82.3% lower than in soybean monoculture. Root biomass density in the middle row of intercropped soybean was also 14.0% lower than the sole soybean. The sole soybean grown averagely greater 50.1% of root biomass density than the intercropped soybean.

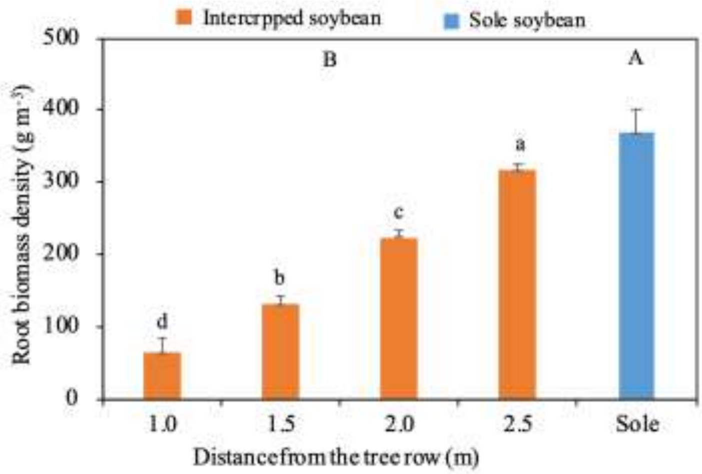

Fig 2: Root biomass density of soybean in agroforestry and monoculture

3.2 Mean rooting depth

No difference in apple mean rooting depth were observed between the 1.0 m and 1.5 m distance, nor between the 2.0 m and 2.5 m distance in both agroforestry and monoculture (Fig 3, $P>0.05$). The greatest mean rooting depth of apple trees was observed at the 1.0 m in both agroforestry and monoculture. The sole apple trees showed greater mean rooting depth at all distance compared with the intercropped apple. The apple associated with soybean declined averagely 1.7 cm of mean rooting depth across the distance.

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Specially, the shifting-down of intercropped apple was 5.9% at the 1.0 m distance, 6.7% at the 1.5 m distance, 5.3% at the 2.0 m distance and 4.4% at the 2.5 m distance, compared to the depth at the 1.0 m distance.

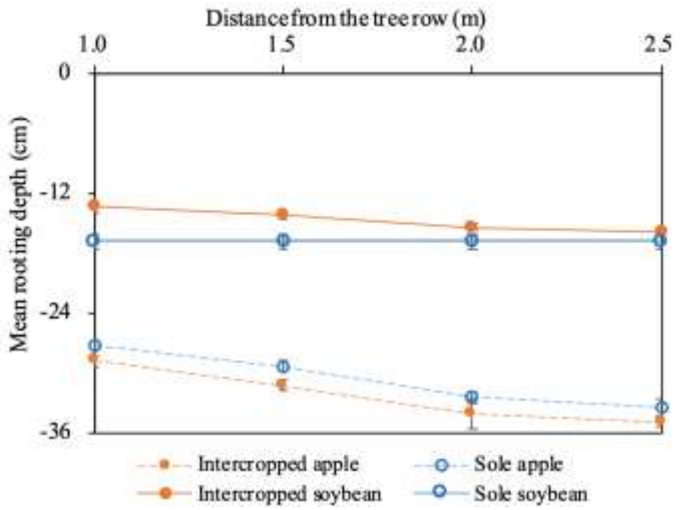

Fig 3: Mean rooting depth of apple and soybean in agroforestry and monocultures

3.3 Soil water effect

Soil water effect in the intercropping area showed a averagely 7.4 negative effect of soybean on apple orchard (soybean effect), averagely 7.6 negative effect of apple trees (apple effect) on soybean monoculture (Fig 4). The mean soil water effect did not differ between the the soybean effect and apple effect (*P*>0.05). The effect of agroforestry on soil water was significantly lower of 7.2 at the 1.5 m, 11.7 at the 2.0 m and 9.3 at the 2.5 m in the agroforestry when compared to the apple monoculture (*P*<0.05). In addition, No differences in soil water effect of apple trees were found between the 1.5 m and 2.0 m away from the tree row (*P*>0.05). Simarially, Neither did the agroforestry system have an effect on soil water at the 1.0 m distance compared with the soybean monoculture.

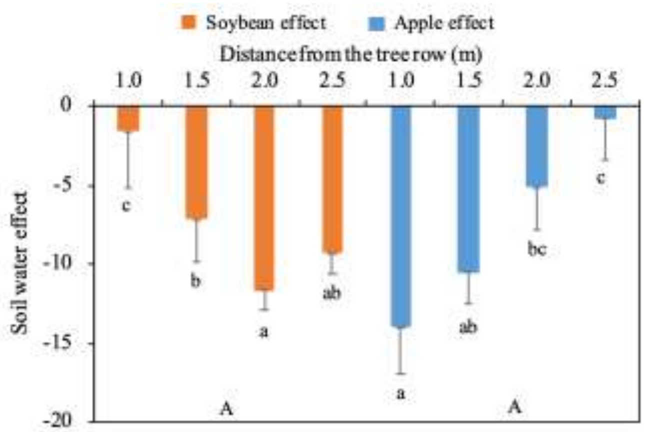

Fig 4: Mean rooting depth of apple and soybean in agroforestry and monocultures

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3.3 Water use efficiency for root production

The water balance calculations indicated water use was greater than the sole soybean, however, water use efficiency in agroforestry was higher than the sole apple (TABLE I). Although $pWER_{soybean}$ and $pWER_{apple}$ was respectively 0.42 and 0.95, the WER value of the agroforestry system was 1.33, signaling that agroforestry improved 33% of water use efficiency in root production.

TABLE I: Water productivity for root production in apple-soybean agroforestry system

Cropping system	**WU (mm)**	**WUE ($mg\ m^{-2}\ mm^{-1}$)**	**$pWER_{soybean}$**	**$pWER_{apple}$**	**WER**
Agroforestry	453±8 a	37±3 a	0.37±0.04	0.96±0.01	1.33±0.05
Sole apple	437±9 ab	26±6 b			
Sole soybean	429±3 b	32±4 ab			

Different letter expresses a significant difference among cropping systems at P= 0.05.

The root biomass density significantly decreased soil moisture (Fig 5, P<0.05). The root biomass density was greatest at the 1.0 m distance in apple-soybean agroforestry, driven by interspecific interaction (Fig 1, Fig 2). The root biomass density in agroforestry was greater than that in apple or soybean monoculture at each distance, and the soil water contents at the 1.0 m distance was higher than in sole apple. But the water consumption in agroforestry was greater than that in apple monoculture. The main reason of the difference was attributed to the lower slope of linear regression equations between root and water in apple monoculture (Fig 5).

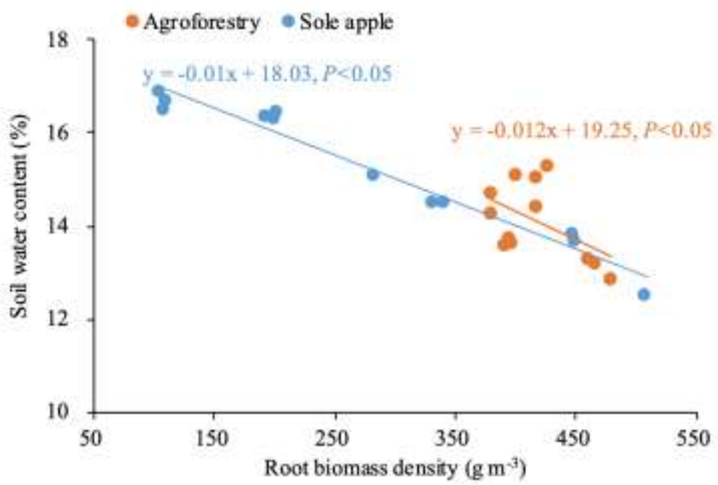

Fig 5: Relationship between roots and soil water in agroforestry and monocultures

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IV. DISCUSSION

4.1 Root response for interspecific interaction

An understanding of root distribution of agroforestry in relation to soil available water is required to interpret the interspecific interactions (competition and complementarity). The current study found that root biomass density of apple declined further away from the apple stems in agroforestry. In contrast, intercropped soybean roots showed an increasing variation with the distance. It is interesting to note that in all four sampling sections, the roots of apple and soybean in mixed system were always lower compared to those in monocultures. As mentioned in the literature review, lateral root spread horizontally around the tree stem [6], indicating that we expected to a declining tree rooting further away from the trees. Sun et al. also showed that the root of sole soybean was greater than that of intercropped soybean in different age apple-soybean agroforestry attributed to the belowground interspecific competition [13]. This root plasticity of soybean in agroforestry was a positive response to the strong belowground interspecific competition and weakened competitiveness of the trees, especially at the nearest crop row from the tree row [14].

The competition or complementarity for soil resources depended not only on the root distribution, but also on the main root zones of different species within specific soil layers in agroforestry [15]. Rooting depth of different plant species in agroforestry is crucial to determining competition for soil water. The intercropped soybean was relatively shallow rooted, with 14.8 cm of mean rooting depth in vertical soil profile, compared to 16.9 cm of mean rooting depth in soybean monoculture. The disparities of mean rooting depth between the sole and intercropped soybean demonstrated the tree competitiveness increased with the distance closed to the trees. These also agree with the earlier observation, which showed that crop presented root traits associated to a more conservative strategy [16]. The trees also relied on surface soil resources but developed roots below the crop rooting zone and may eventually promoted deeper root systems exploiting the available soil water [15]. In this study, apple trees had an averagely 32.4 cm by mean root depth in agroforestry, which was deeper than the mean root depth of intercropped soybean. In addition, 30.7 cm by mean root depth of the sole apple also indicated the root shift-down of the intercropped apple. Duan et al. also represented that main roots of trees tended to move downward in agroforestry, favoring the roots to expand resource space [16].

4.2 Soil water response for root plasticity

The influence of agroforestry on soil water content was progressive as negative effects due to the interspecific competition become rapidly apparent at the nearest distance from the trees, compared with the apple and soybean monocultures. Wu et al. has also found the combined root productivity adjacent to the trees was associated with the lowest soil moisture [17]. And pruning root slightly improved soil moisture and buffered negative soil water effect in agroforestry [18]. These relationships may partly be explained by the differences of the WUE for root production between the apple-soybean agroforestry and monocultures.

Our study showed that the greater the root production, the lower the soil water content, but agroforestry indicated greater water production efficiency for roots (Table 1, Figure 5). This result may be explained by which many studies have expressed the complementarity of soil water capture in agroforestry, so that the system productivity was greater than could be expected from monocultures [19]. Although partial water equivalent ratios for root production of intercropped apple and soybean were negative influence by the agroforestry, the greater root disparity, WUE and WER still supported that migrating soybean into apple orchard promoted an extended exploitation of soil water that would not be utilized by monocultures. This study supports evidence from previous observations [20]. This study also supported the viewpoint which the competition between plants would efficiently utilize environmental resources and promoted productive system [21-22].

V. CONCLUSIONS

The horizontal position showed an obvious negative effect, with lower root production and higher soil water at the 2.5 m distance than that at the 1.0 m distance in agroforestry. However, the apple trees and soybean increased the spatial dissimilarity in exploration of soil water that would otherwise not be utilized, and thereby promote a greater root system. The apple and soybean show a positive plasticity in agroforestry system, as characterized by total root biomass, WUE and WER. This finding should actuate the extension of apple-soybean agroforestry in China, which intend to optimize agricultural water management and advance ecosystem services.

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