Root interactions and tomato growth in tomato/potato onion companion-cropping system under different phosphorus levels

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ABSTRACT

When two plants interact, changes in plant growth are usually related to variations in root distribution and phosphorus (P) levels. However, root distributions and root tendencies are difficult to study because root systems grow beneath the soil surface. In this study, a transparent root box was used to observe interactions between root systems in situ, and the relation between tomato growth and root proliferation at different depths and distance from the rows at no P added and 120 mg kg\(^{-1}\) P added levels were also tested. We found that tomato shoot and total biomass increased and roots grew deeper when companion cropped with potato onion under both P levels. Moreover, tomato roots tended to grow away from the potato onion roots. Our results suggest that a deeper and more evasive root distribution may be related to the increased plant growth of tomato when companion cropped with potato onion.

1. Introduction

Intercropping and companion cropping have long been used to increase crop productivity and biomass advantages in modern agriculture (Tsubo and Walker 2002; Awal et al. 2006; Zhang et al. 2007; Zhou et al. 2011, 2017; Li et al., 2014). Interspecific facilitation achieved by increasing nutrient absorption to benefit intercropped plant growth and yield in agro-ecosystems has been widely observed (Li et al. 2001, 2003, 2007, 2010; Cu et al. 2005; He et al. 2013). Moreover, nutrient absorption is closely related to interspecific belowground interactions. For instance, Zhang et al. (2003) proved that N and P uptake can be increased by approximately 50% of wheat through the belowground interactions of wheat when intercropped with maize. Li et al. (2006) and Gao et al. (2010) also found that greater lateral root deployment and compatibility of spatial root distribution in intercropping species contributed to higher yields and plant growth. Plant root systems are hidden below ground, it is difficult to observe and quantify root growth when two species intercropped (Fang et al. 2009, 2011). Therefore, there are relatively few studies concerning root interactions in the intercropping and companion-cropping agricultural systems.

Plant roots exist in a complex environment such that root growth can be influenced by many factors (Karban 2008). The heterogeneity of water and nutrient supplementation in soil can affect plant roots at the most time (Liao et al. 2001, 2004; Hodge 2004; Fang et al. 2009), particularly for elemental nutrients that are not highly mobile. For example, phosphorus nutrients are heterogeneous in soil because phosphate ions usually become unavailable by reacting with soil cations to form either soluble complexes or insoluble precipitates (Cu et al. 2005), or they adsorb to the surfaces of various positively charged soil particles (Hinsinger et al. 2003). Thus, to activate and utilize more P nutrients, roots always display different levels of plasticity in addition to different P levels (Eissenstat 1992; Narang et al. 2000). Xia et al. (2013) suggested that P application can affect total root length and root space distribution across cropping systems (Xia et al. 2013).

In an intercropping system, root interactions are affected not only by heterogeneous nutrients in soil but also by the presence of neighboring roots (Maina et al. 2002; de Kroon et al. 2003; Falik et al. 2003; Dudley and File 2007; Karban and Shiojiri 2009). The topic of root recognition has attracted the attention of a growing number of scholars. Root behavior always alters by a neighboring species when two plants interact. The presence of a neighboring plant that represents a resource competitor can trigger an increase in root biomass allocation (Gersani et al. 2001; Maina et al. 2002; Falik et al. 2003; O’Brien et al. 2005; Padilla et al. 2013), whereas some plants can recognize other individuals of their own species and limit root proliferation (Dudley and File 2007; Biedrzycki and Bais 2010; Biedrzycki et al. 2010). For example, when planted with nonkin species instead of siblings, the Great Lakes Sea Rocket (Cakile edentula) accumulates more biomass in its fine roots (Dudley and File 2007). In addition, Impatiens pallida plants are capable of kin recognition only when the roots of another plant are present (Murphy and Dudley 2009). Based on these investigations, we conclude that plant root behavior is much more complex than previously thought, particularly when two plants interact, the result of plant growth and root interaction is closely to the nutrient and their neighbors.

Tomato (Solanum lycopersicum L.) is a widely cultivated vegetable around the world, although continuous monocropping of tomato plants and excessive fertilizer application have resulted in soil acidification and salinization in many locations, decreasing tomato yields and fruit quality (Liu...
The potato onion (Allium cepa L. var. aggregatum G. Don) is an onion variety that is widely cultivated in northeastern China and usually acts as a companion plant, which usually used for increasing the main crops yield or growth in companion cropping systems. Previously, we found that companion cropping with potato onion increased tomato yield in the field (Wu et al. 2013). However, we know little about how the roots interact when tomato is companion cropped with potato onion and whether there is a correlation between root growth and companion-cropped tomato at different P levels. In the present study, we used a custom apparatus consisting of a transparent manual root box to observe the root system in situ in a nondestructive manner. We measured how the cropping patterns and P levels influenced tomato growth and root interactions in a tomato/potato onion companion-cropping system with no P added or with 120 mg·kg$^{-1}$ P added. Furthermore, by combining the relationship between root length distribution and tomato growth, we determined the possible beneficial root length distribution. We hypothesized that (1) tomato growth can be increased after companion cropping with potato onion; (2) after companion cropping with potato onion, the extent of tomato root distribution can be more proliferated and more asymmetric than that in monoculture; and (3) a greater space root proliferated may be positively correlated with tomato growth.

2. Results

2.1. Influence of cropping patterns and P levels on tomato plant growth

The cropping pattern and P level treatments both affected shoot biomass and total plant biomass in the tomato plants, and we observed a significant P level × cropping pattern interaction for shoot biomass and plant total biomass ($p > 0.05$; Table 1). Compared with the biomass of monoculture tomato plants, the shoot biomass and total plant biomass of the tomato plants increased significantly when companion cropped with potato onion for both the no P added and 120 mg·kg$^{-1}$ P added treatments. For tomato root biomass, we did not detect any statistically significant interactions between the cropping pattern and P level treatments. However, tomato root biomass was clearly influenced by the cropping pattern ($p > 0.05$; Table 1), although it was not significantly influenced by P level.

2.2. Root length density distribution

Influenced by both neighboring plants and the P application rate, root length density (RLD) was unevenly distributed in the mixed cultures (Figure 1a, b, g, and h) but evenly distributed in the tomato monoculture (Figure 1e and k) and the potato onion monoculture (Figure 1c and l). When tomato plants were companion cropped with potato onion plants (Figure 1a and g), the roots could become more deeply distributed than those observed in the tomato monoculture (Figure 1e and k). For example, the 30 cm/120 cm$^2$ soil RLD contour was distributed in the 19 cm and 16 cm soil layers for the no P added and 120 mg·kg$^{-1}$ P added levels, much deeper than the 10 cm and 12 cm layers observed for the tomato monoculture (Figure 1e and k). In the mixed cultures, the roots of the tomato plants (Figure 1a and g) always avoided contact with the roots of the potato onions, whereas the roots of the potato onion (Figure 1b and h) spread laterally under the neighboring tomato plants under both P application treatments.

The root behavior of plants neighboring the same species was more strongly influenced by P level. In the no P added treatment, the RLD areas of the potato onion and tomato were not intermingled when neighboring the same plant species (Figure 1d and f). By contrast, for the 120 mg·kg$^{-1}$ P added treatment, the RLD areas of potato onion plants neighboring the same species (Figure 1l) were markedly intermingled, whereas the RLD areas of tomato plants neighboring the same species (Figure 1i) were clearly separated.

2.3. Root weight density distribution

The root weight density (RWD) distribution is shown in Figure 2. Under the no P added and 120 mg·kg$^{-1}$ P added treatments, the 0.2 g·kg$^{-1}$ soil RWD contour of the companion cropped tomato plants (Figure 2a and g) occupied the 15 cm soil layer, much deeper than the 9 cm soil layer observed for the tomato monoculture. Under the no P added treatment, the maximum accessible RWD of the companion-cropped tomato plants was 2.2 g/kg soil, while the value for the tomato monoculture was only 1.2 g/kg soil. The 2 g/kg soil RWD contour distribution of companion-cropped potato onion plants (Figure 2b and h) was distributed from 14 to 26 cm in the horizontal direction, much narrower than the 8–26 cm range observed in the potato onion monoculture (Figure 2c and i), and the maximum accessible RWD of the companion-cropped potato onion plants (Figure 2b and h) was 22 g/kg soil, much higher than the 14 g/kg soil observed for the monocultures (Figure 2c and i). The directions of the RWD in both intercropping systems and monocultures were the same as those for the RLD.

In general, the root distributions of the tomato plants became deeper when companion cropped with potato onion plants than those under tomato monoculture, and under the no P added conditions, the RWD of the tomato plants became higher than in monoculture. For the two P levels, the root tendencies of the two crops were significantly different, with the tomato roots avoiding contact with potato onion roots and the potato onion roots clearly extending towards the tomato roots. When the tomato plants were next to the same species, their roots were crossed under the

### Table 1. Effects of companion cropping with potato onion on tomato plant biomass (g plant$^{-1}$) at different P levels.

|                      | P0  | P120 | F-statistics |
|----------------------|-----|------|-------------|
|                      | Monoculture | Mixed culture | Monoculture | Mixed culture | P level | Cropping pattern | P level: Cropping pattern |
| Shoot dry weight     | 0.73 ± 0.05b | 0.99 ± 0.02a | 1.20 ± 0.08b | 1.65 ± 0.07a | 263.83*** | 104.56*** | 7.61* |
| Root dry weight      | 0.18 ± 0.02a | 0.21 ± 0.01a | 0.17 ± 0.01a | 0.20 ± 0.03a | 0.39    | 7.47*   | 0.09 |
| Total plant dry weight | 0.91 ± 0.04b | 1.20 ± 0.02a | 1.37 ± 0.08b | 1.85 ± 0.09a | 214.12*** | 102.80*** | 5.89* |

P0 represents no P added treatment, P120 represents 120 mg·kg$^{-1}$ P added treatment.

* *, **, *** represent significant results at the 0.05, 0.01, and 0.001 probability levels, respectively.
no P added treatment, whereas they avoided crossing under the 120 mg·kg\(^{-1}\) P added treatment. The root distribution of the potato onion plants in the companion-cropping system became narrower than in monoculture. Additionally, the root tendency of the potato onion plants neighboring the same species was opposite that of the tomato roots: under the no P added treatment, the root areas of the potato onion plants neighboring the same species were separated, whereas under the 120 mg·kg\(^{-1}\) P added treatment, the roots were significantly crossed.

2.4. The correlation between the total plant biomass and root length of 12–20 cm soil layer

Pairwise analysis (Figure 3) showed that the total plant biomass of tomato \(r^2 = 0.576\) increased with root length in the 12–20 cm soil layer.

2.5. Root tendency in root boxes

Image data were obtained on the 12th day after transplantation (sampling time was tested in our previous experiment to ensure that the roots of two plants in one box remained uncrossed). Figure 4(a) shows how the root architecture was affected by neighboring plants under the no P added treatment in the root box. In P0MT1 (one tomato plant in monoculture) and P0MO1 (one potato onion plant in monoculture), the roots of tomato plants and potato onion plants were distributed evenly. In the other combinations, the roots were unevenly distributed to a significant extent. In PI (the tomato/potato onion companion-cropping system), the tomato roots avoided the potato onion roots significantly, whereas the potato onion roots spread laterally under the tomato row. In P0MT2 (two tomato plants in monoculture), the roots of the two tomato plants were clearly crossed, whereas the potato onion roots avoided other potato onion roots in P0MO2 (two potato onion plants in monoculture).

For the 120 mg·kg\(^{-1}\) P added treatments (Figure 4b), the root distributions for the different treatment combinations were different from those under the no P added treatments. In PMT1 (one tomato plant in monoculture) and PMO1 (one potato onion plant in monoculture), the tomato and potato onion roots were evenly distributed, which is associated with P deficiency. In PI (the tomato/potato onion intercropping system), the tomato roots also avoided the potato onion roots, whereas the potato onion roots spread in a nearly uniform distribution. In PMT2 (two tomato plants in monoculture) and PMO2 (two potato onion plants in monoculture), the root tendencies of the tomato plants and potato onion plants exhibited opposite trends to those under the no P added treatment; in PMT2, the tomato roots avoided...
intermingling, whereas the potato onion roots showed no significant trend.

### 2.6. Root percentage distribution in root boxes

Consistent with Figure 4, the distribution of the root percentage is shown in Figure 5. In the tomato/potato onion mixed culture, the tomato root length percentage of P0IT in space 2 was significantly higher than that in PIT, and the tomato root length percentage of P0IT in the 6–9 cm spaces was lower than in PIT, indicating that tomato roots more clearly avoided potato onion roots than under the no P added treatment. In the P0MT2 treatment, the root length percentage in the middle area was higher than on the two sides, with horizontal distance 16 cm showing the highest percentage. In PMT2, the root length percentage was higher in horizontal distances 2–6 cm and 24–28 cm than in 12–18 cm. Specifically, when tomato plants were intercropped with the same species, their root growth trend was related to the P level, with the roots crossing under the no P added treatment, whereas they clearly avoided one another under the 120 mg·kg⁻¹ P added treatment.

Figure 5 shows that the root length percentage of potato onion plants in P0IO was higher on the left than on the right, and the root length percentage in horizontal distance 10–18 cm was higher than in PIO. In PIO, the potato onion roots were distributed evenly on both sides, revealing that the potato onion roots tended to extend towards the tomato roots when the species were intercropped under the no P added treatment, although this trend was not significant under the 120 mg·kg⁻¹ P added treatment. In P0MO2, the root length percentages on both sides (2–4 cm and 26–28 cm) were higher than in the middle zone (12–18 cm), whereas in PMO2, there was no obvious trend. In other

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**Figure 3.** The correlation between total plant biomass and root length in the 12–20 cm soil layer.

**Figure 4.** Images of roots from different tomato/potato onion combinations under no P added and 120 mg·kg⁻¹ P added conditions at day 12. ‘P0’ represents ‘no P added’ and ‘P’ represents ‘120 mg·kg⁻¹ P added’. (MT1) One tomato plant in monoculture, (MO1) one potato onion plant in monoculture, (MT2) two tomato plants in monoculture, (I) tomato/potato onion intercropping system, (MO2) two potato onion plants in monoculture.

**Figure 5.** Root percentage in different combinations in 14 spaces. The distribution of the tomato root percentage is shown on the left and potato onion root percentage shown on the right. (P0IT) Tomato in the companion-cropping system with no P added, (P0MT2) tomato monoculture with no P added, (PIT) tomato in the companion-cropping system with 120 mg·kg⁻¹ P added, (PMT2) tomato monoculture with 120 mg·kg⁻¹ P added; (P0IO) potato onion in the companion-cropping system with no P added, (P0MO2) potato onion monoculture with no P added, (PIO) potato onion in the companion-cropping system with 120 mg·kg⁻¹ P added, (PMO2) potato onion monoculture with 120 mg·kg⁻¹ P added.
words, when potato onion plants were intercropped with the same species under the no P added treatments, the roots avoided mixing, whereas there was a less distinct trend under the 120 mg kg⁻¹ P added treatments. All of these data are consistent with the results presented in Figure 4.

3. Discussion

Our results showed that when compared with those measured for the tomato monoculture, the shoot and total biomass increased after companion cropping with potato onion plants under both tested P levels, these results support our first hypothesis before. In later experiments, we found the root distribution of companion-cropped tomato plants could proliferate to a greater extent than in monoculture; for instance, the root of companion-cropped tomato occupied the 19 cm and 16 cm vertical space at no P added and 120 mg kg⁻¹ P added levels, respectively, it is much deeper than the 10 cm and 12 cm observed for tomato monoculture. In addition, the tomato plant biomass is indicated by its positive correlation with the total root length in the 12–20 cm soil layer. These results support our second and third hypotheses as well.

Enhancement of plant biomass under intercropping has been observed in many experiments (Li et al. 1999, 2001; Tsubo and Walker 2002; Awal et al. 2006; Zhang et al. 2007; Xia et al. 2013). In our experiments, the results for both P treatments showed that aboveground tomato biomass and plant total biomass could both be significantly increased by companion cropping with potato onion plants. We detected statistically significant interactions between the cropping patterns and P level treatments for both shoot biomass and total plant biomass of tomato in the companion-cropping system. Regarding the root dry weights of the tomato plants, we did not detect any statistically significant interactions between cropping pattern and P level treatments, although this metric was clearly influenced by cropping pattern (p > 0.05) and not significantly influenced by the P level. In previous studies, few experiments have addressed the effects of the interaction between cropping patterns and P levels on plant growth in companion-cropping systems. However, Li et al. (2008) and Wang et al. (2007) have shown that root biomass can be differentially affected in different intercropping system combinations, increasing in some contexts while remaining the same as in monocultures in others, suggesting that in mixed cultures, root biomass can be influenced by the species type of adjacent plants. In addition, Li et al. (2010) showed that the root biomass of different crops can vary under different P levels. Thus the root biomass in intercropping systems can be affected by many factors. In our experiment, the root biomass of tomato plants was significantly influenced by companion-cropping tomato plants with potato onion plants.

Root interactions have been studied in many intercropping systems, and the spatial distribution of roots and their density in the soil has been shown to determine the ability of a crop to acquire the necessary nutrients and water to sustain growth. In this study, the roots of tomato plants and potato onion plants both showed an extended root distribution, and the RLD and RWD of the tomato plants both became deeper than in tomato monoculture, consistent with the previous literature (Adiku et al. 2001; Li et al. 2006; Gao et al. 2010). Some studies have found that the root distribution can become unbalanced and that roots can extend horizontally to greater distances in an intercropping system (Zhang and Huang 2003), with overyielding of species resulting from the greater lateral deployment of roots and increased RLD. The roots of intercropped plants can extend into the root area of other plants and sometimes penetrate deeper than in monoculture (Adiku et al. 2001; Li et al. 2006), and the compatibility of the spatial root distributions of the intercropped species contributes to interspecific facilitation. In our experiment, the roots of companion-cropped tomato occupied much more vertical space than in the tomato monoculture, particularly in the 12–20 cm soil layer, and the tomato plant biomass was positively correlated with the total root length in the 12–20 cm soil layer. This result may prove that the deeper root distribution of companion-cropped tomato is the main reason for the increase in plant biomass. However, for the time- and labor-intensive operation, only two replicates were created in our experiment, as in the study by Gao et al. (2010). The number of samples, therefore, was not sufficient, giving rise to an r² value of only 0.576; a more reliable correlation can be obtained in large-scale samples in future studies. The root tendencies of the two crops observed in this study were not the same as in previous studies. In the studies by Adiku et al. (2001) and Li et al. (2006), the roots of two crops were found to extend into each other’s root areas. Thus we believe that the root tendency of one plant in an intercropping system may be influenced by both plant species, and depending on whether the roots of the two crops are mixed or separate, these different tendencies could be beneficial for plant nutrient absorption. These tendencies generally involve an extended root distribution, and greater root length can help plants absorb nutrients and increase biomass.

In previous studies, the results of competition have always been connected to resources and plant species. Some authors believe that the results of competition can be variable in different environments, with intraspecific competition being dominant under certain conditions (Shley and Larson 1994; Velagala et al. 1997; Wassmuth et al. 2009) and interspecific competition being stronger under others (Vasquez et al. 2008; Young and Mangold 2008; Blank 2010). Ge et al. (2000) demonstrated that low interroot competition is a more efficient way for adjacent plants to decrease root overlap, and Zhang et al. (2002) showed that when root weight is at its maximum and roots do not overlap in a wheat/faba bean intercropping stage, then competition between the two crops for water and nutrients can be reduced, resulting in higher yields for both species. In our companion-cropping system, the root action of tomato plants was consistent with that observed in the above-mentioned study, and under nutrient-deficient conditions, the roots opted to reduce their overlap and their competition with potato onion plants.

In our analysis of root tendency, when the tomato and potato onion plants were planted with their same species, the reaction of the roots was more closely related to the P level. The roots of the potato onion plants were clearly separated from those of their same-species neighbors under the no P added treatment, which appeared to aid in avoiding competition and improving survival of the species, whereas no distinct root tendency was observed in the absence of P stress. However, the tomato roots intermingled with one another under the no P added treatment, possibly allowing them to compete for more resources, whereas the roots clearly avoided intermingling under the 120 mg kg⁻¹ P added treatment, possibly to avoid competing for resources. Cheplick and Kane (2004) reported that when two kin plants are planted together,
their roots can avoid one another or engage in spatial segregation to avoid competing for resources, whereas when nonkin plants are planted together, the roots usually overlap, allowing for more competition. In these experiments, the root behavior of the potato onions was consistent with previous results, perhaps because this variety was not subjected to artificial transformation. In other words, for the potato onion, the results regarding root recognition appeared biased towards protecting the species itself, thus preventing competition among roots under the no P added treatment. However, the responses of the tomatoes were different from those of Cheplick and Kan. Generally, studies on kin recognition have been conducted on wild plants, whereas few such studies have been performed on crop species (Dudley and File 2007; Murphy and Dudley 2009). Wild plants usually grow under natural conditions in which resources are limited; however, in certain long-term cultivated species grown under resource-rich conditions (Wenke 1980), the ability of roots to recognize those of their kin has gradually decreased, and root recognition can be significantly affected by plant species and genotype (Fang et al. 2011). Therefore, considering that the tomato seeds we selected were subjected to long-term cultivation, we speculate that the root recognition may have been weakened in these plants. In other words, when planted with their siblings under nutrient-deficient conditions, these plants no longer know to protect their kin. The results of our study clearly show that tomato and potato onion roots can respond to nutrients and adjacent plants, consistent with the viewpoint of Cahill et al. (2010), although determining which factors in an intercropping system are most important for controlling root behavior requires further research.

4. Materials and methods

4.1. Plant materials and cultivation conditions

The tomato (Solanum lycopersicum L.) variety Dongnong708 was provided by the Tomato Breeding Center of Northeast Agricultural University (Harbin, China). The potato onion (Allium cepa var. agroatum Don.) variety Sulhua, a native variety with potential allelopathy (Liu et al. 2013), was provided by the Laboratory of Vegetable Physiological Ecology (Harbin, China). Tomato seeds were treated with hot (55°C) water and germinated in Petri dishes with wet gauze in the dark at 28°C. Seedlings with two cotyledons were planted on wild plants, whereas few such studies have been performed on crop species (Dudley and File 2007; Murphy and Dudley 2009). Wild plants usually grow under natural conditions in which resources are limited; however, in certain long-term cultivated species grown under resource-rich conditions (Wenke 1980), the ability of roots to recognize those of their kin has gradually decreased, and root recognition can be significantly affected by plant species and genotype (Fang et al. 2011). Therefore, considering that the tomato seeds we selected were subjected to long-term cultivation, we speculate that the root recognition may have been weakened in these plants. In other words, when planted with their siblings under nutrient-deficient conditions, these plants no longer know to protect their kin. The results of our study clearly show that tomato and potato onion roots can respond to nutrients and adjacent plants, consistent with the viewpoint of Cahill et al. (2010), although determining which factors in an intercropping system are most important for controlling root behavior requires further research.

4.2. Pot experiment: effect of cropping patterns and P levels on tomato plant growth

The primary pot treatments consisted of no additional added P and 120 mg·kg$^{-1}$ P added. These P concentrations were implemented based on previous experiments showing that soil with no additional P is insufficient for tomato growth and that soil with 120 mg·kg$^{-1}$ P added is sufficient. The subpot treatments were applied to a tomato/potato onion companion-cropping system and a tomato monoculture in plastic pots (28 cm diameter, 20 cm height) containing 3 kg soil. At the time of tomato transplantation, the potato onion plants were planted, and the tomato:potato onion ratio was 1:3 in the companion-cropping treatment. The experimental design was a randomized complete block design with three replicates. Four treatments were performed in each block, and four pots were included in each treatment. In all, there were 16 pots per block and with 3 blocks total, yielding a total of 48 pots. Each pot was watered with tap water every 3 days to maintain the soil water content at approximately 60% of the water-holding capacity, and the plants were grown in the phytotron as described earlier.

Sandy loam soil from the 30–50 cm layer under the ground surface was collected from an open field at Northeast Agricultural University (Harbin, China). The soil contained 17.4 g·kg$^{-1}$ organic matter, 40.6 mg·kg$^{-1}$ available N (nitrate and ammonium), 11.4 mg·kg$^{-1}$ Olsen P and 100.9 mg·kg$^{-1}$ available K, and exhibited an electrolytic conductivity (1.5, w/v) of 153.5 mS·cm$^{-1}$ and a pH (1.5, w/v) of 6.98. Previous experiments have shown that even when total P and available P levels are relatively high, soil can still be considered P-deficient for plants if plant growth can be improved by P addition (Holloway et al. 2001; Li et al. 2005; Wang et al. 2007). In a previous experiment, we confirmed that the base soil P content was insufficient for tomato plants (data not shown).

P was added as KH$_2$PO$_4$ at 120 ppm for the 120 mg·kg$^{-1}$ P added treatment, and fertilization with 120 ppm N (in the form of CO(NH$_2$)$_2$ and 120 ppm K (in the form of K$_2$SO$_4$) was performed for both the no P added and 120 mg·kg$^{-1}$ P added treatments; K$_2$SO$_4$ was then used to balance the K rate for the two P level treatments. Plants were harvested on the 20th day after transplantation, thoroughly washed with distilled water and separated into roots and shoots. The shoots and roots were killed by heating at 105°C for 30 min and then dried at 60°C for 72 h.

4.3. Foam box experiment: root distributions and linear correlation between total plant biomass and root length in 12–20 cm soil layer

The same soil and fertilizer management techniques described earlier were used in this experiment. To provide sufficient space for the plant roots and to reduce harm to the root system when sampling, we employed large foam boxes as culture pots; the foam boxes’ internal length, width, and height were 36 cm, 25 cm, and 22 cm, respectively. Each foam box was filled with 20 kg of soil. The experimental design was a randomized complete block design with two replicates, and 10 treatments were used in this experiment. The primary pot treatments were no P or 120 mg·kg$^{-1}$ P added, and the subpot treatment consisted of five intercropping combinations: (1) a tomato/potato onion companion-cropping system, (2) one tomato plant in monoculture, (3) two tomato plants in monoculture, (4) one potato onion in monoculture, and (5) two potato onion plants in monoculture. The tomato-to-potato onion ratio in the intercropping treatment was 1:3. When considering the nutrient balance...
for each box, the three potato onion plants were viewed as equivalent to one plant.

The plants were sampled on the 20th day after transplantation, and root samples were collected using the monolith method, as modified by Li et al. (2006) and Smit et al. (2013). The RLD and RWD were tested to be representative of the population of roots at different depths and distances from the rows (Adiku et al. 2001; Gao et al. 2010; Li et al. 2006). During sampling, the foam box was cut into vertical sections at 10 cm intervals along the wide side, the soil surface was made as smooth as possible, and the roots were then fixed in each 6 × 4 cm area with 5 cm nails. Finally, an iron box with an inner diameter of 6 × 5 × 4 cm was used to remove a 5-cm layer of soil from the center of the foam box; the volume of each soil block was 120 cm³. There were 30 monoliths (5 in the vertical direction and 6 in the horizontal direction) in each soil profile, and 600 monoliths were sampled in total. Each soil sample was placed in a numbered plastic bag.

Two wooden sticks were run through the 13 networks from two sides, and the wire frame was fixed with plastic grips. Two flashlights were used as a light source for taking photographs. After imaging, the roots between every two grids were cut with a pair of scissors as an individual sample, and the root length of each sample was determined using a root system scanner, which we used to calculate the root percentage.

4.4. Statistical analysis

Results regarding plant growth in pot experiments were analyzed using the SAS 8.0 software program (SAS Institute Inc., Cary, USA), and the mean values of the different treatments were compared using Tukey’s test at the \( p = 0.05 \) level. The data are expressed as mean values with standard errors. Data of the significance of primary effects (P level and cropping pattern) and interactions (P level × cropping pattern) on tomato plant growth were subjected to a Two-way factorial ANOVA using the SPSS 13.0 software package.

Data gathered from the monoliths of the white foam box experiment represent the entire root population, so the results are presented as contour diagrams. RLD and RWD contour diagrams were prepared using the Surfer v. 8.0 software program (Golden Software Inc., Golden, CO). SPSS software was used to conduct Spearman correlation analysis to identify correlations between the 12–20 cm of belowground root length and the corresponding aboveground plant biomass.

Images from the root box experiment were obtained in panoramic viewing using an Apple mobile phone. The root was scanned by MICROTEK (Scan Maker i800 plus) and analyzed by the plant root analysis system WS (LA-S2400).

5. Conclusion

Taken together, our results provide evidence that deeper and more evasive root distributions in tomato plants can support greater tomato biomass in tomato/potato onion companion-cropping systems. Furthermore, the cropping pattern has a greater effect on the tomato root distribution than P level does. However, the downside of our study was that we could not ensure how the potato onion affected the tomato root distribution, is the root exudates works, or the changing of soil microorganism works still require further study. Moreover, our findings just did as greenhouse experiments in a
small range, it still requires further validation from large-scale experiments in fields for developing agriculture.

Acknowledgments
We would like to thank Dr. Long Li (Department of Plant Nutrition, China Agricultural University) for his valuable guidance in our experiment’s design and results analysis.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This research was financially supported by the National Natural Science Foundation of China (31672200, 31772361) and China Agricultural Research System (CARS-25-08).

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