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Spatial distribution of soil water, soil temperature, and plant roots in a drip-irrigated intercropping field with plastic mulch

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ABSTRACT

Intercropping and drip irrigation with plastic mulch are two agricultural practices used worldwide. Coupling of these two practices may further increase crop yields and land and water use efficiencies when an optimal spatial distribution of soil water contents (SWC), soil temperatures, and plant roots is achieved. However, this coupling causes the distribution of SWCs, soil temperatures, and plant roots to be more complex than when only one of these agricultural practices are used. The objective of this study thus was to investigate the effects of different irrigation treatments on spatial distributions of SWCs, soil temperatures, and root growth in a drip-irrigated intercropping field with plastic mulch. Three field experiments with different irrigation treatments (high T1, moderate T2, and low T3) were conducted to evaluate the spatial distribution of SWCs, soil temperatures, and plant roots with respect to dripper lines and plant locations. There were significant differences ($p < 0.05$) in SWCs in the 0–40 cm soil layer for different irrigation treatments and between different locations. The maximum SWC was measured under the plant/mulch for the T1 treatment, while the minimum SWC was measured under the bare soil surface for the T3 treatment. This was mainly due to the location of drippers and mulch. However, no differences in SWCs were measured in the 60 100 cm soil layer. Significant differences in soil temperatures were measured in the 0 5 cm soil layer between different irrigation treatments and different locations. The soil temperature in the subsoil (15 25 cm) under mulch was higher than under the bare surface. The overlaps of two plant root systems in an intercropping field gradually increased and then decreased during the growing season. The roots in the 0 30 cm soil layer accounted for about 60% 70% of all roots. Higher irrigation rates produced higher root length and weight densities in the 0 30 cm soil layer and lower densities in the 30 100 cm soil layers. Spatial distributions of SWCs, soil temperatures, and plant roots in the intercropping field under drip irrigation were significantly influenced by irrigation treatments and plastic mulch. Collected experimental data may contribute to designing an optimal irrigation program for a drip-irrigated intercropping field with plastic mulch.

1. Introduction

Intercropping is a very popular agricultural practice used around the world, such as in China (Zhang and Li, 2003), Germany (Munz et al., 2014), Brazil (Crusciol et al., 2014), India (Tanwar et al., 2014), Pakistan (Asghar Shah et al., 2016). It not only improves the land use efficiency (e.g., Dhima et al., 2007; Tanwar et al., 2014; Wang et al., 2015) and the light and radiation use efficiency (Awal et al., 2006), but also enhances crop yields and farmers' income(Gou et al., 2016). However, there are often different water requirements needed by two different crop species during the growing period, which the traditional flood irrigation, incapable of providing different irrigation amounts in one field at the same time, cannot satisfy. This results in a low water use efficiency (WUE) in intercropping fields (Sampathkumar et al., 2012). On the other hand, drip irrigation with plastic mulch can be an effective practice to increase soil temperatures, the WUE, and crop yields (e.g., Hou et al., 2010; Liu et al., 2012; Yahgi et al., 2013; Wang et al., 2014). Combining drip irrigation with intercropping can increase not only crop yields, but also the land and water use efficiencies. Such a system may provide independent drip irrigation lines for different crop species, and thus optimize irrigation for every crop species and their different root systems (Sampathkumar et al., 2012). However, such a multi-practice system produces more complex spatial distributions

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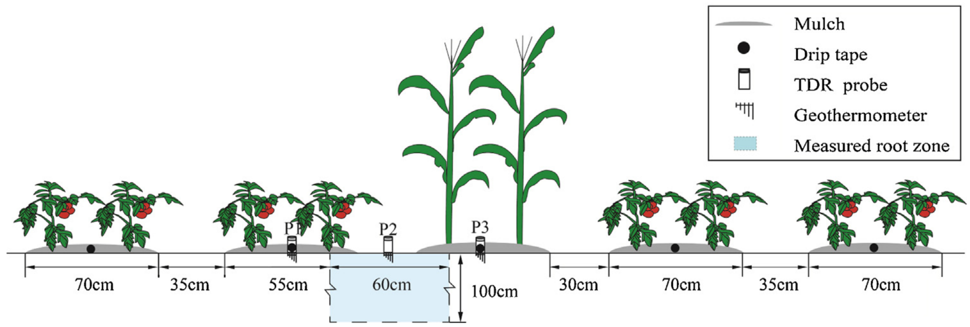

Fig. 1. Schematic showing the cropping pattern (with two double rows of tomatoes and one double row of corn), the arrangement of drip tapes, and locations of TDR probes, geothermometers, surface mulch, and measured root zone.

of soil water contents, soil temperatures, and root growth, when compared to a single-practice system. It is thus important to investigate variations in soil water contents (SWC), soil temperatures, and root distribution, and to study the competitive mechanisms in such multi-species systems in order to design optimal irrigation programs for drip-irrigated intercropping fields with plastic mulch.

Soil water movement under drip irrigation with different crops has been studied during the last few decades, both through experimentation (e.g., Yahgi et al., 2013; Badr and Abuarab, 2013) and the use of simulation models (e.g., Skaggs et al., 2004; Kandelous et al., 2011; Arbat et al., 2013). For example, the effects of different drip irrigation frequencies (Abou Lila et al., 2013), different drip patterns (Skaggs et al., 2010), and different irrigation amounts (van Donk et al., 2013) on soil water movement and crop growth were all researched in many countries. Results in general show that drip irrigation produces a higher WUE and lower leaching compared to surface irrigation (Patel and Rajput, 2008). Additionally, the effect of the drip irrigation on root growth is very complicated. Sharma et al. (2014) found that while deficit irrigation (50% of ET_c) increased the root length density of one variety of melon (cv. Mission), it did not have any impact on another variety (cv. Super Nectar), and it even decreased the root length density in the third variety (cv. Da Vinci).

The spatial distribution of roots in an intercropping field is different from the distribution in a single crop system. The overlapping root systems of two crop species lead to the competition for water and nutrients. For example, an uneven distribution of roots was measured in a maize/cabbage intercropping system (Zhang and Huang, 2003), with the roots of maize extending horizontally to greater distances than those of cabbage. The roots of the two crops extended into the rhizospheres of each other in the maize/cowpea intercropping field (Adiku et al., 2001), with the roots of maize being much larger.

Plastic mulch not only increases crop yields, soil temperatures, and the WUE, but it also stabilizes the daily range of soil temperatures (Xing et al., 2012), which can benefit crop growth. Although the thermal effects of SWC on soil temperature in a soil system with plastic mulch have been studied by many scientists (Mahrer et al., 1984; Hunt et al., 2010), much less similar work has been done for drip-irrigated intercropping systems with plastic mulch. Such systems are much more complicated because the spatial distribution of SWCs is affected by the different water consumptions of two crop species and their overlapping or not overlapping root systems, depending on crop species and their particular growing periods (Gao et al., 2010). The SWCs and root distribution in a drip-irrigated intercropping field are thus influenced not only by drip wetting patterns, but also by the root water uptake competition between two crops (Gao et al., 2010; Sampathkumar et al., 2012).

The spatial distribution of soil temperature is influenced not only by plastic mulch and water contents, but also by the different heights of two crops and their shading of the soil surface. All these factors, i.e., water contents, soil temperatures, and the presence or absence of surface mulch, affect root growth (Ceccon et al., 2011). Understandably, the spatial distributions of SWCs, soil temperatures, and root systems in a drip-irrigated intercropping field with plastic mulch are very complex and difficult to predict.

The main objectives of this study therefore are (i) to analyze the effects of drip irrigation on SWCs under different drip irrigation practices in an intercropping field, (ii) to evaluate the distribution of soil temperature in a drip-irrigated intercropping field with plastic mulch, and (iii) to compare root system distributions under different irrigation treatments.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted at the Dunkou Agroecosystem Experimental Station (40°20′15″N, 107°1′45″E, altitude 2004 m), located at the western Hetao Irrigation District, in the Yellow River basin of Northwest China, during the 2012 and 2013 seasons. The main soil texture on the site is sandy clay loam, and the groundwater table is between 70 and 250 cm deep. The site is representative of inland arid climate with a long-term average annual rainfall of 198 mm and an average annual potential evapotranspiration of 2460 mm. Note that average annual potential evapotranspiration is 12.4 times higher than average annual precipitation, which makes irrigation necessary for crop growth.

2.2. Experimental treatments and procedures

The planting pattern in the intercropping field consisted of 4 rows of tomatoes and 2 rows of corn. One drip line was used for both two crop rows and one mulch strip in order to reduce irrigation costs (Fig. 1). Two rows of crops were irrigated with one drip line and covered with one white plastic mulch sheet with 80 cm width. Three irrigation treatments, with high T1 (Conventional drip irrigation), moderate T2 (about 75% of T1), and low T3 (about 50% of T1) irrigation amounts (which were the same in each irrigation event in a particular year, but different between treatments) (Table 1), were delivered in three replicates in a completely randomized block design of 9 plots, and the more detail agronomic management can be found in paper of Li et al. (2015). Different irrigation amounts were adopted for tomato and corn in one irrigation treatment (Table 1). Two water meters (with a precision of 0.001 m^3) were used to control irrigation amounts in each treatment. Corn was direct-seeded in the field (with a 40 cm row spacing), while tomatoes were transplanted to an intercropping field (with a 40 cm row spacing). After transplanting, all treatments received a large flood irrigation (about 55 mm) on day of year (DOY)

Table 1
Amounts of irrigation water in a single irrigation event in different irrigation treatments during two years.

Irrigation amount (mm)		
Treatment	Tomato	Corn
T1	22.5	30
T2	16.5	22.5
T3	10.5	15

132 (2012 season) and 125 (2013 season) for crop survival. Drip irrigation was applied on DOY 167, 175, 190, 196, 199, and 214 to both crops in the 2012 season, and DOY 141, 156, 171, 188, 198, and 221 in the 2013 season. Corn received two additional irrigations on DOY 222 and 228 in the 2012 season, and one additional irrigation on DOY 229 in the 2013 season.

2.3. Meteorological measurements

Continuous data were collected for solar radiation (S-LIB-M003), photosynthetically active radiation (S-LIA-M003), air temperature, relative humidity (S-THB-M002), air pressure (S-BPA-CM10), wind speed (S-WCA-M003), and precipitation (S-BPA-CM10) at the automatic meteorological station installed about 500 m away from the experiment field. Data were averaged and recorded at one-hour intervals, and stored in a datalogger (H21-001 DT-80), from which they were automatically downloaded. Reference crop evapotranspiration (ET_0) rates during the 2012 and 2013 seasons, calculated using the Penman–Monteith equation (Allen et al., 1998), are presented in Fig. 2.

2.4. Soil water and soil temperature measurements

TDR probes (TRIME-PICO-IPH, IMKO GmbH, Germany) for measuring SWC and mercury-in-glass geothermometers with bent stems (Hongxing Thermal Instruments, Wuqiang County, Hebei Province, China) for measuring soil temperature were installed in the middle of two rows of tomatoes (P1), two rows of tomato and corn (P2), and two rows of corn (P3) in each treatment plot

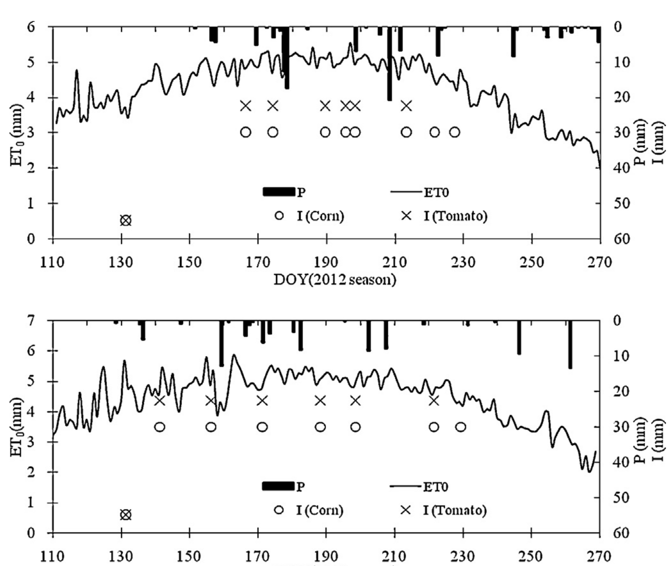

Fig. 2. Potential evapotranspiration (ET_0), precipitation (P), and irrigation (I) for the T1 treatment during the entire growing season 2012 (top) and 2013 (bottom). There were different irrigation amounts for tomato and corn, while two additional irrigations were applied to corn on DOY 222 and 228 in the 2012 season, and one additional irrigation was applied to corn on DOY 229 in the 2013 season.

(Fig. 1). SWC measurements were taken once a week at soil depths of 0 10, 10 20, 20 40, 40 60, 60 80, and 80 100 cm. Soil temperature measurements were taken between sowing and harvesting at soil depths of 5, 10, 15, 20 and 25 cm and at 08:00 h, 10:00 h, 12:00 h, 14:00 h, 16:00 h, 18:00 h and 20:00 h at a 10-day interval. Inter-day temperature measurements were averaged to give daily soil temperature.

2.5. Root measurements

Since measurements of the root spatial distribution are very time and labor intensive, four measurements of the root distribution were carried out to study root distributions at different growth stages only for the T1 treatment. Measurements were taken on June 6, June 22, July 21, and August 20 in the 2012 season, and on June 5, June 28, July 24, and August 21 in the 2013 season. To study the effect of the soil water content on root growth, root measurements for all three treatments (T1, T2, and T3) were taken in July during both seasons. Horizontal and vertical root distributions of corn and tomato were obtained from a soil transect (Ozier-Lafontaine et al., 1999; Adiku et al., 2001; Gao et al., 2010), which was dug between the tomato and corn strips, and which was on one side of the 60 cm long, 100 cm wide, and 100 cm deep trench (Fig. 1). After the trench was dug, the working surface of the soil profile was smoothed, the face of the pit was trimmed to be vertical, and then the vertical plane was divided into square, 5×5 cm cells, and 5 cm long nails were driven into it every 5 cm along its length and width.

Soil samples were soaked for 15 min in water and then washed using a root washing machine (Delta-T, CSIRO, Australia). Washed root samples were scanned by a root system scanner (Reagent Instruments Inc.; Perfection 4870photo, Epson, Japan) using the 450 dpi resolution. Root length (cm), root volume (cm^3), and root surface area (cm^2) were determined using the WinRHIZO software (ver. 2003b, Reagent Instruments Inc., Quebec, Canada). After the analysis, root samples were dried at 65◦C for 3 days to measure the root dry mass (g) (Leskovar and Cantliffe, 1991; Sharma et al., 2014).

2.6. Statistical analysis

All data were analyzed by the analysis of variance (ANOVA) using the SPSS software (Version 16.0.0). A Duncan's multiple range tests were applied to detect differences among the means of treatments and locations for SWCs, soil temperatures, and root parameters. Values reported in the tables below and marked with different letters are considered statistically significant at a level of 0.05 (the p value) (McCullough and Wilson, 2002).

3. Results

3.1. The effect of irrigation amounts on SWC in a drip-irrigated intercropping field

Movement of soil water directly influences variations in soil temperature and migration of crop nutrients, thus affecting crop growth and crop yield. Average SWCs (Table 2) in the 0 10, 10 20, 20 40, 40 60, and 60 100 cm soil layers were analyzed for all three irrigation treatments during both seasons (Fig. 3). Results showed that the average SWC in the 0 40 cm soil layer significantly decreased ($p < 0.05$) with the reduction of the irrigation amount, especially between the T1 and T3 treatments. Differences between different treatments gradually decreased in deeper soil layers (>40 cm), and virtually disappeared in the 60 100 cm soil layer (at $p > 0.05$). Average SWCs in all three treatments (Fig. 3) displayed large fluctuations in the 0 10 and 10 20 cm soil layers during both seasons due to precipitation and irrigation events, and only

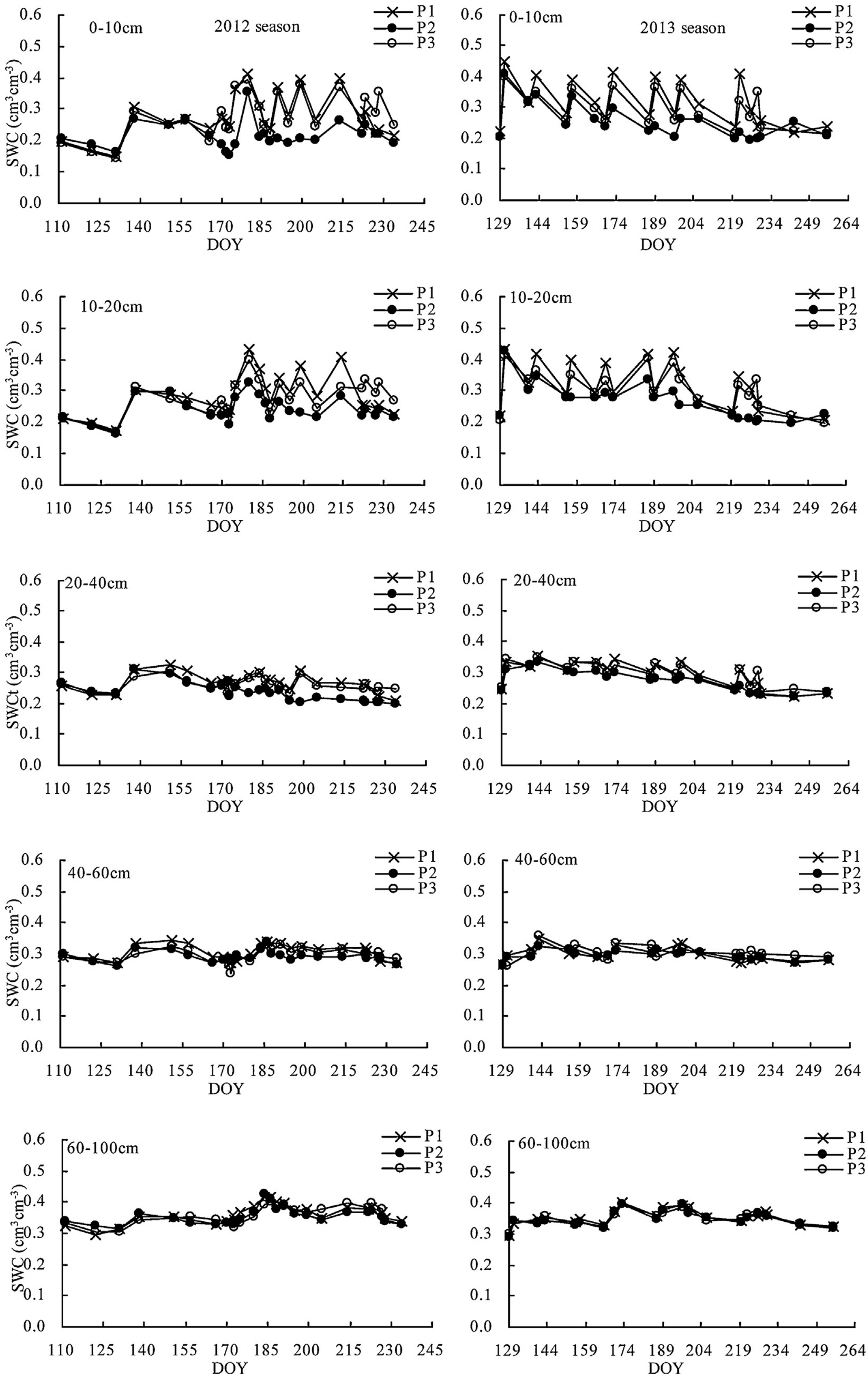

Fig. 3. A comparison of SWCs at P1 (tomato), P2 (bare), and P3 (corn) locations at depths of 0–10 (top), 10–20, 20–40, 40–60, and 60–100 (bottom) cm during the 2012 (left) and 2013 (right) seasons.

Table 2
Average SWCs (cm^3 cm^{-3}) at different locations (P1, P2, and P3) for different treatments (T1, T2, and T3).

Treatment	0 20 cm		20 40 cm		40 60 cm		60 100	
Irrigation(Ir)	2012	2013	2012	2013	2012	2013	2012	2013
T1	0.277a	0.305a	0.278a	0.305a	0.304a	0.304a	0.362a	0.355a
T2	0.256a	0.296a	0.256b	0.297ab	0.293b	0.301a	0.357a	0.352a
T3	0.240b	0.273b	0.236c	0.264b	0.300a	0.294b	0.354a	0.348a
Position(P)								
P1	0.278a	0.315a	0.269a	0.295ab	0.307a	0.300a	0.362a	0.355a
P2	0.228b	0.260b	0.239b	0.274b	0.291b	0.295b	0.355a	0.350a
P3	0.277a	0.299ab	0.261a	0.296a	0.296b	0.305a	0.356a	0.351a
ANOVA	*P*-value							
Ir	0.010	0.023	0.001	0.001	0.039	0.121	0.238	0.276
P	0.001	0.001	0.001	0.006	0.005	0.065	0.287	0.546
Ir × P	0.541	0.893	0.009	0.008	0.001	0.005	0.722	0.989

According to the Duncan's multiple range test, values followed by the same letter within a column are not significantly different at $p \le 0.05$.

small fluctuations in the 20 100 cm soil layers. Soil water in the top soil (0 30 cm) was provided mainly by drip irrigation and average SWCs were 25.7 cm^3 cm^{-3} and 29.0 cm^3 cm^{-3} during the 2012 and 2013 seasons, respectively. On the other hand, soil water in the subsoil (40 100 cm) was provided not only by irrigation, but also by groundwater. Consequently, average SWCs reached values of 32.8 cm^3 cm^{-3} and 32.6 cm^3 cm^{-3} during the 2012 and 2013 seasons, respectively (Table 2). Average SWCs (over two years) in deeper horizons (60 100 cm) were 35.5 cm^3 cm^{-3}, mainly due to the influence of the shallow groundwater that was often only about 120 cm below the soil surface during the crop growth period. As a result, the root system in the region, for conditions with deficit irrigation, has a tendency both to be deeper, and to reach higher SWCs in the subsoil.

The largest difference in SWCs, 22.0 cm^3 cm^{-3}, was measured in the 0 20 cm soil layer between P1 and P3 locations (Table 2). There were highly significant ($p < 0.01$) differences in SWCs in the 0 40 cm soil layer among different locations, but these differences decreased with depth. In the 40 60 cm soil layer, only in the 2012 season were there significant differences ($p < 0.05$) in SWCs among three locations. Because of small differences between root systems, small effects of irrigation and precipitation, and a large influence of shallow groundwater in the 60 100 cm soil layer, no differences in SWCs were observed among P1, P2, and P3 locations ($p = 0.287$ in 2012; $p = 0.546$ in 2013). The plots of SWCs were practically overlapping at deeper depths at different locations (Fig. 3).

The spatial and temporal distributions of SWCs are very complicated in a drip-irrigated intercropping field with plastic mulch. There were significant differences in SWCs in the 0 40 cm soil layer among different irrigation treatments and different locations (Fig. 3). As expected, irrigation treatments with higher irrigation amounts produced higher SWCs. SWCs at crop locations P1 and P3 were higher than at the bare location (P2) because of mulch. There were only small differences in SWCs in the 40 100 cm soil layer, and almost none in the 60 100 cm soil layer.

3.2. *The effect of irrigation amounts on soil temperature in a drip-irrigated intercropping field*

Soil temperature data during the mid-season crop growth stages (from mid-July to mid-August) was used because of maximum differences in SWCs among different locations and maximum differences in crop heights between tomato and corn during this time period. Two-dimensional soil temperature profiles for both seasons and for three treatments are shown in Fig. 4. Fig. 4 shows distinctive differences in temperatures at different locations. Soil temperature at the corn location (P1) was clearly higher than at the tomato location in the top 0 10 cm soil layer, especially in the topsoil (0 5 cm) ($p < 0.05$). Soil temperature in the subsoil (15 25 cm) at the mulch locations (P1 and P3) was significantly higher than at the non-mulch (bare) location (P2) ($p < 0.05$). Only small differences were observed among plots with different irrigation treatments (Fig. 4), although in general, slightly higher soil temperatures were observed in plots with the low irrigation treatment because of lower SWCs.

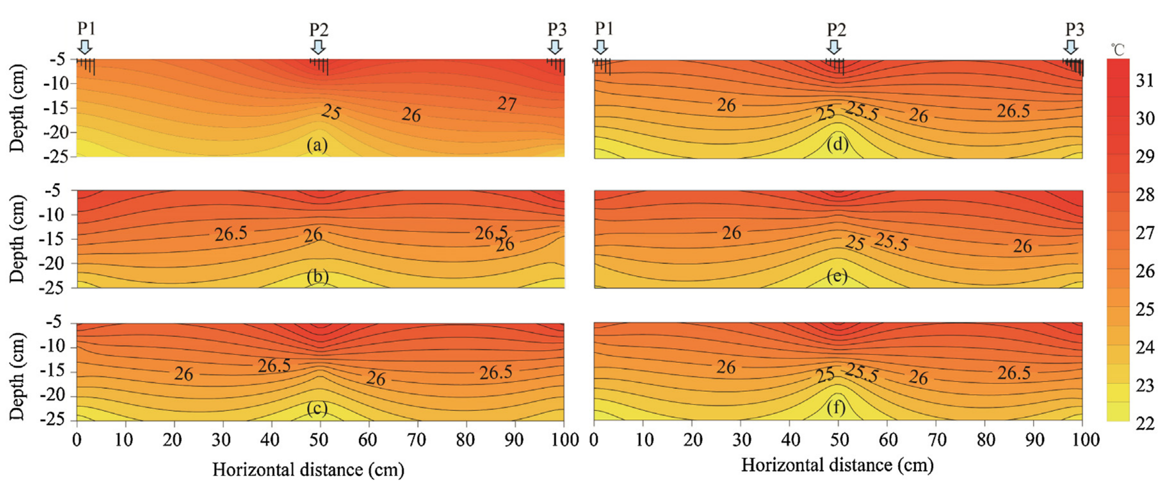

Fig. 4. Comparison of spatial distributions of average soil temperatures of daytime in the 2012 (left) and in 2013 (right) seasons for treatment T1 (top; a, d), T2 (middle; b, e) and T3 (bottom; c, f) from mid-July to mid-August.

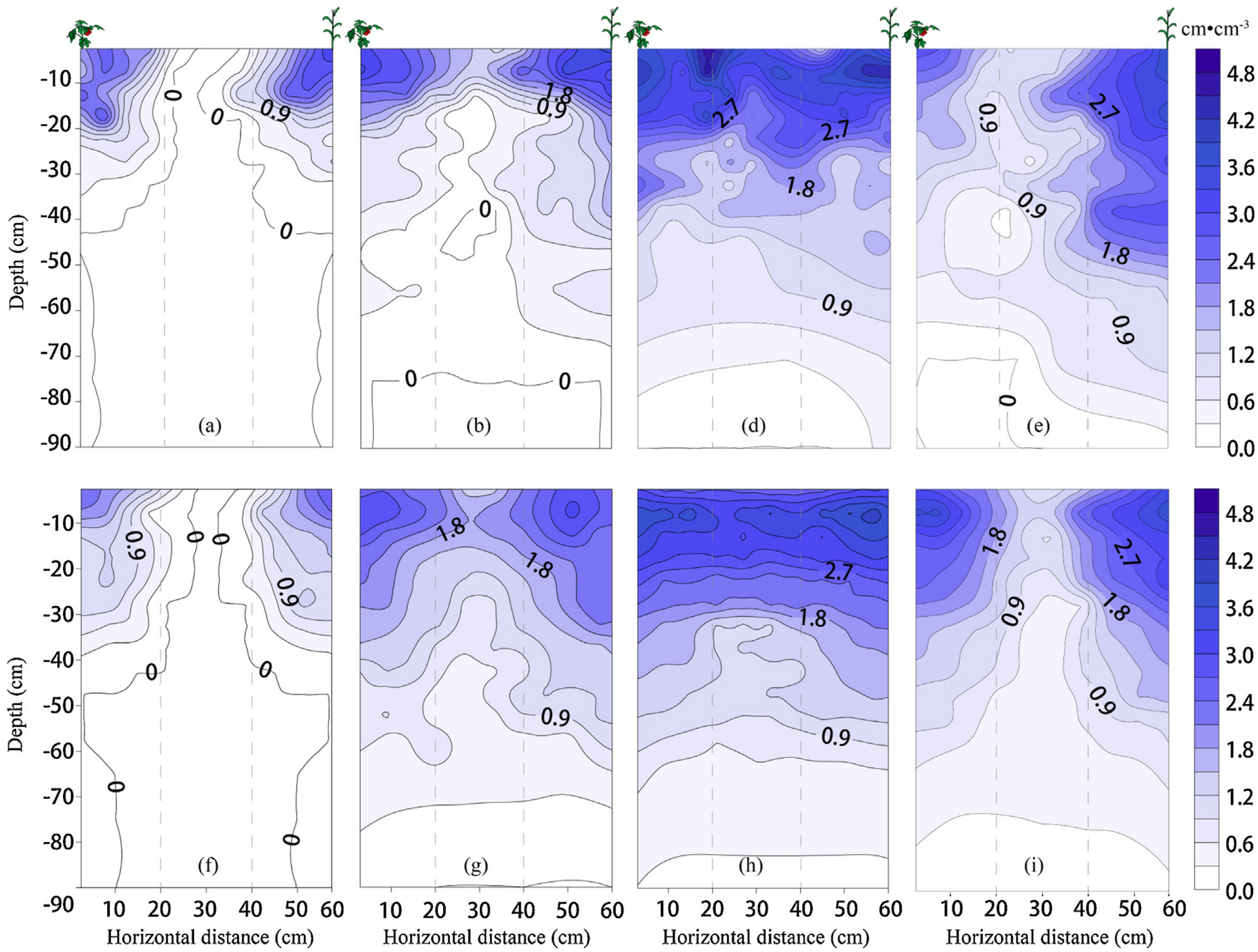

Fig. 5. Two-dimensional root length density distributions at different growth stages.
(left: a, f) Initial stage; (b, g) Development stage; (c, h) Mid-season stage; (right: d, i) Late season stage; in the 2012 (top) and 2013 (bottom) seasons.

3.3. *The root system growth during different growth stages in a drip-irrigated intercropping field*

To simplify the analysis, the sampled root region was divided into 3 sections (the dotted lines in Fig. 5) representing the tomato region, the bare region, and the corn region. The root length density (RLD) and root percentage for the three regions and the different crop growth stages are shown in Table 3. Since the crop roots were not yet entirely developed during the initial crop growth stage (from seeding to mid-June) and the root lateral distance was less than 20 cm, there were very few roots and little competition in the bare region (Table 3; Fig. 5). During the development crop growth stage (from mid-June to mid-July), the crop roots developed quickly and the roots of the two species extended into the bare region, resulting in an overlap of the two root systems and competition for soil resources. The percentage of roots in the bare region reached 18 25%, compared with only 3 4% during the initial growth stage (Table 3). However, the rooting depth was still rather shallow, within the top 30 cm. During the mid-season crop growth stage (from mid-July to mid-August), the root systems were already well developed, with the maximum expansion in both horizontal and vertical directions. The roots of both plants extended into the bare region, which now contained almost one third of all roots (30 33%). During the late crop growth stage (from mid-August to mid-September), tomatoes gradually wilted, since no irrigation was any longer given to the tomato strip, producing more dying roots than new ones. Additionally, the corn roots grew mainly downwards, producing more deep roots and fewer in the bare region. Consequently, there was a reduction in roots overlapping, and the percentage of roots in the bare region dropped to about 19 27%. The pattern of roots overlapping in this intercropping field thus developed from none to little to full and back to little again from the initial crop growth stage to the late season stage (Fig. 5), respectively.

Percentages of roots in the bare region developed as follows: 3.06, 18.0, 32.7, and 26.7% in the 2012 season, and 3.62, 24.8, 30.4, and 19.3% in the 2013 season from the initial crop growth stage to the late season stage (Table 3), respectively. Average percentages of roots in the tomato region during the 2012 and 2013 seasons were 32.8 and 36.2%, respectively, and in the corn strip 42.4 and 40.5%, respectively.

3.4. *The effect of irrigation amounts on root growth in a drip-irrigated intercropping field*

The largest overlap of the roots of the two species and the largest SWC variations in an intercropping field occurred during the mid-season crop growth stages. It is thus important to identify the effects of soil water contents on roots during this crop growth period. The root length density (RLD), root weight density (RWD), root volume density (RVD), and root surface area density (RSD) for every soil layer were averaged and analyzed (Table 4). The results show that the crop roots were concentrated mainly in the top 0 10 cm soil layer (Fig. 6) and that their content quickly decreased with depth. More than 50% of roots were in the top 0 20 cm soil

Table 3
RLD distributions in different soil regions at different growth stages during 2012 and 2013 seasons.

Region	Parameter	Year	Initial	Development	Mid-season	Late season
Tomato	Average RLD (cm/cm^3)	2012	0.83	1.21	2.21	1.29
		2013	0.91	2.14	3.01	2.36
	Root percentage (%)	2012	48.46	33.95	33.71	25.55
		2013	47.44	35.62	34.33	37.99
Bare	Average RLD (cm/cm^3)	2012	0.05	0.64	2.15	1.35
		2013	0.07	1.49	2.66	1.20
	Root percentage (%)	2012	3.06	17.98	32.71	26.68
		2013	3.62	24.83	30.39	19.26
Corn	Average RLD (cm/cm^3)	2012	0.83	1.71	2.20	2.42
		2013	0.96	2.38	3.09	2.98
	Root percentage (%)	2012	48.47	48.07	33.58	47.77
		2013	50.02	39.56	35.29	47.97

Table 4
Effects of different irrigation treatments on root distribution.

Treatment		RLD (cm cm^{-3})		RVD (cm^3 cm^{-3} × 10^{-3})		RSD (cm^2 cm^{-3})		RWD (g cm^{-3} × 10^{-3})	
irrigation		2012	2013	2012	2013	2012	2013	2012	2013
0 30	T1	2.84a	2.89a	8.06a	6.36a	0.64a	0.48a	1.74a	1.76a
	T2	2.54a	2.68b	6.86ab	6.13a	0.56a	0.45a	1.55ab	1.68a
	T3	2.18b	2.37c	5.95b	4.99b	0.50b	0.38b	1.33b	1.50a
30 100	T1	0.98a	1.07b	3.07a	1.59b	0.25a	0.14b	0.55a	0.57a
	T2	1.16a	1.15ab	3.55a	1.60b	0.28a	0.15b	0.63a	0.64a
	T3	1.28a	1.30a	3.68a	1.93a	0.30a	0.18a	0.63a	0.70a
Depth(cm)									
0–10		2.75a	2.88a	9.33a	7.24a	0.59a	0.50a	1.97a	1.74ab
10 20		2.71a	2.83a	6.57b	6.00b	0.60a	0.46b	1.55b	1.84a
20–30		2.10b	2.24b	4.97c	4.25c	0.51b	0.34c	1.09c	1.36ab
30–40		1.71c	1.66c	4.41cd	2.56d	0.38c	0.23d	0.84d	0.96b
40–60		0.85d	1.23d	3.54d	1.71e	0.26d	0.15e	0.53e	0.66bc
60–100		0.28e	0.49e	1.39e	0.77f	0.08e	0.07f	0.21f	0.21c
ANOVA		*P*-value							
Irrigation (0 30)		0.003	0.001	0.041	0.014	0.019	0.001	0.034	0.133
Irrigation (30 100)		0.145	0.012	0.358	0.070	0.338	0.004	0.580	0.149
Depth		0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Irrigation(0 100) × Depth		0.001	0.001	0.025	0.002	0.009	0.001	0.010	0.985

According to the Duncan's multiple range test, values followed by the same letter within a column are not significantly different at $p \leq 0.05$.

layer, reaching 60 70% in the top 0 30 cm soil layer. The average RLD and RWD percentages for all three treatments in the 0 30 cm soil layer were 68.9% and 71.9% in the 2012 season and 69.3% and 72.1% in the 2013 season, respectively.

The RLD, RWD, RVD and RSD were divided into two parts of 0 30 cm and 30 100 cm in order to study the effects of soil water on root growth under drip irrigation (Table 4). The results showed that there were significant differences in all four root measures ($p < 0.05$) in the 0 30 cm soil layer, except in RWD in the 2013 season. Highly significant differences were observed in RLD ($p < 0.01$) during the 2012 and 2013 seasons in the top 0 30 cm soil layer. However, although the overall crop root densities increased for deficit irrigation in the 30 100 cm soil layer, significant differences in RLD and RSD were observed during the 2013 season. There were highly significant differences in all four root parameters ($p < 0.01$) in the vertical direction, and the root densities significantly decreased with soil depth.

4. Discussion

4.1. The effects of irrigation treatments and location on SWCs and soil temperatures

Since the drip irrigation was used in our study, the wetting front usually did not travel further than about 30 40 cm below the soil surface, as was similarly reported in Machado and Oliveira (2005). Hence, SWCs were affected by the drip irrigation mainly in the region about 40 cm below the soil surface, and the higher the irrigation amounts, the higher SWCs (Table 2) (Patel and Rajput, 2008). Capillary rise from shallow groundwater caused higher SWCs at greater depths, especially in the 60 100 cm soil layer (Table 2; Fig. 3), as also observed by Ren et al. (2016). Due to capillary rise from groundwater, smaller irrigation amounts produced higher WUE, as also reported by Yahgi et al. (2013) and Ren et al. (2016).

Large observed differences in SWCs between different locations in an intercropping field were due to the presence of plastic mulch. Since no direct irrigation or mulching was applied in a bare region between double crop rows (P2), average SWCs were significantly lower in this region as compared to mulched regions (P1 and P3) (Table 2; Fig. 3) (see also Hou et al., 2010; Yahgi et al., 2013). SWCs were also slightly different between tomato (P1) and corn (P3) locations, because of different root water uptake and different irrigation amounts for the two species in an intercropping field (Fig. 3). Although more irrigation water was applied to corn (P3) than to tomato (P1), a higher water requirement and root water uptake of corn (P3) resulted in slightly lower SWCs than at the tomato location (P1), as also reported by Allen et al. (1998) and Li et al. (2015). However, SWCs at both P1 and P3 locations were still higher than at the bare location (P2) (Fig. 3).

Soil temperatures in an intercropping field were not affected only by soil water contents, but also by crops and location. Soil temperatures were higher at the corn row (P3) than at the tomato row (P1) (Fig. 4). One reason for that was that SWCs at the corn location (P3) were lower than at the tomato location (P1) (Table 2). Since dry soil has a lower heat capacity than wet soil, there are higher soil temperatures at lower SWCs during the daytime (as drier soil

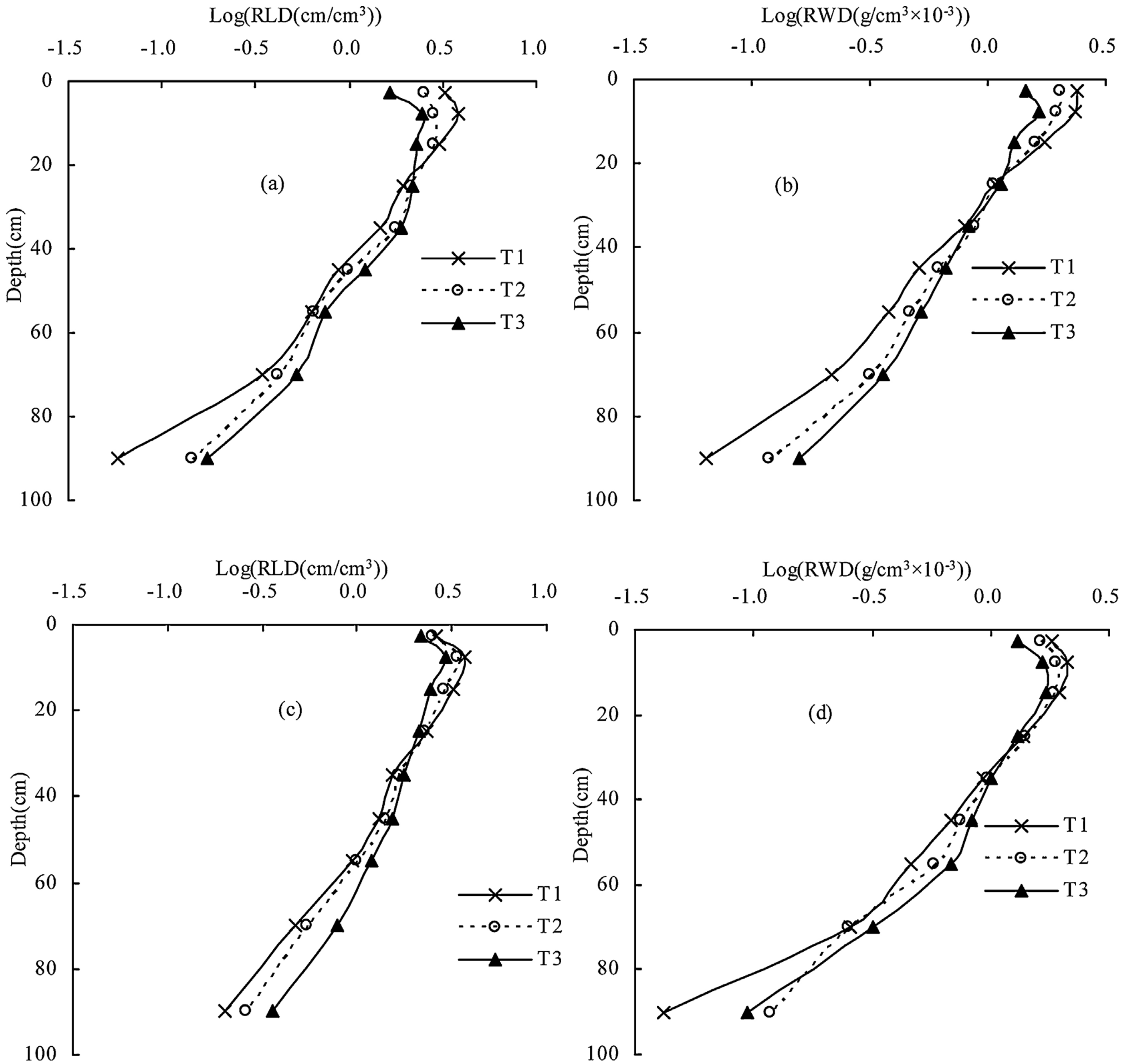

Fig. 6. Vertical distributions of RLD (left: a, c) and RWD (right: b, d) in the mid-season crop growth stage during the 2012 (top: a, b) and 2013 (bottom; c, d) seasons.

warms up more easily) (e.g., Hunt et al., 2010). Another reason was that tomato leaves spread out to shade the ground surface, while with corn, the sunlight could more easily reach the soil surface (Awal et al., 2006). The lowest SWCs and the maximum direct sunlight occurred at the bare location (P2), as compared to other locations. As a result, soil temperature of the topsoil was higher than at the tomato location (P1), but close to that recorded at the corn location (P3). The lowest soil temperature was observed in the 20 25 cm soil layer under the bare location (P2) (Fig. 4). Heat from the subsoil was more easily lost to the atmosphere through the bare soil surface without mulch (Yahgi et al., 2013). Therefore, there were much higher differences in soil temperatures between the topsoil (0 5 cm) and the subsoil (20 25 cm), compared to locations with mulch (P1 and P3) (Fig. 4).

4.2. The effects of irrigation treatments and location on the root growth

Root distribution plays an important role in the interactions between species within intercropping fields. In such fields, root distributions are different for different species in time and space, and there is interspecies competition for resources, such as soil water and/or nutrients, which is very different from monoculture fields (Mushagalusa et al., 2008). In the corn/tomato intercropping field, the corn root system was more developed than the tomato root system, and also more than that of the cabbage (Zhang and Huang, 2003) and cowpea (Adiku et al., 2001). Especially during the late season, the corn root percentages were 9.98% and 22.2% higher than for the tomato during the 2012 and 2013 seasons, respectively. Based on the percentage of roots in different regions (Table 3) and the two-dimensional root profile (Fig. 5), the roots developed first both laterally and vertically, and then degenerated. Consequently, the roots of the two crop species first displayed no overlap, then significant overlap, and finally again less overlap during the late crop growth. The overlap of the two root systems in time and space in the intercropping field may lead to the interspecies competition for soil water and/or nutrients. The less competitive crop may thus occasionally experience stress due to deficiency of soil water and/or nutrients (Zhang and Huang, 2003; Mushagalusa et al., 2008). When conventional surface irrigation is applied, it is difficult to achieve high WUE for both crop species. However, high WUE for both crop species can be achieved with drip irrigation, which can directly target different demands by the two crop species at the same time. Drip irrigation also could easily be adjusted to mainly wet the soil with roots by changing the irrigation amount, which could improve the WUE and reduce wasteful evaporation and deep drainage. This demonstrates the advantage of intercropping fields (Sampathkumar et al., 2012; Li et al., 2015).

There was a large influence of SWCs on root growth; RLD and RWD increased with decreasing irrigation amounts in the top layer and decreased below the 30 cm soil depth. Higher drip irrigation amounts produced higher SWCs in the 0 30 cm soil layer (wetted by irrigation), producing a well-developed root system in this soil layer (Fig. 6). Similar observations were made by Sharp and Davies (1985), who also observed increased root growth under a mild water stress compared to well-watered conditions. Since there was an insufficient amount of soil water in the upper soil layer during deficit irrigation, while soil water was available in the subsoil, especially in the 60 100 cm soil layer (Fig. 3), roots tended to grow downward toward these water sources. Consequently, more roots were often measured in the subsoil for deficit irrigation (Sharma et al., 2014). For example, the root densities in the T3 treatment in the 0 30 cm soil layer were lower than in the T1 and T2 treatments, but the opposite was observed in the 30 100 cm soil layer. However, the roots in the 0 30 cm soil layer still accounted for a majority of roots in all treatments. The root densities were higher for the high irrigation treatment than for the low irrigation treatment in the entire root system.

5. Conclusions

SWCs, soil temperatures, and crop root growth were observed and analyzed for different irrigation treatments and at different locations in a drip-irrigated intercropping field with plastic mulch. The effects of irrigation amounts on the distribution of SWCs, soil temperatures, and root growth, and the differences in different locations (mulch in tomato, corn surface and non-mulch in bare surface) were studied. SWCs for different irrigation treatments and at different locations were significantly different in the 0 40 cm soil layer, with the highest SWC measured at the tomato location and the lowest SWCs at the bare location. There were much smaller differences in SWCs in the 40 100 cm soil layer between different irrigation treatments and different locations. Almost no differences in SWCs were observed in the 60 100 cm soil layer.

There were different soil temperatures in the 0 10 cm soil layer, and especially in the 0 5 cm soil layer, among different irrigation treatments and different locations. Soil temperature at the mulched locations (P1 and P3) was higher than at the non-mulched bare location (P2) in the subsoil (15 25 cm). The maximum difference in temperatures in the vertical direction was measured at the non-mulched location. The soil temperature at the tomato location (P1) was lower than at the corn (P3) and bare (P2) locations.

The crop root pattern of "no, little, maximum, and little overlap" was observed between the initial crop growth stage and the late season growth stage. The percentage of roots in the bare region developed from small, to intermediate, to large, and back to small during the growth season. The majority of crop roots were in the top 0 30 cm soil layer (soil wetted by drip irrigation), where about 60 70% of the roots were located. There were significant differences in RLD, RWD, RVD, and RSD among different irrigation treatments. Higher irrigation amounts produced higher RLD and RWD in the 0 30 cm soil layer, and lower RLD and RWD in the 30 100 cm soil layer.

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