Root distribution and yield responses of wheat/maize intercropping to alternate irrigation in the arid areas of northwest China

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ABSTRACT

A field experiment was conducted to investigate the effects of alternate irrigation (AI) on root distribution and yield of wheat (*Triticum aestivum* L.)/maize (*Zea mays* L.) intercropping system during the period of 2007–2009 in an oasis of arid north-west China. Five treatments, i.e. sole wheat with conventional irrigation (W), sole maize with alternate irrigation (AM), sole maize with conventional irrigation (CM), wheat/maize intercropping with alternate irrigation (AW/M), and wheat/maize intercropping with conventional irrigation (CW/M). The results showed that root growth was significantly enhanced by alternate irrigation (AI), root weight density (RWD), root length density (RLD) and root-shoot ratios (R/S) in AI treatments were all higher than those in conventional irrigation (CI) treatments. Moreover, intercropped wheat and maize also had a greater root development at a majority of soil depths than wheat and maize in monoculture. In three years, AW/M always achieved the highest total seed yield under different treatments. Higher yield and reduced irrigation resulted in higher water use efficiency (WUE) for the AW/M treatment. Our results suggest that AI should be a useful water-saving irrigation method on wheat/maize intercropping in arid oasis field where intercropping planting is decreased because of limited water resource.

Keywords: intercropping; root growth; irrigation; *Triticum aestivum*; *Zea mays*

Intercropping is the agricultural practice of cultivating two or more crops in the same space at the same time (Andrews and Kassam 1976), an intensive management for crop production both in time and in space. Compared to corresponding sole crops, higher agricultural resources utilization of intercropping were recorded in many studies, i.e. radiation use efficiency (Tsubo et al. 2001, Awal et al. 2006), nutrient use efficiency (Li et al. 2001, 2009, Rowe et al. 2005), water use efficiency (Reddy and Willey 1981, Morris and Garrity 1993), and land use efficiency (Zhang et al. 2007, Banik et al. 2009). It was long practiced in many parts of the world (Francis 1986). In China, one-third of the cultivated lands is used with intercropping systems and produces about half of the total grain yield (Zhang and Li 2003). It can be said that intercropping has played a very important role in securing food supply and increasing farmers' income in China (Zhang et al. 2007).

Wheat/maize intercropping system has a long history in grain production in northwestern China, especially in areas with irrigation where climatic conditions allow only one cropping season annually (Li et al. 2001). In the 1970s, wheat/maize intercropping system was introduced to Hexi Corridor of Gansu Province PRC, a typical oasis agricultural region with abundant sunlight and temperature for developing intercropping; in the 1990s, the area under wheat/maize intercropping was extended by more than 300 000 ha every year, and the average yield was higher than 13 500 kg/ha. It contributed a lot in resolving the conflict between ever increasing food demand and gradually decreasing area of arable land in that area. However, it was investigated that yield increase was mainly attained from the amounts of water used in irrigation to satisfy the biological characteristics of water demand.

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In recent years, competition for limited water resources has resulted in serious loss of natural vegetation, gradual soil desertification in the oasis region of northwest China (Kang et al. 2004). It has become an urgent issue to improve water use efficiency through proper irrigation design and management. Alternate irrigation (AI) has been proposed from this consideration and applied successfully in some cases on field crops and fruit orchards (Dry and Loveys 1998, Kang et al. 1998, Kirda et al. 2004, Du et al. 2006, Shahnazari et al. 2007). In most cases, AI showed a great potential to increase WUE and to maintain yield.

Water management under alternate irrigation mainly focuses on efficient use of limited soil water. Root growth is critical for crops to use soil water and obtain high yield under water deficit conditions (Robertson et al. 1993). Even though only a fraction of roots are distributed in deep soil, they play a very important role in plants for the maintenance of life activities and in the adaptation to adverse environments (Gale and Grigal 1987, Jackson et al. 1996). Some studies showed that moderate water stress would help root systems grow toward deeper soil (Zhang et al. 1997). In this study, we carried out a field experiment to investigate the effects of alternate irrigation on the root distribution, yield and water use efficiency of wheat/maize intercropping in an arid oasis area where irrigation is virtually the only way for the crop to receive water.

MATERIALS AND METHODS

Experimental site

The field experiment was conducted during 2007–2009 at the experimental station of Gansu agricultural university, Huangyang town, Liangzhou section, Wuwei city, Gansu province of PRC (about 37°52'20''N, 102°50'50''E). This station is in the eastern part of the Hexi corridor of Gansu province (Figure 1), located at the temperate arid zone in the hinterland of the Euro-Asia Continent, with the average annual sunshine duration of more than 3010 h, annual accumulated temperature above 10°C of more than 2985.4°C. The frost-free period is 160–180 days, mean annual precipitation of 110 mm (the precipitation during June–September accounts for 60% of the annual precipitation), and the total precipitation vary considerably from year to year, 192.9 mm was received during the 2007 growing season, 103.7 mm during the 2008 growing season and 96.7 mm during the 2009 growing season, respectively. Mean annual evaporation from a free water surface was 2644 mm, which exceeds precipitation throughout the year. The ground water table depth is consistently 14–18 m under ground.

The study was established in a field consisting of silt loam. Soil depth in the region averages 150 cm. The top layer of the soil (0–40 cm) contains 15.90 g organic matter, 0.85 g total nitrogen, 60.43 mg available nitrogen, 0.93 g total phosphorus, 6.22 mg available phosphorus, and 236.24 mg available potassium per kilogram of dry soil, and with averaged field moisture capacity of approximately 0.278 cm^3/cm^3 in the upper 1.5 m of the soil profile and soil bulk density of about 1.33 g/cm^3. The experimental field was cropped previously for sole-cropped wheat (*Triticum aestivum*).

Experimental design

The field experiment included five treatments, i.e. sole wheat with conventional irrigation (W), sole maize with alternate irrigation (AM), sole maize with conventional irrigation (CM), wheat/maize intercropping with alternate irrigation (AW/M), and wheat/maize intercropping with conventional irrigation (CW/M). Alternate irrigation (AI) means that one of the two neighboring furrows was alternately irrigated during consecutive watering in sole maize, and was alternatively watered in a separate band according to different water demands of wheat and maize in wheat/maize inter-

Figure 1. A schematic map of the study region

Table 1. Details of irrigation on wheat and maize grown in different treatments in arid areas

Treatments	Irrigation details (mm)								
	wheat seedling	maize seedling	wheat booting	maize big rumpet	wheat filling	maize heading	maize flowering	maize filling	irrigation amount
W	75.0	–	120.0	–	75.0	–	–	–	270.0
AM	–	75.0	–	90.0	–	75.0	60.0	60.0	360.0
CM	–	75.0	–	90.0	–	75.0	60.0	60.0	360.0
AW/M	37.5	37.5	60.0	45.0	37.5	37.5	30.0	30.0	315.0
CW/M	45.0	0.0	80.0	0.0	65.0	0.0	80.0	45.0	315.0

W – sole wheat with conventional irrigation; AM – sole maize with alternate irrigation; CM – sole maize with conventional irrigation; AW/M – wheat/maize intercropping with alternate irrigation; CW/M – wheat/maize intercropping with conventional irrigation

cropping. Conventional irrigation (CI) was the conventional way where every row was irrigated during each watering. The timing of irrigation strictly followed the local practice and the amount of irrigation was based on conventional irrigation water amount in the local planting practice during 3 years (Table 1).

The field experiment had 15 plots in total, arranged in a randomized block design with three replicates per treatment. Each plot area was 48 m^2 (4.8 × 10 m), with a 50 cm wide space ridging between two neighboring plots to eliminate the effect of lateral soil water movement. The furrows inside the plot were used for irrigation as the treatments specified in Figure 2. The irrigation water was supplied by the pipes with a diameter of 0.13 m and the amount of water applied was measured with a water meter installed at the discharging end of the pipes.

In strip intercropping system, wheat and maize was planted in a west-east row orientation in alternating 160 cm wide strips, each wheat strip consists of a 80 cm wide wheat strip (six rows of wheat with 12 cm inter row distance), and a 80 cm maize strip of two rows with 40 cm inter-row distance. There was a 30 cm wide gap between wheat and maize strips (Figure 2).The spacings were specially designed to represent typical intercropping practices in the region. The planting density was 675 000 plants/ha for wheat and 82 500 plants/ha for maize. In order to compare the intercropping with sole cropping in the present study, the structure and density of wheat or maize in sole cropping is the same as that in intercropping.

Crop management

In 2007, the field was ploughed on March 18. All plots were given identical applications of N at 300 kg/ha as ammonium nitrate and of P at 200 kg/ha as ammonium dihydrogen phosphate. The rates of fertilization were recommended by the local agronomists for intercropping systems. All the P fertilizer and one half of the N was evenly broadcast and incorporated into the soil prior to sowing; the other half of the N fertilizer was divided into two portions applied at the elongation stage and the pre-tasselling stage for intercropped and sole cropped maize. Before preparation of the experimental land, a 120-mm winter water was applied in the last year.

Selected spring wheat and maize cultivars were Yong-liang 4 and Sheng-dan 16, respectively. In 2007, the dates of sowing were March 25 for wheat and April 16 for maize. The dates of harvest were July 28 for wheat and October 2 for maize.

In 2008, the field was ploughed on March 21. The seeds were sown on March 25 for wheat and April 16 for maize. The dates of harvest were July 23 for wheat and September 28 for maize.

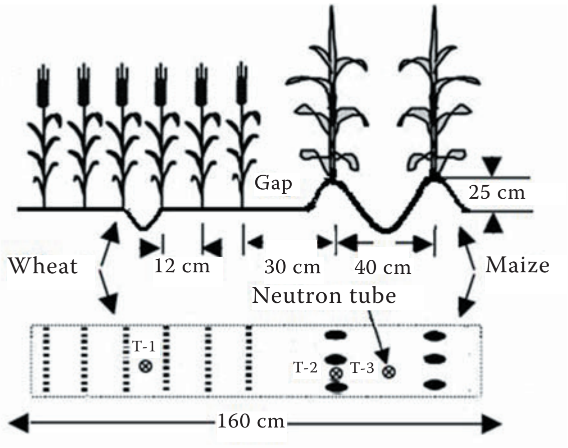

Figure 2. Layout of alternate irrigation for wheat/maize intercropping in field experiment. T-1, T-2 and T-3 indicate the positions of aluminums access tubes, which were used to measure soil moisture of different root-zones

In 2009, the field was ploughed on March 19. Dates of sowing were March 26 for wheat and April 8 for maize. The dates of harvest were July 15 for wheat and September 26 for maize. The cultivar, fertilizing, insect control and strip form in all plots were the same during the 3 years.

Measurements

Root sample collection. A monolith method (Smit et al. 2000) was adapted to sample roots at different growth stages of wheat and maize during 3 years. Soil samples were collected under wheat and maize row at 10 cm thickness to the maximum possible depth of 80 cm to determine the vertical root distribution. Trenches with the long wall perpendicular to the crop row were dug manually in each of the plots. To determine the horizontal distribution of roots, the trenches included at least a complete strip of an intercropped combination of two crop species, and at least three-row spacing for sole wheat and one-row spacing for sole maize. After the trenches had been dug, the working face or wall of the profile was smoothed, and then marked with a 10 × 10 cm grid line on the profile wall. Soil blocks with 10 cm length, 10 cm width, and 10 cm depth (1000 cm^3) were taken from the smoothed wall layer by layer, using a broad knife and metal sheets sharpened on one side. The collected samples were sealed in plastic bags and stored in a refrigerator with 4°C quickly for 20 h. New roots were then separated by hand from old dead roots, soil particles and debris, and washed free of soil with tap water in the laboratory. The roots of wheat and maize were distinguished by their different colors, textures and rooting patterns. In the wheat/maize intercropping, for example, the roots of wheat were yellowish and hairy compared to those of maize, which had smooth surfaces and white color.

The plant and root samples were dried at 80°C until the weights of the samples became constant when weighed. Root weight density (RWD) was calculated by dividing the root weight (g) with the volume (cm^3) of the sampling block. Root/shoot ratio (R/S) is the root dry weight over the shoot dry weight.

Root lengths were estimated by counting the number of intersections of roots with a 1 cm mesh grid, using the modified Newman-line-intersect method (Tennant 1975). Root length density (RLD) for each block was calculated from the volume (cm^3) of the soil sample and the length of roots (cm) of each species.

Yield and water use efficiency. The total grain yield of each plot was determined by hand harvesting 5 m of each row in each plot at maturity. All the harvested seeds were weighed for each plot as final yield in 3 years.

The approximate evapotranspiration (ET_c) (in mm) of each plot was determined using water balance equation as follows:

$$ET_c = P + I + S_o - S_h \qquad (1)$$

Where: P is the rainfall in the growth period (mm) (Figure 3), I is the irrigation quota (mm), S_o and S_h is the amount of soil moisture stored in 1.5 m depth at planting and harvesting (mm), respectively, based on the mean value from the tubes in each plot. Soil surface water contents were measured using the oven drying method, while a neutron probe (NMM 503DR, USA) was used to measure soil water contents from 30 to 90 cm depth by 20 cm increments and from 90 to 150 cm depth by 30 increments.

Water use efficiency (WUE) was calculated using the following formula:

$$WUE = \frac{Y}{ET_c} \qquad (2)$$

Where: Y is the total seed yield of each plot, ET_c is the total actual evapotranspiration over the whole growing season calculated from Eq. (1).

Statistical analysis

Final results were analyzed by the Duncan's multiple-range test using Statistical Analysis Software (SPSS software, 13.0, SPSS Institute Ltd, USA). All the treatment means were compared in the same column or row for any significant differences using the Duncan's multiple range tests at the significance level of 0.05.

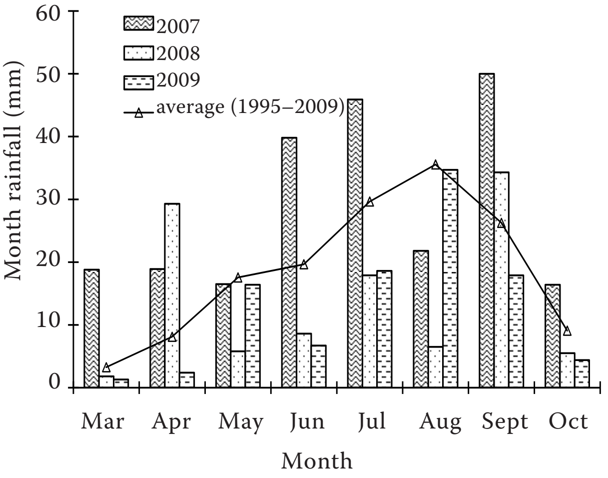

Figure 3. Distribution of rainfall at the trial site in 1995–2009

RESULTS AND DISCUSSION

Vertical root distribution

Vertical root distribution of wheat in different treatments at different growth stages are presented in Table 2. The results showed that RWD gradually decreased with soil depth. The RWD of intercropped wheat had a higher RWD at all soil depths than sole-cropped. At heading stage, compared to W treatment, AW/M and CW/M treatment increased wheat RWD by 11.7 to 67.9% and 10.8 to 46.9%, respectively, and significant differences were observed at a majority of soil depths ($P < 0.05$). In addition, AW/M treatment had significantly higher RWD below 20 cm soil depth than CW/M treatment. The greater RWD in AW/M treatment resulted in greater ability to take up water and nutrients, which can effectively use soil moisture and keep soil water balance. When wheat reached filling, the total RWD of wheat in all treatments peaked, and then declined, the differences in RWD among treatments had the same trend and became larger when measured below 30 cm soil depth. At maturity stage, RWD in the top 30 cm soil decreased, but that below 30 cm soil depth increased in all treatments.

Table 2. Root weight density (10^{-4}g/cm^3) of wheat under different treatments at jointing, heading, filling and maturity stage of wheat in arid areas during 2007–2009

Year	Soil depth (cm)	Jointing stage			Heading stage			Filling stage			Maturing stage		
		W	AW/M	CW/M	W	AW/M	CW/M	W	AW/M	CW/M	W	AW/M	CW/M
2007	0–10	1.29^{c}	2.53^{a}	2.80^{a}	2.77^{c}	3.27^{b}	3.64^{a}	5.98^{a}	6.12^{a}	6.07^{a}	5.30^{a}	3.67^{c}	4.22^{b}
	10–20	0.92^{b}	1.41^{a}	1.31^{a}	1.13^{b}	1.41^{a}	1.21^{b}	1.72^{b}	2.63^{a}	1.99^{b}	1.41^{c}	2.62^{a}	1.92^{b}
	20–30	0.43^{b}	0.60^{a}	0.64^{a}	0.57^{b}	1.06^{a}	0.52^{b}	1.63^{c}	2.01^{b}	3.28^{a}	1.30^{b}	1.69^{a}	1.38^{b}
	30–40	0.07^{b}	0.35^{a}	0.29^{a}	0.42^{c}	0.95^{a}	0.66^{b}	1.48^{b}	1.83^{a}	1.59^{b}	1.57^{b}	1.75^{b}	1.93^{a}
	40–50	0.15^{b}	0.26^{a}	0.33^{a}	0.27^{b}	0.40^{a}	0.28^{b}	1.13^{b}	1.29^{a}	0.89^{c}	1.29^{b}	1.27^{b}	1.34^{a}
	50–60	0.08^{b}	0.19^{a}	0.13^{a}	0.18^{b}	0.25^{a}	0.22^{a}	0.83^{a}	0.67^{b}	0.40^{c}	1.25^{a}	0.97^{b}	0.42^{c}
	60–70	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{c}	0.16^{a}	0.07^{b}	0.70^{a}	0.84^{a}	0.41^{b}	0.36^{a}	0.17^{c}	0.23^{b}
	70–80	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.22^{a}	0.21^{a}	0.01^{b}	0.32^{b}	0.44^{a}	0.25^{c}
2008	0–10	1.76^{b}	1.99^{a}	2.09^{a}	2.39^{b}	2.36^{b}	2.94^{a}	5.51^{a}	4.57^{b}	4.90^{b}	3.49^{b}	4.58^{a}	4.57^{a}
	10–20	1.19^{b}	1.53^{a}	1.41^{a}	1.29^{b}	1.69^{a}	1.58^{a}	1.14^{b}	2.93^{a}	0.90^{c}	1.29^{b}	1.63^{b}	2.66^{a}
	20–30	0.45^{b}	0.62^{a}	0.60^{a}	0.54^{b}	0.55^{b}	0.63^{a}	1.40^{b}	1.82^{a}	1.77^{a}	0.38^{b}	0.73^{a}	0.45^{b}
	30–40	0.34^{b}	0.46^{a}	0.41^{a}	0.46^{a}	0.47^{a}	0.46^{a}	2.09^{b}	2.57^{a}	1.52^{c}	0.34^{b}	0.74^{a}	0.29^{b}
	40–50	0.08^{b}	0.32^{a}	0.11^{b}	0.33^{b}	0.35^{b}	0.39^{a}	0.62^{c}	1.82^{a}	1.19^{b}	0.57^{c}	0.87^{b}	1.19^{a}
	50–60	0.06^{b}	0.18^{a}	0.07^{b}	0.27^{c}	0.48^{a}	0.38^{b}	0.38^{b}	0.95^{a}	0.78^{a}	0.61^{a}	0.51^{a}	0.13^{b}
	60–70	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{c}	0.32^{a}	0.16^{b}	0.14^{b}	0.21^{a}	0.13^{b}	0.38^{a}	0.31^{a}	0.08^{b}
	70–80	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{c}	0.21^{a}	0.03^{b}	0.30^{a}	0.09^{b}	0.10^{b}	0.49^{a}	0.22^{b}	0.05^{c}
2009	0–10	1.71^{b}	1.91^{b}	2.51^{a}	3.09^{b}	3.24^{b}	3.75^{a}	4.18^{c}	6.54^{a}	5.21^{b}	3.88^{a}	3.54^{b}	4.07^{a}
	10–20	0.91^{c}	1.29^{b}	1.64^{a}	0.60^{c}	1.54^{a}	1.28^{b}	2.21^{b}	3.36^{a}	2.55^{b}	1.94^{b}	2.52^{a}	1.85^{b}
	20–30	0.47^{b}	0.54^{b}	0.75^{a}	0.18^{c}	0.81^{a}	0.55^{b}	1.24^{c}	2.56^{b}	4.19^{a}	0.85^{b}	1.63^{a}	1.33^{a}
	30–40	0.20^{b}	0.32^{a}	0.21^{b}	0.04^{b}	0.62^{a}	0.06^{b}	0.59^{c}	2.03^{a}	1.07^{b}	0.92^{b}	1.69^{a}	1.86^{a}
	40–50	0.06^{c}	0.40^{a}	0.13^{b}	0.03^{b}	0.31^{a}	0.09^{b}	0.57^{c}	2.14^{a}	1.42^{b}	1.18^{b}	1.23^{a}	1.29^{a}
	50–60	0.07^{b}	0.10^{a}	0.06^{b}	0.03^{b}	0.14^{a}	0.10^{a}	0.50^{b}	0.86^{b}	1.03^{a}	0.41^{b}	0.93^{a}	0.41^{b}
	60–70	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{c}	0.18^{a}	0.06^{b}	0.45^{b}	1.08^{a}	0.52^{b}	0.27^{a}	0.23^{a}	0.22^{a}
	70–80	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.23^{a}	0.27^{a}	0.02^{b}	0.04^{b}	0.02^{b}	0.24^{a}

Means within the rows at the same growth stage followed by different letters are significantly different at $P_{0.05}$ level; values are mean of three plots of each treatment. Details of treatments are shown in Table 1

Table 3 shows the vertical root distribution of maize in different treatments at different growth stages. At heading growth stage, the RWD of maize in AI treatments was significantly higher than that in CI treatments below 20 cm soil depth, there were significant differences at a majority of soil depths among treatments ($P < 0.05$). As the crop grew, the roots penetrated further to the deeper soil layer, but the RWD at the shallow soil layer still remained the highest. At filling and maturity stage, the RWD of maize below 30 cm soil layer in AI was also significantly increased than that in CI. Compared to CM treatment, AM treatment increased the mean RWD below 30 cm soil depth by 54.5 to 66.1% at heading, 34.8 to 69.4% at filling and 25.7 to 57.2% at maturity, meanwhile, AW/M treatment increased mean RWD below 30 cm soil depth by 16.1 to 82.9% at heading, 47.5 to 53.5% at filling and 22.8 to 39.8% at maturity compared to CW/M treatment in the three years of study.

Horizontal root distribution

Horizontal root distribution was significantly influenced by different treatments. At each of the growth stages when the root weight was measured, the RWD of each section in the horizontal direction decreased gradually with increasing distance from the crops row (Figure 4). Before wheat harvest, a high density of wheat roots extended up to the maize row in wheat/maize intercropping, the RWD were the highest immediately under the wheat row and declined progressively toward the maize row. The average RWD of wheat at 10 and 20 cm from the wheat row were 52.5% and 31.8% of RWD at the wheat row position in AW/M treatment. Compared to CW/M treatment, AW/M treatment significantly increased mean wheat RWD in 30 to 60 cm soil depth by 35.0 to 92.5% and 60.0 to 114.5% at 10 and 20 cm distance from the wheat row, respectively. Horizontal root spread in

Table 3. Root weight density (10^{-4}g/cm^3) of maize under different treatments at shooting, heading, filling and maturity stage of maize in arid areas during 2007–2009

Year	Soil depth (cm)	Shooting stage				Heading stage				Filling stage				Maturity stage			
		AM	CM	AW/M	CW/M	AM	CM	AW/M	CW/M	AM	CM	AW/M	CW/M	AM	CM	AW/M	CW/M
2007	0–10	2.97^{c}	2.34^{d}	3.38^{b}	4.02^{a}	9.59^{b}	13.69^{a}	8.35^{c}	10.81^{ab}	14.66^{ab}	14.67^{ab}	12.21^{b}	18.03^{a}	20.23^{b}	22.51^{a}	18.73^{c}	21.60^{b}
	10–20	1.22^{a}	0.97^{b}	1.25^{a}	1.09^{b}	2.55^{b}	2.67^{b}	5.72^{a}	4.98^{a}	4.99^{b}	5.40^{b}	6.59^{a}	7.04^{a}	6.30^{b}	8.58^{a}	9.22^{a}	6.50^{b}
	20–30	1.04^{a}	0.75^{ab}	0.58^{b}	0.29^{c}	2.71^{ab}	1.67^{c}	2.10^{b}	3.78^{a}	3.44^{a}	3.56^{a}	3.14^{a}	2.57^{b}	4.70^{b}	3.67^{c}	6.31^{a}	3.64^{c}
	30–40	0.67^{a}	0.37^{b}	0.38^{b}	0.20^{c}	1.36^{b}	0.57^{c}	1.99^{a}	2.27^{a}	2.53^{a}	2.02^{ab}	1.84^{b}	1.19^{c}	3.97^{b}	2.62^{c}	4.72^{a}	2.53^{c}
	40–50	0.19^{b}	0.04^{c}	0.26^{a}	0.06^{c}	1.28^{b}	0.74^{c}	1.79^{a}	1.22^{b}	4.88^{a}	1.12^{c}	3.46^{a}	1.83^{b}	2.34^{a}	1.32^{b}	3.13^{a}	1.73^{b}
	50–60	0.08^{b}	0.00^{c}	0.15^{a}	0.00^{c}	0.35^{b}	0.05^{c}	0.99^{a}	0.51^{b}	1.86^{a}	0.60^{b}	1.84^{a}	0.30^{c}	1.39^{b}	1.16^{c}	2.31^{a}	1.86^{b}
2008	0–10	3.22^{b}	3.29^{b}	3.62^{ab}	2.36^{d}	10.19^{b}	13.82^{a}	9.74^{b}	10.90^{b}	15.70^{b}	18.65^{a}	15.14^{b}	15.49^{b}	18.93^{b}	20.42^{a}	17.99^{b}	18.30^{b}
	10–20	0.75^{c}	0.53^{c}	0.69^{c}	1.69^{a}	2.74^{b}	2.74^{b}	3.48^{a}	4.50^{a}	6.68^{b}	10.06^{a}	7.78^{b}	5.50^{b}	12.34^{a}	12.48^{a}	9.59^{b}	11.44^{b}
	20–30	0.16^{c}	0.23^{c}	0.71^{a}	0.55^{b}	1.46^{b}	1.54^{b}	2.83^{a}	1.95^{b}	5.08^{a}	4.65^{a}	3.35^{b}	2.97^{b}	2.33^{b}	1.34^{c}	3.12^{a}	2.97^{a}
	30–40	0.18^{d}	0.38^{c}	0.28^{d}	0.47^{b}	0.63^{a}	0.31^{b}	0.80^{a}	0.21^{b}	3.28^{a}	2.01^{b}	1.89^{b}	0.68^{c}	1.96^{b}	1.31^{c}	2.86^{a}	1.93^{b}
	40–50	0.13^{b}	0.19^{b}	0.00^{c}	0.35^{a}	0.94^{a}	0.23^{b}	1.07^{a}	0.13^{b}	1.99^{a}	1.89^{a}	1.31^{b}	1.02^{c}	2.20^{a}	1.88^{b}	1.96^{a}	1.76^{b}
	50–60	0.00^{b}	0.00^{b}	0.00^{b}	0.48^{a}	0.07^{c}	0.14^{b}	0.35^{a}	0.04^{c}	2.05^{a}	0.87^{b}	0.93^{b}	0.47^{c}	1.92^{a}	1.33^{b}	1.76^{a}	1.39^{b}
2009	0–10	3.85^{b}	4.21^{a}	4.30^{a}	3.24^{c}	12.25^{b}	14.50^{a}	10.68^{c}	13.81^{ab}	14.12^{b}	17.14^{a}	12.76^{b}	17.37^{a}	19.91^{a}	21.03^{a}	20.46^{a}	18.98^{a}
	10–20	1.16^{bc}	0.94^{d}	1.61^{a}	1.54^{a}	3.27^{b}	3.41^{b}	7.31^{a}	6.37^{a}	4.81^{b}	5.20^{b}	6.35^{a}	6.78^{a}	6.36^{c}	11.87^{ab}	10.17^{b}	12.25^{a}
	20–30	0.43^{c}	0.25^{d}	0.77^{b}	0.81^{a}	3.47^{b}	2.14^{c}	2.68^{c}	4.83^{a}	2.35^{b}	2.43^{b}	3.03^{a}	2.48^{b}	4.50^{b}	6.09^{a}	2.41^{c}	2.04^{c}
	30–40	0.27^{c}	0.65^{b}	0.86^{b}	0.62^{b}	1.74^{b}	0.72^{c}	2.91^{a}	1.65^{b}	1.47^{a}	0.95^{b}	1.78^{a}	1.15^{b}	2.10^{a}	1.10^{b}	2.05^{a}	1.93^{a}
	40–50	0.19^{b}	0.04^{c}	0.41^{a}	0.31^{ab}	2.92^{a}	0.95^{d}	2.29^{b}	1.56^{c}	4.70^{a}	1.08^{b}	1.41^{b}	0.80^{c}	2.02^{a}	0.40^{c}	2.29^{a}	1.29^{b}
	50–60	0.27^{a}	0.00^{c}	0.26^{a}	0.14^{b}	0.44^{b}	0.06^{c}	0.88^{a}	0.65^{ab}	2.35^{a}	0.58^{c}	1.81^{b}	0.29^{d}	1.42^{a}	0.87^{b}	1.44^{a}	0.79^{b}

Means within the rows at the same growth stage followed by different letters are significantly different at $P_{0.05}$ level; values are mean of three plots of each treatment. Details of treatments are shown in Table 1

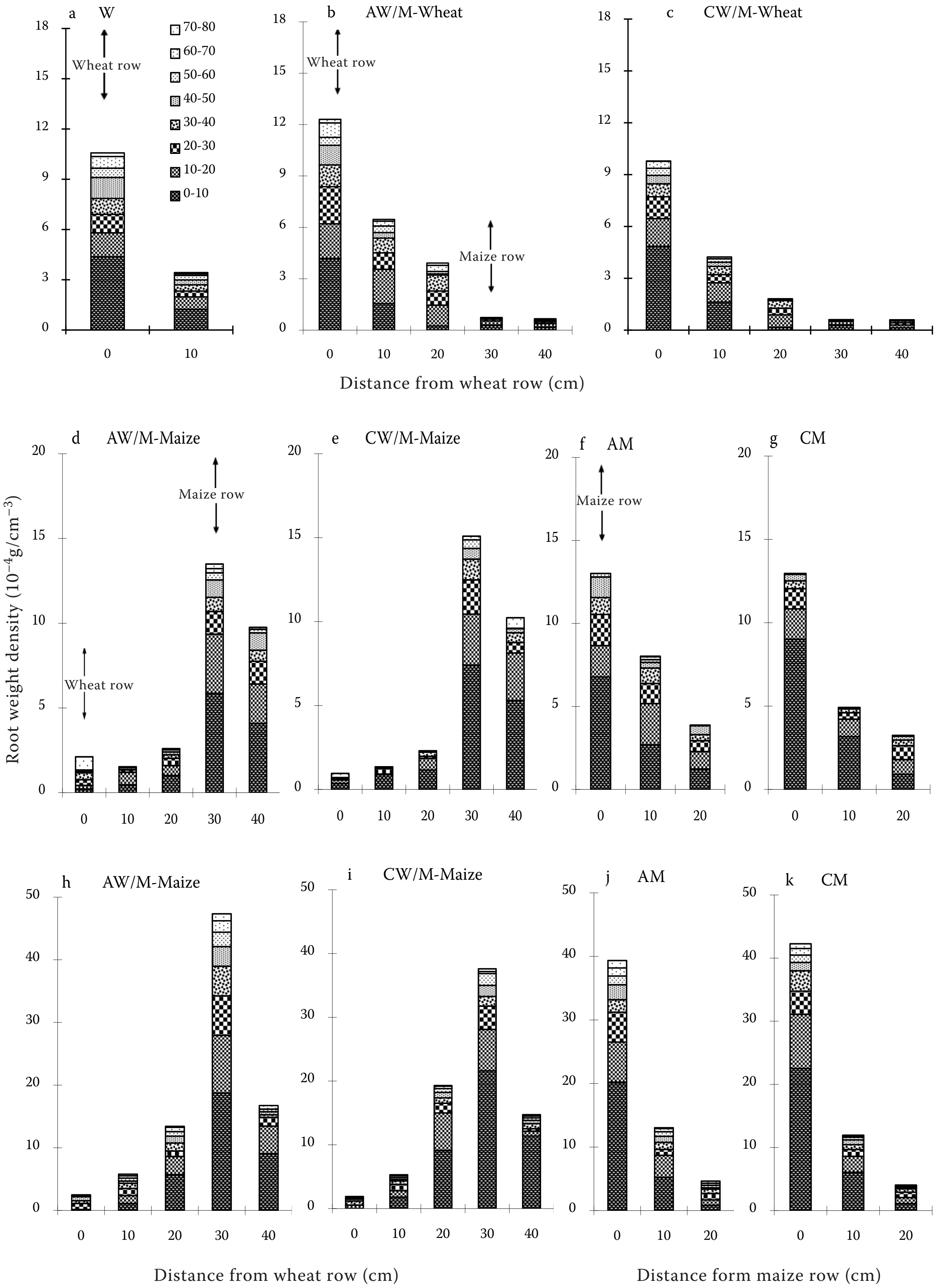

Figure 4. Root weight densities at different horizontal distances from the crop rows at the coexistence period of wheat (a–c) and maize (d–g), and maize (h–k) after wheat harvest under different treatments in 2007, values at different depths at the same sampling position are not additive

Table 4. Root length density (cm/cm^3) and root-shoot ratio of wheat and maize in all treatments in arid areas during 2007–2009

Crops	Treatments	2007				2008				2009			
		shoot dry weight	root dry weight	root-shoot ratio	root length density	shoot dry weight	root dry weight	root-shoot ratio	root length density	shoot dry weight	root dry weight	root-shoot ratio	root length density
		(g/plant)				(g/plant)				(g/plant)			
Wheat	W	10.01	1.99	0.20^{a}	0.82^{c}	7.47	2.15	0.29^{b}	1.43^{b}	7.09	1.91	0.27^{a}	0.86^{b}
	AW/M	9.31	2.12	0.23^{a}	1.22^{a}	8.09	2.58	0.32^{a}	2.27^{a}	8.59	2.33	0.27^{a}	1.37^{a}
	CW/M	9.66	2.02	0.21^{a}	1.02^{b}	8.14	2.37	0.29^{b}	1.78^{b}	8.31	2.27	0.27^{a}	1.29^{a}
Maize	AM	211.48	45.47	0.22^{c}	0.81^{bc}	179.85	53.81	0.30^{b}	0.94^{b}	201.40	65.75	0.33^{bc}	1.09^{b}
	CM	216.78	48.98	0.23^{bc}	0.69^{c}	184.61	46.6	0.25^{c}	0.98^{b}	208.66	56.95	0.27^{c}	0.71^{c}
	AW/M	196.76	55.45	0.28^{a}	1.23^{a}	175.67	72.66	0.41^{a}	1.49^{a}	198.55	88.79	0.45^{a}	1.29^{a}
	CW/M	207.37	52.08	0.25^{b}	1.02^{b}	194.07	66.70	0.34^{b}	1.02^{b}	219.34	81.50	0.37^{b}	0.94^{b}

Means within the columns for the same crop followed by different letters are significantly different at $P_{0.05}$ level; values are mean of three plots of each treatment. Details of treatments are shown in Table 1

sole cropping was significantly lower than that in wheat/maize intercropping. Compared to W treatment, AW/M and CW/M significantly increased mean RWD at 10 cm distance from the wheat row by 88.6% and 23.5%, respectively. In contrast with wheat, maize roots were mainly distributed directly under the maize row. The average RWD at 10 and 20 cm from the maize row toward the gap were only 17.2% and 10.1% of RWD under the row in wheat/maize intercropping, respectively.

After wheat harvest, intercropped maize occupied two crops rootzones, expanding the scope of water and nutrient absorption. AW/M treatment significantly increased RWD at 10 and 20 cm from the maize row below 30 cm soil depth by 34.9 to 67.2% and 23.3 to 79.2% than CW/M treatment, respectively. As shown in the case of AW/M treatment, moderate soil drying implied enhanced translocation of phytosynthates to the roots, which is consistent with the theory (Smucker and Aiken 1992) that moderate amount of water deficit benefits to root growth. Compared to sole maize, wheat/maize intercropping significantly improved RWD in 0 to 60 cm depth at 10 and 20 cm distance from the maize row by 11.2 to 53.2% and 11.8 to 52.2%, respectively.

Root length density and root-shoot ratio

The RLD and R/S of wheat and maize in different treatments are shown in Table 4. For wheat, AW/M and CW/M treatment had significantly higher RLD than that in W treatment. Moreover, a significant difference in RLD was also found between AW/M and CW/M treatment. Compared to W treatment, AW/M and CW/M treatment significantly increased RLD by 48.1 to 59.9% and 24.1 to 50.2%, respectively. However, AW/M treatment slightly influenced growth of the aboveground parts of wheat plant; no significant differences in R/S were found among treatments.

For maize, AI treatments induced growth of the aboveground parts, but AI had higher root dry weight than CI treatments. Therefore, this results in higher R/S in AI treatments. Furthermore, R/S in intercropped maize was significantly higher than that in sole cropped treatment. On the other hand, higher RLD was observed in AW/M; apparently such response should enhance the maize absorptive capacity in AW/M.

Yield and water use efficiency

The result showed that the AI treatment on wheat/maize strip intercropping did not reduce crop production. On the contrary, the yield of intercropped maize in AI was always better than that in CI, and yield of intercropped wheat did not change significantly. Compared to CW/M, AW/M increased mean intercropped maize by 17.4% during 3 years. Moreover, wheat/maize intercropping has an obvious yield advantage in arid areas of northwest China (Table 5). Previous studies also showed that the yield in the wheat/maize inter-

Table 5. Yield and water use efficiency (WUE) (kg/ha/mm) in all treatments in arid areas during 2007–2009

Treatments	2007			2008			2009		
	yield (kg/ha)		WUE	yield (kg/ha)		WUE	yield (kg/ha)		WUE
	wheat	maize		wheat	maize		wheat	maize	
W	5714.6	–	12.52^{c}	6972.6	–	22.43^{c}	5542.0	–	17.58^{c}
AM	–	10481.9	18.69^{b}	–	10954.9	24.16^{a}	–	10743.9	23.23^{a}
CM	–	10763.1	19.03^{b}	–	11002.7	23.07^{b}	–	10344.6	18.12^{bc}
AW/M	3667.1	7423.7	20.47^{a}	3876.5	7298.7	25.12^{a}	3475.2	7482.5	25.00^{a}
CW/M	4013.8	6365.4	20.00^{a}	3926.3	5883.7	22.84^{c}	3581.4	6701.9	19.67^{b}

Means within the columns followed by different letters are significantly different at $P_{0.05}$ level; values are mean of three plots of each treatment. Details of treatments are shown in Table 1

cropping system was significantly greater than that in sole-cropping (Li et al. 2001). AW/M always achieved the highest yield during 3 years.

On the other hand, the highest WUE was obtained in AW/M treatment during 3 years. Compared to sole wheat and maize, AW/M significantly improved WUE by 12.0 to 63.5% and 6.4 to 20.9%, respectively. Furthermore, AW/M treatment significantly increased WUE by 2.4%, 10.0% and 27.1% than CW/M treatment in 2007, 2008 and 2009, respectively. Improved irrigation method (AI) with lower irrigation amount corresponded to the highest WUE; the higher WUE in AW/M could be attributed to a better root development and higher extraction of water. The extra benefit for AW/M treatment was that both the total seed yield and WUE were the highest during 3 years. Therefore, if the climatic conditions allow, AI method could be a useful improvement in irrigation practices on wheat/maize intercropping in areas where irrigation is the major water supply.

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