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Soil water distribution, uniformity and water-use efficiency under alternate furrow irrigation in arid areas

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Abstract Soil water distribution, irrigation water advance and uniformity, yield production and water-use efficiency (WUE) were tested with a new irrigation method for irrigated maize in an arid area with seasonal rainfall of 77.5–88.0 mm for 2 years (1997 and 1998). Irrigation was applied through furrows in three ways: alternate furrow irrigation (AFI), fixed furrow irrigation (FFI) and conventional furrow irrigation (CFI). AFI means that one of the two neighboring furrows was alternately irrigated during consecutive watering. FFI means that irrigation was fixed to one of the two neighboring furrows. CFI was the conventional method where every furrow was irrigated during each watering. Each irrigation method was further divided into three treatments using different irrigation amounts: i.e. 45, 30, and 22.5 mm water for each watering. Results showed that the soil water contents in the two neighboring furrows of AFI remained different until the next irrigation with a higher water content in the previously irrigated furrow. Infiltration in CFI was deeper than that in AFI and FFI. The time of water advance did not differ between AFI, FFI and CFI at all distances monitored, and water advanced at a similar rate in all the treatments. The Christiansen uniformity coefficient of water content in the soil (CU_s) was used to evaluate the uniformity of irrigated water distribution and showed no decrease in AFI and FFI, although irrigation water use was smaller than in CFI. Root development was significantly enhanced by AFI treatment. Primary root numbers, total root dry weight and root density were all higher in AFI than in the FFI and CFI treatments. Less irrigation significantly reduced the total root dry weight and plant height in both the FFI and CFI treatments but this was less substantial with AFI treatments. The most surprising result was that AFI maintained high grain yield with up to a 50% reduction in irrigation amount, while the FFI and CFI treatments all showed a substantial decrease of yield with reduced irrigation. As a result, WUE for irrigated water was substantially increased. We conclude that AFI is an effective water-saving irrigation method in arid areas where maize production relies heavily on repeated irrigation.

Introduction

Efficient irrigation is now essential in the Hexi Corridor of Northwest China because the ground water table is falling steadily year by year and the environmental deterioration is intensifying. The desert is expanding to some oases because of a shortage of water resources. At the same time, water resources are poorly managed, especially for irrigated agriculture. Studies have shown that agricultural water-use efficiency (WUE) in this area is relatively low (Kang et al. 1999). To reach a sustainable development, it is important to improve the existing irrigation systems and management practices.

Many ways to save agricultural water use have been investigated. Various researchers (Stewart et al. 1981; Musick and Dusek 1982; Hodges et al. 1989; Graterol et al. 1993; Stone and Nofziger 1993) have used wide-spaced furrow irrigation or skipped crop rows as a means of improving WUE. They selected some furrows for irrigation while other adjacent furrows were not irrigated for the whole season. In general, these techniques

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are a trade-off of a lower yield for a higher WUE. Water was saved mainly because of reduced evaporation from the soil surface, as is the case for drip irrigation.

Ideally, WUE should be improved by a reduced leaf transpiration. Stomata control the door of plant gas exchange and transpiration water loss. Recent investigations have shown that stomata may directly respond to the availability of water in the soil such that they may reduce their opening according to the amount of water available in the soil (Davies and Zhang 1991; Tardieu and Davies 1993). The advantage of such a regulation is that plant may delay the onset of an injurious leaf water deficit and enhance its chance of survival under unpredictable rainfall conditions; the so-called optimization of water use for CO_2 uptake and survival (Jones 1980; Cowan 1982). More recent evidence has shown that such a feed-forward stomatal regulation process works through a chemical signal, the increased concentration of abscisic acid (ABA), in the xylem flow from roots to shoots (Zhang and Davies 1989a, b, 1990, 1991). The part of the root system in drying soil can produce large amounts of ABA while the rest of the root system in wet soil may function normally to keep the plant hydrated (Zhang and Davies 1987; Zhang et al. 1987). The result of such a response is that the plant may have a reduced stomatal opening in the absence of a visible leaf water deficit.

To take advantage of such a plant response, Kang et al. (1997) suggested that irrigation might be designed so that part of the root system is exposed to drying soil while the remaining part is in wet soil. They hoped that such a design could lead to a reduced stomatal opening without leaf water deficit. Kang et al. (1998) also conducted an experiment with pot-grown maize plants where the plant root system was divided into two or three parts and watered alternately. Compared with conventional watering or watering on fixed parts of the root system, alternate irrigation on root-divided maize reduced water consumption by 35% with a total biomass reduction of only 6–11%.

The study reported in this paper took this approach in a field experiment on irrigated maize plants for two consecutive years. The hypothesis was that by irrigating alternate furrows, (1) less surface soil is wetted and less evaporation from the surface occurs, (2) more water alternately concentrated in a furrow may improve the conductivity of the soil–root system to water and fertilizers (Kang and Zhang 1997), and (3) more lateral roots are stimulated and a chemical signal is produced in drying roots to reduce the shoot water loss. In all, irrigation water use can be decreased while maintaining the same yield level, and hence the WUE might be enhanced. Such an approach was also encouraged by more recent investigations on grapevines (Dry et al. 1995; Fuller 1997). They suggested a partial rootzone drying approach and found that WUE was nearly doubled by using this technique.

Materials and methods

The field experiment was conducted during 1997/1998 at Xiaobakou Irrigation Experiment Station (38°05′N, 103°03′E), Mingqin County, Gansu, China. The area is in an arid zone with an average annual rainfall of about 110 mm and the ground-water table 13–18 m below the soil surface. The soil was a sandy loam and had a moderately slow water permeability and moderate organic matter content. Field capacity, defined as the water content at −0.02 MPa, was approximately 308 mm in the upper 1.0 m of the soil profile, and the bulk density was about 1.4 g cm^{-3}.

Experiments were conducted in the same field for both years. The maize cultivar (hybrid cv. Duanyu 13, high yield and moderate drought-tolerance), fertilization and insect control in all the plots were the same in both years. Sowing dates were 20 April and 11 April and harvest dates were 2 September and 28 August, respectively, for 1997 and 1998. The experimental design was a randomized block design with three replications. Each plot was 70 m long (in a 100 m field, final harvesting length 60 m) and 5 m wide (in five rows, the central three rows were harvested for yield assessment), and the plot area was graded to a slope of 0.4% in the direction of water flow before the maize was planted each year. Sowing density was 5 plants m^{-2}.

Three irrigation methods were designed and each method consisted of three levels of irrigation (nine treatments in all, see Table 1). The irrigation methods were alternate furrow irrigation (AFI), fixed furrow irrigation (FFI) and conventional furrow irrigation (CFI). AFI means that one of the two neighboring furrows was alternately irrigated during consecutive waterings. FFI means that irrigation was fixed to one of the two neighboring furrows. CFI was the conventional method, where every furrow was irrigated during each watering. In 1997, only two irrigation methods,

Table 1 Details of irrigation treatments on maize grown in arid areas. *AFI*, *FFI* and *CFI* are alternate, fixed and conventional furrow irrigation respectively. *Numbers* following treatment codes indicate different amounts of water irrigated each time. *DAS* Days after sowing

Year	Irrigation treatments	Irrigation details		
		Times (no.)	Amount (mm/time)	Timing (DAS)
1997	AFI2	7	30.0	39, 65, 77, 86, 96, 106, 123
	AFI3	7	22.5	
	CFI1	7	45.0	
1998	AFI1	7	45.0	40, 58, 72, 85, 100, 112, 125
	AFI2	7	30.0	
	AFI3	7	22.5	
	FFI1	7	45.0	
	FFI2	7	30.0	
	FFI3	7	22.5	
	CFI1	7	45.0	
	CFI2	7	30.0	
	CFI3	7	22.5	

AFI and CFI, and three treatments (Table 1) were applied because of the initial limitation of field size.

Soil water contents were measured with a neutron probe, at 5-day intervals, and in 20 cm increments from the surface to 100 cm deep into the profile. Apart from the regular measurements, soil water content was also measured the days before and after each irrigation. Tubes 1.2 m long, for the neutron probe, were installed in each plot for such measurements. They were placed in the central furrows, one for the CFI system, and two in both a wetted furrow and a dry furrow for AFI and FFI systems, respectively; with the first one at the head end of the furrows and the other tubes placed at 10 m intervals along the furrows for each treatment in order to analyze the soil water infiltration distribution along the furrows. Daily rainfall was measured with rain gauges installed at the experimental site.

Irrigation was applied at different intervals according to the soil water content measurements. During the seedling stage, when the soil water content in the upper 40 cm soil profile reached 40% of its field capacity in the CFI3 treatment of, plots were irrigated. After stem elongation, when such a value reached 45% in the upper 60 cm soil profile in the CFI3 treatment after the stem elongation stage, irrigation was applied. In total, seven irrigations were applied during the growing season for all the treatments (see details in Table 1).

The amount of water applied was measured with a flow meter installed on the gated plastic pipes. The flow rate for the treatments in both years was 0.95 l s^{-1} for one furrow. This flow rate was predetermined according to the technique of Merriam and Shearer (1980). The advance rates of water in the furrows were basically the same and the horizontal infiltration was minimized. Predetermined flow rates for FFI, AFI and CFI were not same for irrigation uniformity measurement plots, which were intended to compare the differences of the advance rates in three furrow irrigation systems. Equal advance rates are desirable so that horizontal infiltration for each treatment will be minimized. Water advance was determined at six distances from the front end to 1/6, 1/3, 1/2, 2/3, 5/6, and 6/6 of the furrow length in 1998.

Irrigation runoff was negligible in this study. Thus, the net amounts of irrigation were the amounts of water added to the field.

Furrows were irrigated with gated plastic pipes which delivered water to individual furrows and were controlled through calibrated orifices. After the water had wet the length of the furrow, the furrow stream was cut back until the designated amount of water had been applied.

It was very difficult to measure infiltration water depth at different points in the irrigated furrows directly. We used the uniformity coefficient of water in the soil to evaluate irrigation water distribution uniformity; the Christiansen uniformity coefficient of water content in the soil (CU_s) is defined as follows:

$$CU_s = \left[1 - \frac{\sum_{i=1}^{n} |\theta_i - \bar{\theta}|}{N\bar{\theta}}\right] \times 100 \tag{1}$$

where θ_i is the observed water content for the ith grid (cm^3/cm^3) and N is the number of grids, θ is the mean water content, i.e.:

$$\bar{\theta} = \frac{\sum_{i=1}^{n} \theta_1}{N} \tag{2}$$

Evapotranspiration was calculated using the formula:

$$ET = Rainfall + Total \ \ irrigation + S_g - D - R_f - \Delta W \tag{3}$$

where ET is evapotranspiration, ΔW is the soil water change (final minus initial), which was calculated by subtracting the total soil water content at 100 cm depth of soil profile determined during the calculated period, S_g is the capillary contribution from ground water table to the crop root zone, D is the downward drainage from the crop root zone, R_f is the surface water runoff. In this experiment, the ground water table was lower than 10 m, and S_g was negligible because when the ground water table is lower than 5 m below the ground surface, S_g is nearly zero (Zhang et al. 1995). R_f was negligible because rainfall was very small. Deep drainage D was evaluated graphically (Grimes et al. 1992; Saeed and El-Nadi 1997) by plots of cumulative dry matter yield as a function of total water from Rainfall + Total irrigation − ΔW. Drainage was taken into account by excluding data from dry matter yield-ET analysis.

Two kinds of water-use efficiency were estimated: total water-use efficiency (WUE_{ET}) is the yield produced per m^3 total water used:

$$WUE_{ET} = Yield/ET \tag{4}$$

and irrigation water-use efficiency (WUE_I) is the yield produced per m^3 irrigation water:

$$WUE_I = Yield/Total \ \ irrigation \tag{5}$$

During the maize growth season in 1998, on six separate dates (shown in Table 5) three plants were measured for their leaf transpiration rate and photosynthesis rate using a photosynthesis analysis system (CI-301PS, CID, USA). Prior to harvest for yield assessment, ten plants were sampled at random from interior rows of each plot for the determination of plant height, stem diameter, and total biomass accumulation in the shoot. The primary root numbers for these ten plants were also recorded. Total root biomass and root density in the soil was investigated in a 40 × 40 cm^2 area surrounding the plant and a 60 cm deep soil volume. Data were averaged for each plot. Final results were tested with Duncan's multiple-range test.

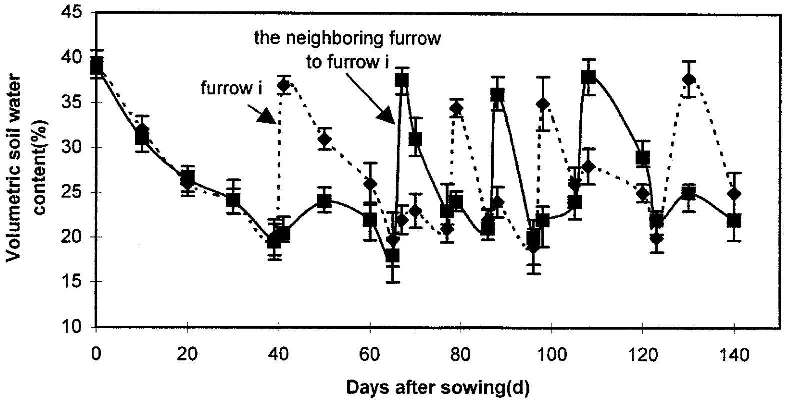
Results

Soil water distribution and water balance

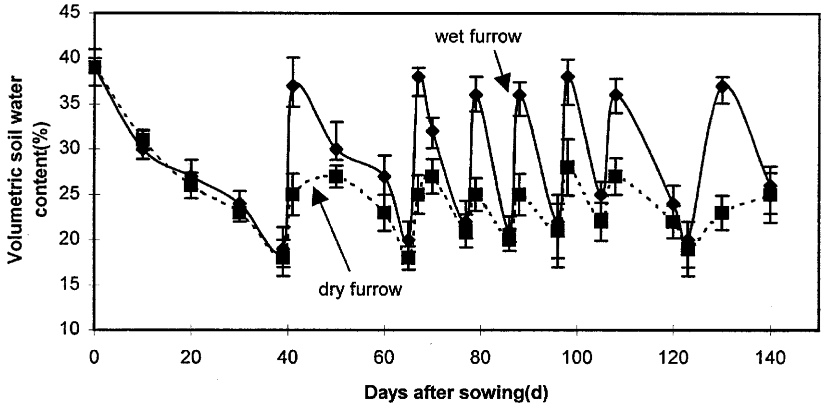
Average soil moisture changes in 50 cm soil depth for AFI, FFI and CFI in the maize growing season are presented in Fig. 1. Soil moisture distribution with soil depth in soil profiles perpendicular to the furrows are shown in Fig. 2 for AFI, FFI and CFI. It was shown that the soil water contents between the two neighboring furrows in AFI remained different until the next irrigation, with a higher water content in the previously irrigated furrow. This pattern of soil water distribution in the maize root zone should allow part of the root system to be always exposed to a drying soil.

The average soil water suction in the maize growing season, calculated from soil water content, is plotted against soil depth in Fig. 3 for the different irrigation treatments. The total irrigation amount was 315 mm for the CFI, and 210 mm for the AFI and FFI treatments chosen for this measurement. The irrigation amount for each furrow in the CFI was therefore only 75% of that for the irrigated furrows of AFI and FFI. Results showed that the average soil water suction in CFI was smaller than that in AFI and FFI. The average suction profiles for the two sides of the plants had no significant difference in AFI. In comparison, there was a huge difference in suction between the irrigated and non-irrigated furrows in FFI. The important result was that the average soil water suction was smaller in the middle layer, but larger in the shallow layer and deep layer in CFI than in AFI and FFI, and the zero flux plane (i.e. $\partial S/\partial z = 0$) occurred significantly at 70 cm depth. This demonstrated that deep percolation had occurred below 70 cm depth in the maize growing season in CFI. However, the zero flux plane did not occur in AFI and FFI.

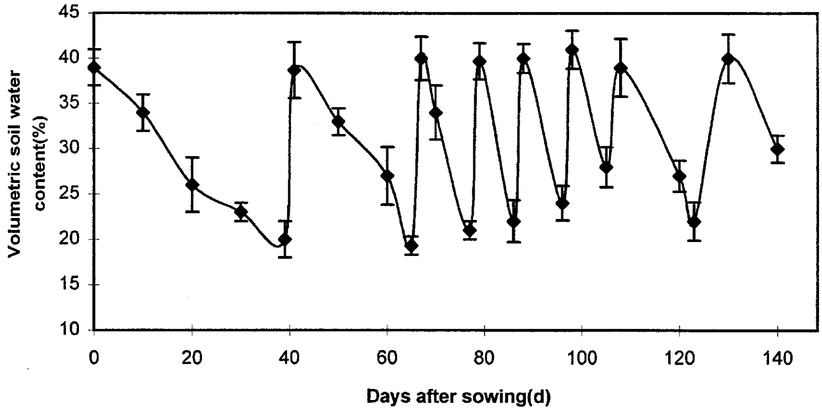
Fig. 1 Average soil water contents in the top 50 cm layer for three irrigation systems in a maize field during the growing season. Inserted *error bars* denote standard error of soil water measurements



(a). AFI(irrigation water amount is 45 mm/time)



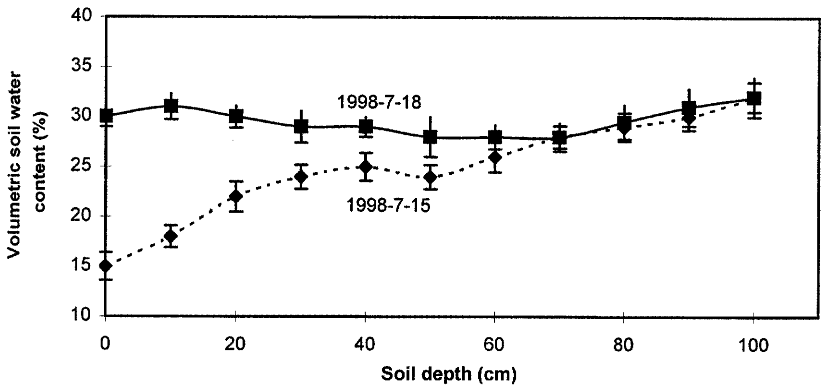
(b). FFI(irrigation water amount is 45 mm/time)



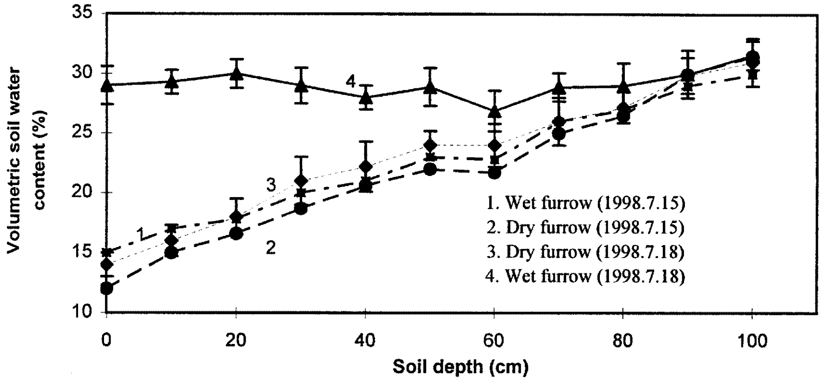
(c). CFI(irrigation water amount is 45 mm/time)

Figure 4 illustrates the development of soil water suction after irrigation in different treatments. It shows that the suction in the dry furrow was apparently larger than in the watered furrow in AFI (Fig. 4a, b), and the infiltration peak moved into a lower depth in the soil profile of the watering furrow after irrigation. The peak was at 50 cm and 70 cm on days 2 and 7 after irrigation, respectively. The infiltration peak disappeared on day 12 after irrigation. The soil water suction of the dry furrow was reduced on day 2 after irrigation, as a result of lateral infiltration, but it increased again on day 7 after irrigation (Fig. 4b), and was larger in the shallow layer, but smaller in the deep layer; the zero flux plane (i.e. $\partial S/\partial z = 0$) did not occur in the soil profile, the gradient of soil water suction ($\partial S/\partial z$) was always upward. The infiltration peak in CFI occurred at 70 cm depth on day 2 after irrigation (Fig. 4c), indicating that the infiltration in CFI was faster than in AFI. The suction profile of CFI was generally larger in the top and deep layers and smaller in the middle layer. The gradient of soil water suction was upward in the top 70 cm, downward below 70 cm, and continued to day 7 after irrigation. Only the

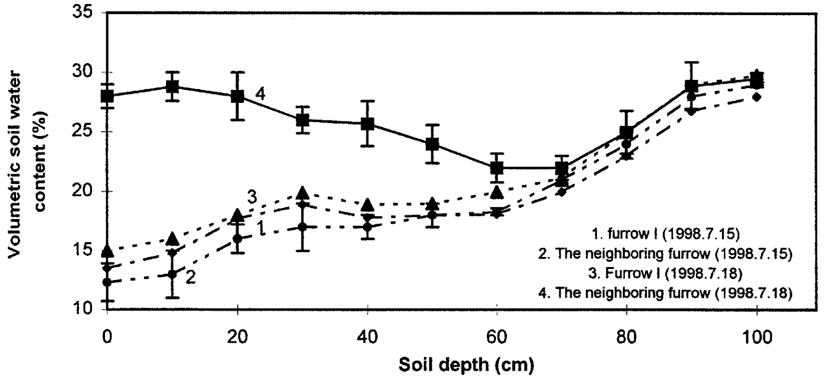
Fig. 2 Soil moisture distribution in soil profiles perpendicular to the furrows for three irrigation systems 1 day before (15 July 1998) and 2 days after (18 July 1998) irrigation. Inserted *error bars* denote standard error of soil water measurements



(a).CFI(irrigation water amount is 45mm/time, irrigation date is 1998.7.16)



(b).FFI(irrigation water amount is 45 mm/time, irrigation date is 1999.7.16)



(c).AFI(irrigation water amount is 45 mm/time, irrigation date is 1998.7.16)

upward gradient of the suction existed in the profile 12 days after irrigation, i.e. only upward flow flux occurred.

The result of water balance estimation is shown in Table 2 for different irrigation treatments. It can be seen that soil water changes (ΔW) ranged from 2.8 mm to 50.7 mm after the maize season. AFI and FFI had smaller changes when compared with CFI, indicating that less supplemental irrigation was needed to retain a suitable water content for the next year's crop. The result of drainage calculation in the maize growing season was also shown in Table 2. The downward drainage from the crop root zone was about 17.16–83.32 mm for the three irrigation treatments in 1997/7998. The drainage in 1997 was slightly larger than in 1998 because of different rainfall. It also illustrates that drainage in AFI and FFI was smaller than in CFI. This is in agreement with the data for soil water suction distribution presented in Figs. 3 and 4.

Water advance and irrigation uniformity

Water advance time did not differ between AFI, FFI and CFI at all distances monitored (Fig. 5). Water did

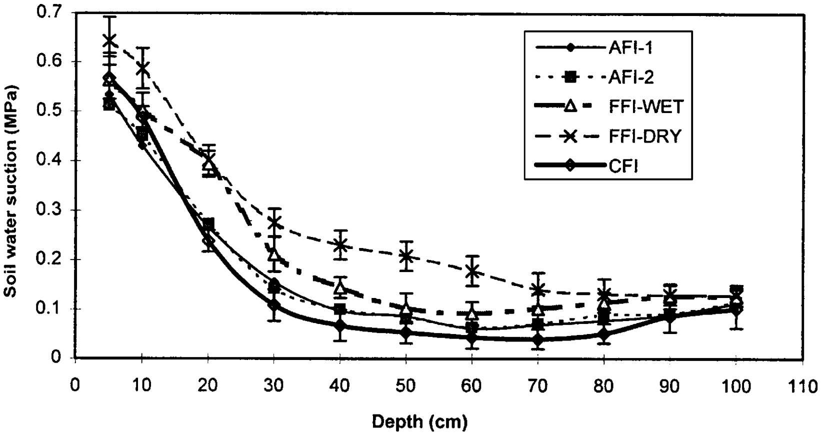


Fig. 3 Average soil water suction distribution with depth during the maize-growing season under three irrigation treatments. The total irrigation amount was 315 mm for the CFI and 210 mm for the AFI and FFI treatments. Inserted *error bars* denote standard error of soil water suction

not advance more slowly in AFI than in FFI and CFI under a covering of plastic film over the soil surface.

The Christiansen uniformity coefficient (CU_s) was used to evaluate irrigation water distribution uniformity in the soil (Table 3). Results showed that there was no significant difference among the treatments although irrigation water use in AFI and FFI was smaller than that in CFI, possibly because water flow was increased in the furrows by covering the surface with plastic film. The uniformity of soil water distribution in the AFI and FFI treatments did not change noticeably when irrigation amount was reduced.

Root and shoot development, yield and WUE

When part of the root zone was alternately irrigated, maize plants showed considerable primary root initiation and greater root biomass build-up in the soil. Table 4 presents data showing that AFI treatments were better than FFI and CFI treatments in terms of root establishment. Too little irrigation, i.e. when watering was halved (the 157.5 mm watering), led to less primary root initiation and less root biomass accumulation in the FFI and CFI treatments but this was less significant with AFI treatments. The results demonstrate that AFI not only enhanced root development, but also helped relieve the adverse effect on the root development when watering was cut too severely.

The data in Table 4 also show that moderate soil drying, such as that found with the AFI2 and CFI2 treatments, might also enhance root development in terms of primary root numbers and root biomass accumulation, when compared to the adequate watering of AFI1 and CFI1.

With less irrigation, plant height was reduced with FFI and CFI treatments (Table 4). Again this effect was not significant with AFI treatments, indicating that less water deficit developed in the shoots of AFI3 when less water was applied. Stem diameter showed no significant changes in all the treatments. This suggests that there was no serious water deficit in the shoots at the seedling stage.

Less irrigation also significantly reduced the total dry matter accumulation in the shoots of CFI treatments. Such an effect was so apparent with AFI and FFI treatments (Table 5).

The most important result from the 2-year investigation was that when less irrigation was introduced, the AFI had the least grain yield reduction (Table 5). In fact, such a yield reduction was not statistically significant in the AFI treatments, but was substantial and significant with FFI and CFI treatments. Both years' data showed that if the AFI method was used, less irrigation could maintain the same grain yield production as that of conventional irrigation with high irrigation amounts.

Two kinds of water-use efficiency, WUE_{ET} and WUE_I, were larger in AFI than in CFI and FFI with the same irrigation amounts. Data for 1998 also showed a consistently higher WUE with a lower irrigation amount.

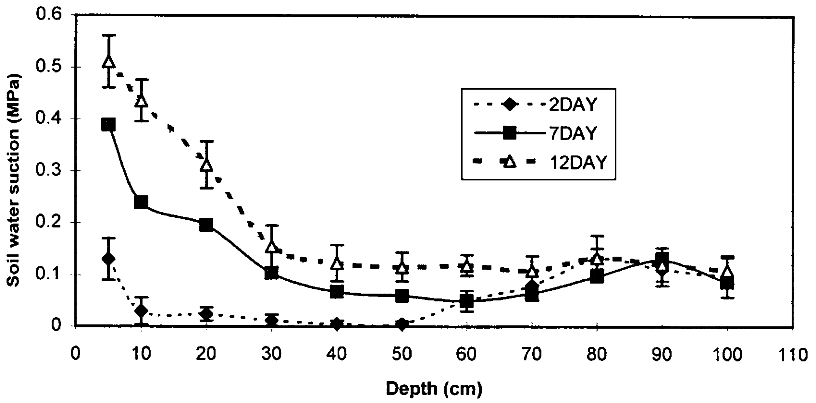
Table 6 shows the rates of photosynthesis and transpiration measured from 39 to 99 days after sowing. The results showed that restriction was more profound on transpiration than on photosynthesis when irrigation amounts were reduced.

Discussion

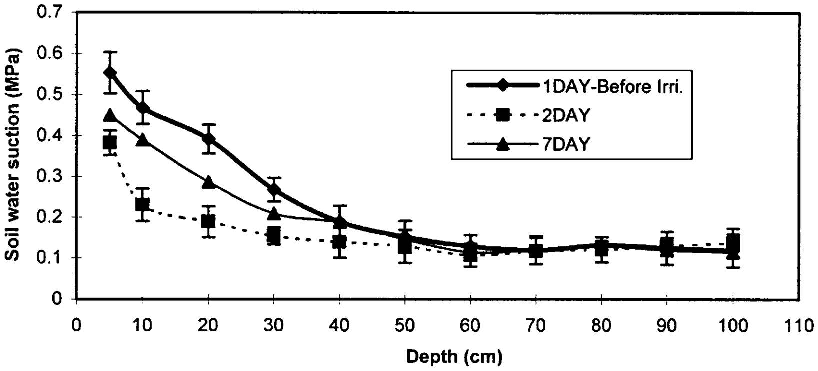
Why could the AFI method save water without a trade-off of grain yield? We believe this is a result of a continuous regulation by root drying signal on stomatal opening. When roots are in drying soil, even in a situation where only part of the root system is dried, substantial amounts of ABA can be produced in the roots and transported through the xylem to the shoots where stomatal opening can be regulated (see review by Davies and Zhang, 1991). AFI takes advantage of such a physiological response and exposes part of the root system alternately to the drying soil. As our earlier paper described (Kang et al. 1998), such a method of watering can lead to continuous stomatal inhibition and reduced leaf transpiration.

The measurements of leaf transpiration and photosynthesis rate in the field showed that transpiration was

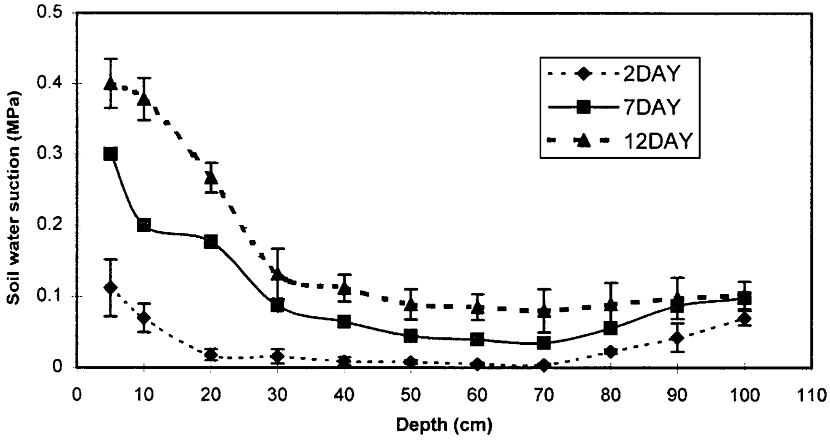
Fig. 4 Changes of soil water suction profile after the fourth irrigation in 1998. The irrigation amount was 30 mm. Inserted *error bars* denote standard error of soil water suction



(a). AFI-Wet furrow



(b). AFI-Dry furrow



(c). CFI

more inhibited as a result of reduced irrigation than photosynthesis was (Table 6). This may be explained by the fact that the relationship between photosynthesis and stomatal opening is a saturation relationship, especially in C_4 plants such as maize, where CO_2 supply rarely limits its assimilation; while the relationship between transpiration and stomatal opening is a linear one. Initial reduction of stomatal opening from maximum may reduce transpiration more than photosynthesis (e.g. Jones 1992). This leaves us with a gap where any limitation of stomatal opening from their 'luxury' state may reduce plant water use with only a small effect on photosynthesis.

Maize plants grown under conditions of AFI succeeded in taking up more applied irrigation water because of a larger and deeper root system than that found under CFI. The deep percolation found in CFI was larger than in AFI. Therefore more irrigated water was taken up by the plants with AFI than with CFI. This also contributed to the improvement of WUE in the AFI treatments.

We believe that AFI can avoid the severe leaf water deficit that can develop in the shoots when irrigation is drastically reduced. The AFI treatments showed no significant reduction in terms of shoot height and dry matter

Table 2 Water balance during the maize season for different irrigation treatments. *AFI*, *FFI* and *CFI* are alternate, fixed and conventional furrow irrigation respectively. *Values* are means of three plots for each treatment. *Letters following numbers* indicate statistical significance within the same column at $P < 0.05$ using Duncan's multiple-range test

Year	Irrigation treatments	Rainfall (mm)	Total irrigation (mm)	ΔW (mm)	ET (mm)	D (mm)
1997	AFI2	88.0	210.0	39.1bc	273.09b	64.01b
	AFI3	88.0	157.5	50.7a	226.93b	69.27b
	CFI1	88.0	315.0	42.6ab	362.28a	83.32a
1998	AFI1	77.5	315.0	33.7bcd	387.61a	38.59d
	AFI2	77.5	215.0	28.1de	281.83b	33.77df
	AFI3	77.5	157.5	8.8fg	226.64b	17.16h
	FFI1	77.5	315.0	31.0cde	387.24a	36.26d
	FFI2	77.5	215.0	2.8g	278.29b	37.21df
	FFI3	77.5	157.5	12.7f	227.18b	20.52g
	CFI1	77.5	315.0	39.1bc	385.25a	46.35c
	CFI2	77.5	215.0	35.6bcd	280.04b	43.06c
	CFI3	77.5	157.5	22.3e	227.24b	30.06f

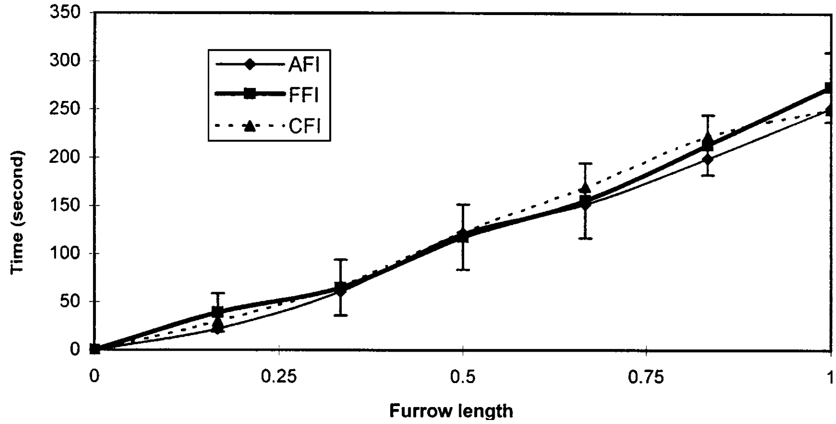


Fig. 5 Water advance in the furrows for different irrigation systems. Results were measured on 2 July 1998 at the fourth irrigation. Irrigation amount was 30 mm and irrigation water flow rate in the irrigated furrows was the same at 0.95 $\mathrm{l\ s^{-1}}$ for the three irrigation systems. *Points* are means of three plots. Inserted *error bars* denote standard errors

Table 3 Uniformity coefficient of soil water content distribution in furrows after irrigation for three irrigation systems. *AFI*, *FFI* and *CFI* are alternate, fixed and conventional furrow irrigation respectively. *Values* are means of three plots for each treatment. *Letters following numbers* indicate statistical significance within the same column at $P < 0.05$ using Duncan's multiple-range test

Irrigation date	Irrigation water use (m^3) in a furrow	Flow rate in furrow ($\mathrm{l\ s^{-1}}$)	Irrigation treatments	Uniformity coefficient CU_s
1998/6/17	1.86	0.95	CFI	0.85ab
	3.72		FFI	0.87ab
	3.72		AFI	0.88ab
1998/7/2	1.86	0.95	CFI	0.83b
	3.72		FFI	0.86ab
	3.72		AFI	0.88ab
1998/7/16	1.86	0.95	CFI	0.86ab
	1.86		FFI	0.86ab
	1.86		AFI	0.87ab
1998/7/30	1.86	0.95	CFI	0.85ab
	1.86		FFI	0.82b
	1.86		AFI	0.85ab
1998/8/10	1.86	0.95	CFI	0.88ab
	1.86		FFI	0.90a
	1.86		AFI	0.93a
1998/8/19	1.86	0.95	CFI	0.89ab
	3.72		FFI	0.92a
	3.72		AFI	0.91a

accumulation when watering was reduced. It is well known that leaf growth and shoot elongation are very sensitively inhibited when shoot water deficit is developed and turgor is reduced (e.g. Bradford and Hsiao, 1982).

Why does alternate drying work better than the constant exposure of a fixed part of the root system to dry soil? This is because prolonged exposure of roots to dried soil may cause anatomical changes in the roots, e.g. suberization of epidermis, collapse of cortex and loss of succulent secondary roots (North and Nobel, 1991). These changes are such that roots in the dried soil may become similar to 'pipes' which do not respond to the dried soil any more. Alternate wetting may improve this situation through a continuous stimulation of new secondary roots on these 'pipes'. It has been shown that rewatering can greatly enhance the initiation and growth of lateral roots (Liang et al. 1996). The newly formed roots may recover the sensitivity of the root system to the drying soil.

Our results have shown that alternate irrigation and drying on part of the root system is better than constant drying on a fixed part of the root zone. Substantially more roots were stimulated as a result of the former treatment. Another advantage for the larger and more evenly distributed root system is that nutrients in the soil can be better utilized. This will be especially important in areas where soil nutrients, such as phosphorus, are limited.

Table 4 Root and shoot development of irrigation treatments on maize grown in an arid area in 1998. *AFI*, *FFI* and *CFI* are alternate, fixed and conventional furrow irrigation respectively. Stem diameter was measured at the base of stem above soil surface. *Numbers following treatment codes* indicate different amount of water irrigated. *Values* are means of three plots for each treatment. *Letters following numbers* indicate statistical significance within the same column at $P < 0.05$ using Duncan's multiple-range test

Irrigation treatment	Total irrigation (mm)	Primary root number	Root/shoot ratio	Root dry weight (g/plant)	Root density (mg cm^{-3})	Plant height (cm)	Stem diameter (cm)
AFI1	315.0	46ab	0.109de	129.15b	1.5422a	252.9ab	2.10ab
AFI2	210.0	48a	0.166a	148.05a	1.3453b	252.6b	2.11ab
AFI3	157.5	46ab	0.151ab	123.9b	1.2906b	251.3bc	2.18a
FFI1	315.0	41cd	0.136bc	119.8b	1.2479b	245.7d	1.96bcd
FFI2	210.0	40d	0.131c	92.4c	0.9625c	244.8d	2.05ab
FFI3	157.5	35e	0.127cd	86.1cd	0.8969cd	238.0e	2.02ab
CFI1	315.0	43bcd	0.075f	73.5de	0.9953c	257.6a	1.82d
CFI2	210.0	44bc	0.116cd	95.55c	0.7656d	255.6ab	1.86cd
CFI3	157.5	45ab	0.095e	67.2e	0.7000d	246.6cd	2.00bc

Table 5 Grain yield, dried mass production and WUE in irrigation treatments of maize grown in an arid area in 1997 and1998. *AFI*, *FFI* and *CFI* are alternate, fixed and conventional furrow irrigation respectively. *Numbers following treatment codes* indicate different amount of water irrigated. *Values* are means of three plots for each treatment. *Letters following numbers* indicate statistical significance within the same year at $P < 0.05$ using Duncan's multiple-range test

Year	Irrigation treatments	Total irrigation (mm)	Grain yield (kg ha^{-1})	Dry matter (kg ha^{-1})	WUE_{ET} (kg m^{-3})	WUE_{I} (kg m^{-3})
1997	AFI2	210	10611.0a	17630.0ab	3.886a	5.053ab
	AFI3	157.5	9058.5a	16061.5b	3.992a	5.751a
	CFI1	315	10690.5a	19070.0a	2.951c	3.394e
1998	AFI1	315	8694.3a	16093.8a	2.243f	2.760f
	AFI2	210	8414.8a	14932.8ab	2.986d	4.007d
	AFI3	157.5	8133.8a	14541.7ab	3.589ab	5.164ab
	FFI1	315	8272.1a	15751.7a	2.140f	2.626f
	FFI2	210	8025.8a	15742.8a	2.884d	3.822de
	FFI3	157.5	6966.0b	14751.0ab	3.066c	4.423c
	CFI1	315	8363.3a	16160.4a	2.171f	2.655f
	CFI2	210	6818.1b	13512.6b	2.421ef	3.247e
	CFI3	157.5	6584.1b	13345.2b	2.547e	4.180d

Table 6 Rates of leaf photosynthesis and transpiration of maize plants under irrigation treatments in an arid area in 1998. *AFI*, *FFI* and *CFI* are alternate, fixed and conventional furrow irrigation respectively. *Numbers following treatment codes* indicate different amount of water irrigated. *Values* are means of three plots for each treatment. *Letters following numbers* indicate statistical significance within the same year at $P < 0.05$ using Duncan's multiple-range test. The transpiration and photosynthesis rates in series numbers 1, 2, 3, 4, 5, 6, were measured 1 d before and 3 d after the first irrigation, 1 d before and 3 d after the second irrigation, 3 d after the fourth irrigation, and 1 d before the fifth irrigation, respectively. *AVE* Average value of six measurements

Irrigation treatments	Transpiration rate (μmol$H_2O/m^2/s$)							Photosynthesis rate (μmol$CO_2/m^2/s$)						
	1	2	3	4	5	6	AVE	1	2	3	4	5	6	AVE
AFI1	3.01	4.15	2.89	4.63	4.24	2.85	3.63b	14.3	16.3	13.8	16.9	17.6	15.4	15.72a
AFI2	2.53	4.16	2.43	4.51	4.40	2.36	3.40bc	12.3	16.1	12.9	17.2	16.0	14.8	14.88b
AFI3	1.96	3.90	1.74	3.72	4.10	2.17	2.93c	11.0	15.2	10.3	16.4	18.5	13.3	14.12b
FFI1	2.72	3.21	1.94	4.00	3.45	2.15	2.91c	13.6	16.1	12.3	15.4	17.5	12.7	14.60b
FFI2	2.16	3.42	1.66	3.91	3.55	2.46	2.86c	9.6	14.3	10.3	14.0	16.1	13.0	12.88c
FFI3	1.52	3.67	5.60	3.52	3.28	2.17	3.29bc	9.0	14.5	10.0	13.8	13.4	10.9	11.93d
CFI	2.96	5.31	3.21	6.11	6.73	3.21	4.59a	11.7	20.8	13.2	19.3	21.4	10.3	16.12a
CFI2	2.30	4.96	2.87	5.80	5.31	2.96	4.03a	10.8	15.3	7.4	16.3	19.0	9.9	13.12c
CFI3	2.12	5.06	2.33	6.12	5.24	2.10	3.83ab	6.7	16.3	5.4	14.3	17.3	6.3	11.05d

Moreover, deep percolation and soil surface evaporation can be reduced as a result of local root-zone watering, and the ratio of transpiration to the sum of irrigation and rainfall can be improved without influencing the advance of water in the furrows and irrigation water distribution uniformity.

AFI is a practicable method, and should be of significant value to arid areas because many of these areas face diminishing water resources. A sustainable use of water resources is increasingly becoming an urgent world-wide problem. Moreover, the difference in yield is sufficient to entice farmers to do the extra work involved in changing the openings on the gated pipes to alternate the flow to different furrows for each irrigation.

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