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Alternate furrow irrigation for maize production in an arid area

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Abstract

A new irrigation method for maize production was designed and tested for yield and water use efficiency (WUE). A field experiment was conducted in an arid area, with seasonal rainfall of 80 mm, over 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 way where every furrow was irrigated during each watering. Each irrigation method was further divided into three sub-treatments with different irrigation amounts: 45, 30 and 22.5 mm water at each application.

Results showed that 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 FFI and CFI treatments. Less irrigation significantly reduced the total root dry weight and plant height in both FFI and CFI treatments but not as substantially with AFI treatments. The most surprising result was that AFI maintained high grain yield with up to 50% reduction in irrigation amount, while FFI and CFI all showed a substantial decrease in yield with reduced irrigation. As a result, WUE for irrigated water was substantially increased. We conclude that AFI is a way to save water in arid areas where maize production relies heavily on repeated irrigation.

Keywords: Irrigation; Soil drying; Water use efficiency; Maize (*Zea mays*)

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1. Introduction

Agriculture in arid areas relies heavily on irrigation. This is especially true for the Hexi Corridor of Northwest China where annual rainfall is below 200 mm and agriculture depends almost totally on the water from a mountain glacier. Efficient use of water has become extremely important in recent years because the glacier has been retreating rapidly. Desert is expanding to some traditional agricultural areas with the shrinking of available water resources (Kang et al., 1996).

Many ways of conserving agricultural water have been investigated. Researchers (e.g. Stewart et al., 1981; Musick and Dusck, 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 to improve water use efficiency (WUE). They fixed some furrows for irrigation, while adjacent furrows were not irrigated for the whole season. In general, these techniques are a trade-off: a lower yield for a higher WUE. Water was saved mainly by reduced evaporation from the soil surface, as in the case of drip-irrigation.

Ideally, WUE should be improved by reduced leaf transpiration as stomata control leaf gas exchange and transpirational water loss. Recent investigations have shown that stomata may directly respond to the availability of water in the soil by reducing their opening accordingly (e.g. Davies and Zhang, 1991; Tardieu and Davies, 1993). The advantage of this type of regulation is that plants may delay the onset of serious leaf water deficit and enhance their chance of survival in times of unpredictable rainfall: the optimization of water use for CO_2 uptake and survival (Jones, 1980; Cowan, 1982). More recent evidence has shown that this feed-forward stomatal regulation works through a chemical signal, i.e. increased concentration of abscisic acid (ABA), in the xylem flow from roots to shoots (Zhang and Davies, 1989a, b, 1990, 1991). Part of the root system in drying soil can produce large amount 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 is that plants may have a reduced stomatal opening with the absence of visible leaf water deficit.

To take advantage of this type of 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 rest is in wet soil. They hoped that such a design could lead to reduced stomatal opening without leaf water deficit. Kang et al. (1998) conducted an experiment with pot-grown maize plants where the plant root system was divided into two or three containers which were watered alternately. Compared to conventional watering or watering fixed parts of the root system, alternate irrigation reduced water consumption by 35% with a total biomass reduction of only 6–11%.

We adopted this approach in a field experiment on irrigated maize plants for 2 consecutive years. The hypothesis was that irrigating alternate furrows, i.e. partial wetting of the root system alternatively, might save water. WUE might be increased with a small reduction in grain yield although the total biomass might be reduced with less irrigation. This approach was also encouraged by the results of more recent investigation on grapevines (see Dry et al., 1995; Fuller, 1997). They adopted a partial root-zone drying approach and found that WUE was nearly doubled with better quality grapes and no yield reduction.

2. 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 an underground water table 13–18 m below the soil surface. The soil, a sandy-loam, had a moderately slow water permeability and a moderate organic matter content. Field capacity, defined as the water content at −0.02 MPa, was approximately 0.308 m in the upper 1.0 m of the soil profile. The bulk density was about 1.4 g cm^{-3}. The soil water content was near the field capacity before the sowing. The field was covered with plastic film mulch, a practice that has been used widely in this area for many years (Kang et al., 1996).

The top layer of the soil (40 cm) contained total organic matter of 0.88%, nitrogen of 0.074%, and available phosphate of 7.86 mg kg^{-1}. The soil was fertilised and well mixed in the top 20 cm before sowing. A complete fertilizer (NPK) in pellets was applied at 112 g m^{-2}.

The experiments were conducted in the same field for the 2-year period. The cultivar (hybrid cv. Duanyu 13, high yield and moderate drought-tolerance), fertilizing, and insect control in all plots were the same for the 2 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 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 center three rows were harvested for yield assessment). Sowing density was five plants per m^2.

The design consisted of three irrigation methods, three levels of irrigation amount (i.e. nine treatments, 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 watering. FFI means that irrigation was fixed to one of the two neighboring furrows. CFI was the conventional way where all furrows were irrigated for every irrigation. In 1997, because of field size limitation, only two irrigation methods, AFI and CFI, were used, with two irrigation levels for the AFI treatment and one for the CFI treatment.

Soil water content was measured with a neutron probe in all plots, at 5-day intervals, in 20 cm increments to a depth of 100 cm. The probes were installed in the middle of rows for both irrigated and non-irrigated furrows. There were four probes for each plot. Apart from the regular measurements, soil water content was also measured 1 day before and after each irrigation. Rainfall was monitored with a rain gauge installed in the experimental site.

Irrigation was applied at different intervals according to the soil water content measurements. During the seedling stage, all the plots were irrigated when the soil water content in the upper 40 cm soil profile reached 50% of its field capacity in the treatment of CFI3 (the least irrigated plot). After stem elongation stage, irrigation was applied when this a value reached 55%. A total of seven irrigations during the growing season (see details in Table 1) were applied to all the treatments.

The amount of irrigated water was measured with a flow meter installed on the gated plastic pipes. The flow rate for all the treatments in both years was 0.95 l s^{-1} for one

Table 1
Details of irrigation treatment on maize grown in an arid area. AFI, FFI and CFI are alternate, fixed and conventional furrow irrigation, respectively

Year	Irrigation treatment[a]	Seasonal rainfall (mm)	Irrigation details		
			Times (no.)	Amount (mm/irrigation)	Timing (DAS)[b]
1997	AFI2	88.0	7	30	39, 65, 77, 86, 96, 106, 123
	AFI3	88.0	7	22.5	
	CFI1	88.0	7	45	
1998	AFI1	77.5	7	45	40, 58, 72, 85, 100, 112, 125
	AFI2	77.5	7	30	
	AFI3	77.5	7	22.5	
	FFI1	77.5	7	45	
	FFI2	77.5	7	30	
	FFI3	77.5	7	22.5	
	CFI1	77.5	7	45	
	CFI2	77.5	7	30	
	CFI3	77.5	7	22.5	

[a] Numbers following treatment codes indicate the different amounts of water irrigated each time.
[b] DAS means days after sowing.

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. Irrigation runoff was negligible. Thus, the net amount of irrigation was the amount of water added to the field. All the treatments were watered on the same day.

Prior to harvest for yield assessment, 10 plants were sampled at random from interior rows of each plot to determine plant height, stem diameter, and total biomass accumulation in the shoot. Stem diameter was measured at the base of stem above soil surface. The primary root numbers for these 10 plants were also recorded. Total root biomass and root density in the soil was investigated in a 50×40 cm^2 area on one side of a row for two plants. Roots were dug out and collected in a 60 cm deep soil volume. Roots on both sides of a row, irrigated or non-irrigated furrows, were harvested for all the treatments but data were pooled and presented as average for individual plant. Data were averaged for each plot and final results were tested by Duncan's multiple range test.

3. Results

When furrows were alternately irrigated maize plants showed high numbers of primary root initiation and more root biomass build-up in the soil. Table 2 presents data showing that the AFI system was better than either FFI or CFI treatments in terms of root development. Deficit irrigation, i.e. when the quantity of water was halved (the 157.5 mm level), led to significantly less primary root initiation and root biomass accumulation in the FFI and CFI treatments but smaller differences with AFI treatments. This demonstrates that the AFI system results in better root development compared to the

Table 2
Effects of irrigation treatments on root development of maize grown in an arid area in 1998

Irrigation treatment[a]	Total irrigation (mm)	Primary root number[b]	Root/shoot ratio	Root dry weight (g plant^{-1})	Root density (mg cm^{-3})
AFI1	315	46ab[c]	0.109de	129.15b	1.5422a
AFI2	210	48a	0.166a	148.05a	1.3453b
AFI3	157.5	46ab	0.151ab	123.9b	1.2906b
FFI1	315	41cd	0.136bc	119.8b	1.2479b
FFI2	210	40d	0.131c	92.4c	0.9625c
FFI3	157.5	35e	0.127cd	86.1cd	0.8969cd
CFI1	315	43bcd	0.075f	73.5de	0.9953c
CFI2	210	44bc	0.116cd	95.55c	0.7656d
CFI3	157.5	45ab	0.095e	67.2e	0.7000d

[a] AFI, FFI and CFI are alternate, fixed and conventional furrow irrigation, respectively. Numbers following treatment codes indicate the different amounts of water irrigated. Values are means of three plots for each treatment.

[b] Data show roots that were harvested in 60 cm deep soil.

[c] Letters following numbers indicate statistical significance within the same column at $P_{0.05}$ level using Duncan's multiple range test.

other methods and a smaller reduction in root development when irrigation is cut drastically.

Data in Table 2 also show that moderate soil drying, as in the case of AFI2 and CFI2 treatments, results in better root development, in terms of primary root numbers and root

Table 3
Effects of irrigation treatments on shoot development, grain yield, dried mass production, and WUE (grain production for irrigated water) of maize grown in an arid area in 1997 and 1998

Year	Irrigation treatment[a]	Total irrigation (mm)	Plant height (cm)[b]	Stem diameter (cm)	Grain yield (kg ha^{-1})	Dry matter (kg ha^{-1})	WUE (kg m^{-3})
1997	AFI2	210	249b	2.43ab	10611.0a	17630.0ab	5.053
	AFI3	157.5	250b	2.50a	9058.5a	16061.5b	5.751
	CFI1	315	258a	2.30b	10690.5a	19070.0a	3.394
1998	AFI1	315	252.9ab	2.10ab	8694.3a	16093.8a	2.760
	AFI2	210	252.6b	2.11ab	8414.8a	14932.8ab	4.007
	AFI3	157.5	251.3bc	2.18a	8133.8a	14541.7ab	5.164
	FFI1	315	245.7d	1.96bcd	8272.1a	15751.7a	2.626
	FFI2	210	244.8d	2.05ab	8025.8a	15742.8a	3.822
	FFI3	157.5	238.0e	2.02ab	6966.0b	14751.0ab	4.423
	CFI1	315	257.6a	1.82d	8363.3a	16160.4a	2.655
	CFI2	210	255.6ab	1.86cd	6818.1b	13512.6b	3.896
	CFI3	157.5	246.6cd	2.00bc	6584.1b	13345.2b	5.016

[a] AFI, FFI and CFI are alternate, fixed and conventional furrow irrigation, respectively. Numbers following treatment codes indicate the different amounts of water irrigated. Values are means of three plots for each treatment.

[b] Letters following numbers indicate statistical significance within the same year at $P_{0.05}$ level using Duncan's multiple range test

biomass accumulation, when compared to the adequate irrigation levels of AFI1 and CFI1.

With less irrigation, plant height was reduced with FFI and CFI treatments (Table 3). This effect was not significant with AFI treatments, showing that a smaller water deficit developed in the AFI3 when less water was irrigated, as compared with the parallel treatments of the FFI and CFI methods. 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 when the stem diameter was determined.

Low irrigation levels also significantly reduced the total dry matter accumulation in the shoots of CFI treatments, but not so with AFI and FFI treatments (Table 3).

The most important result from the 2-year investigation was that when less irrigation was applied, the alternate furrow irrigation (AFI) system had the smallest grain yield reduction (Table 3). In fact, this yield reduction was not statistically significant in the AFI treatments, but 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 as that of conventional irrigation with high irrigation amount. The conclusion is that the AFI system can substantially save water.

4. Discussion

How can the AFI method save water without a trade-off in grain yield? We believe this is the result of the continuous regulation, by a root drying signal of the stomatal opening. When roots are in drying soil, even in a situation where only part of the root system is dry, substantial ABA is produced in the roots and transported through the xylem to the shoots where stomatal opening is regulated (see review by Davies and Zhang, 1991). AFI takes advantage of this physiological response and exposes part of the root system alternatively to the drying soil. As our earlier paper described (Kang et al., 1998), this method of watering can lead to continuous stomatal inhibition and reduced leaf transpiration. Photosynthesis and dry matter accumulation are less affected by such partial stomatal closure because photosynthesis and stomatal opening have a saturation relationship. Maximum stomatal opening does not necessarily lead to maximum photosynthesis. Transpiration and stomatal opening, however, have a linear relationship.

We believe that AFI can avert severe leaf water deficit, which develops in the shoots when irrigation is drastically reduced. Evidence for this conclusion is that the AFI treatments show no significant reduction in terms of shoot height and dry matter accumulation when irrigation was reduced. It is well known that leaf growth and shoot elongation are inhibited when shoot water deficit develops and turgor is reduced as a result (e.g. Bradford and Hsiao, 1982).

Why use alternate furrow irrigation instead of continuously exposing part of the root system to drying, i.e. the FFI system? This is because prolonged exposure of roots to dried soil may cause some anatomical changes in the roots (North and Nobel, 1991), e.g. suberization of root epidermis, collapse of cortex and loss of the succulent secondary roots. The effect of such changes is that the roots develop a much reduced water permeability on their surface and no longer respond to the dried soil. Alternate wetting may improve this situation through a continuous stimulation of new secondary roots on these suberised primary roots. 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 roots to the drying soil.

Our results show that alternative drying of part of the root system is better than the drying of fixed part of the root zone. Substantially more roots were stimulated as a result of the treatment. In addition, our earlier results have shown that AFI drying led to an even distribution of the root system in the soil, while drying of the fixed root zone resulted in more roots in the wet and less in the dried zone (Kang et al., 1998).

Another advantage of the larger and more evenly distributed root system is that nutrients in the whole root zone are better utilized. This is especially important in areas where soil nutrition, such as phosphorus, is limited.

In conclusion, our method of irrigation can save a substantial amount of water and maintain grain yield in maize production in areas where irrigation is essential. This result should be of significant value in arid areas with shrinking water resources as the sustainable use of water is increasingly a worldwide problem.

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References

Bradford, K.J., Hsiao, T.C., 1982. Physiological responses to moderate water stress. In: Lange, O.L. et al. (Eds.), Physiological Plant Ecology II. Springer, Berlin, pp. 263–324.

Cowan, I.R., 1982. Regulation of water use in relation to carbon gain on higher plants. In: Lange, O.L. et al. (Eds.), Physiological Plant Ecology II. Springer, Berlin, pp. 589–614.

Davies, W.J., Zhang, J., 1991. Root signals and the regulation of growth and development of plants in drying soil. Annu. Rev. Plant Physiol. Plant Mol. Biol. 42, 55–76.

Dry, P., Loveys, B., Botting, D., During, H., 1995. Effects of partial root-zone drying on grapevine vigour, yield, composition of fruit and use of water. In: Proceedings of Ninth Australian Wine Industry Technical Conference, pp. 128–131.

Fuller, P., 1997. Less water more grapes, better quality, an ecological breakthrough in viticultural science. Wine Industry J. 12 (2), 155–157.

Graterol, Y.E., Eisenhauer, D.E., Elmore, R.W., 1993. Alternate-furrow irrigation for soybean production. Agric. Wat. Manage. 24, 133–145.

Hodges, M.E., Stone, J.F., Garton, J.E., Weeks, D.L., 1989. Variance of water advance in wide spaced furrow irrigation. Agric. Wat. Manage. 16, 5–13.

Jones, H.G., 1980. Interaction and integration of adaptive responses to water stress: the implications of an unpredictable environment. In: Turner, N.C., Kramer, P.J. (Eds.), Adaptation of Plants to Water and High Temperature Stress. Wiley, New York, pp. 353–365.

Kang, S., Cai, H., Liang, Y., 1996. A discussion of the basic theoretical problem in crop water management of water-saving agriculture. J. Hydraulic Eng. (Chinese) 5, 9–17.

Kang, S., Zhang, J., Liang, Z., 1997. The controlled alternate irrigation: a kind of new thinking of water-saving on farmland. Chinese Agric. Res. Arid Areas 15 (1), 1–6.

Kang, S., Liang, Z., Hu, W., Zhang, J., 1998. Water use efficiency of controlled root-division alternate irrigation on maize plants. Agric. Wat. Manage. 38, 69–76.

Liang, J., Zhang, J., Wong, M.H., 1996. Effects of air-filled soil porosity and aeration on the initiation and growth of secondary roots of maize (*Zea mays*). Plant and Soil 186, 245–254.

Merriam, J.L., Shearer, M.N., 1980. Evaluating irrigation systems and practices. In: Jensen M.E. (Ed.), Design and Operation of Farm Irrigation System, Monograph Number 3. American Society of Agriculture Engineers, St. Joseph.

Musick, J.T., Dusck, D.A., 1982. Skip-row planting and irrigation of graded furrows. Trans. Am. Soc. Agric. Engr. 25, 82–87.

North, G.B., Nobel, P.S., 1991. Changes in hydraulic conductivity and anatomy caused by drying and rewetting roots of *Agave deserti* (*Agavaceae*). Am. J. Bot. 78, 906–915.

Stewart, B.A., Dusck, D.A., Musick, J.T., 1981. A management system for conjunctive use of rainfall and limited irrigation of graded furrows. Soil Sci. Soc. Am. J. 45, 413–419.

Stone, J.F., Nofziger, D.L., 1993. Water use and yields of cotton grown under wide-spaced furrow irrigation. Agric. Wat. Manage. 24, 27–38.

Tardieu, F., Davies, W.J., 1993. Integration of hydraulic and chemical signaling in the control of stomatal conductance and water status of droughted plants. Plant, Cell and Environ. 16, 341–349.

Zhang, J., Davies, W.J., 1987. Increased synthesis of ABA in partially dehydrated root tips and ABA transport from roots to leaves. J. Exp. Bot. 38, 2015–2023.

Zhang, J., Davies, W.J., 1989a. Abscisic acid produced in dehydrating roots may enable the plant to measure the water status of the soil. Plant, Cell and Environ. 12, 73–81.

Zhang, J., Davies, W.J., 1989b. Sequential responses of whole plant water relations towards prolonged soil drying and the mediation by xylem sap ABA concentrations in the regulation of stomatal behaviour of sunflower plants. New Phytol. 113, 167–174.

Zhang, J., Davies, W.J., 1990. Changes in the concentration of ABA in xylem sap as a function of changing soil water status will account for changes in leaf conductance. Plant, Cell and Environ. 13, 277–285.

Zhang, J., Davies, W.J., 1991. Antitranspirant activity in the xylem sap of maize plants. J. Exp. Bot. 42, 317–321.

Zhang, J., Schurr, U., Davies, W.J., 1987. Control of stomatal behaviour by abscisic acid which apparently originates in roots. J. Exp. Bot. 38, 1174–1181.