Water-Saving Agriculture and Sustainable Use of Water and Land Resources

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Foreword

Shortage of water resources and deterioration in the quality and availability of agricultural land are worldwide problems. Water and land are critical resources and cannot be regarded as available in abundance. Degradation of land, reduction of river flow and the increasing frequency of severe dust storms have seriously damaged the natural environment and retarded economic development. These problems have reached dangerous levels in many countries. It is widely believed that an increase the efficiency with which water is used in agriculture is one key way to reduce many of these problems. For many countries, agriculture is the largest water user and to improve water use efficiency in agriculture would have a significant impact on sustainable development. It is not only important to ensure availability of water in the right quantity at the right time, but also important to ensure that water of an appropriate quality is used in agriculture. Therefore, research on water efficient agriculture, and on sustainable use of water and land resources in arid and semiarid areas has a high international priority.

Water shortage in China, particularly in Northwest China is very serious. This region (including Shaanxi, Gansu, Ningxia, Qinghai, Xingjiang and Western Inner Mongolia) accounts for 1/3 of the area of China, but has only 8.3% of total national available water resources. While the water shortage in this region is serious, the waste of water resources and water pollution remain as major issues. Overall irrigation water use efficiency is approximately 40%, with atypical irrigation water productivity around 0.46 kg/m^3. Excessive irrigation in Ningxia and Inner Mongolia have had a significant influence on Yellow River downstream water users. The frequency and severity of dust storms, sourced from the Northwestern China, have been increased every year. This is accompanied by an increase in the desertification of large areas of land.

The importance of water-saving agriculture and sustainable use of water and land resources are increasingly being recognized by public and government authorities. To address many of the important issues raised above, the “International Conference on Water-saving Agriculture and Sustainable Use of Water and Land Resources” (ICWSAWLR) will be held on October 26-29, 2003 in Yangling, Shaanxi Province of P.R. China, which organized by Northwest Sci-Tech University of Agriculture and Forestry (NWSUAF) of China and the Lancaster Environment Center, Lancaster University (LEC) of UK, and sponsored by NWSUAF, the Journal of Experimental Botany (JXB), National Natural Science Foundation of China (NSFC), Chinese Hydraulic Engineering Society (CHES), Chinese Society of Agricultural Engineering (CSAE), the Key Lab of Agricultural Soil and Water Engineering in Arid and Semiarid Areas of Ministry of Education of China (LASWE), Center of Agricultural Water Research in China (CAWR) of China Agricultural University.

The objectives of the conference are to bring together a multi-disciplinary group of researchers, engineers and regulators to present and discuss current research. The conference themes include biological mechanisms of water-saving agriculture, agronomic technology and plant improvement for water-saving in water-limited areas and dryland, irrigation technology and water management, sustainable use of water resources in arid and semiarid areas, agricultural water and land environment. The secretariat received more than 240 abstracts, all of them were edited, they and with the selected some full papers will be published in the special issue of Journal of Experimental Botany, and the other full papers, which the secretariat received, are published in this proceedings. We thank Du Taisheng, Martin Parkes, Jeff Gale, Rupert Knowles, Rachel Caiger,Wang Zhinong, Hu Xiaotao, Ma Xiaoyi and the anonymous reviewers who helped in checking papers and in preparing the conference.

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Section I

Biological Mechanisms of Water-Saving Agriculture

Compensatory effects of inorganic nutrition on yield components and water use efficiency of dry land spring wheat

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Abstract

Two experiments were conducted in the hilly loess area in Ningxia Hui Autonomous Region, to assess the compensation effect of inorganic nutrition on spring wheat yield and water use efficiency (WUE). A comparison of wheat yield and WUE sequences under four planting densities with five fertilizer levels showed that maximum yield and highest WUE were achieved under the optimum fertilizer input of 90 kg N and 135kg P_2O_5 per ha with 500 seeds/m^2. Increasing the amount of fertilizer was positively correlated with grain yield (r = 0.959) and WUE (0.894) of spring wheat. However, planting density was poorly correlated with yield and WUE. Increasing the fertilizer level significantly increased fertile spikelet number, kernels per spike and kernel weight. These components decreased with an increase in planting density. The number of fertile spikelets was sensitive to fertilization, whereas kernel number and weight were mainly affected by plant density. Fertilizer applied in spring wheat improved development of the root system and especially enhanced root growth in the cultivated soil layer (0-20 cm). The enhanced root system was able to improve crop water use and nutrient absorption. Hence, crop yield and WUE also increased. Grain yield of spring wheat increased by 44.6% and 55.4% when P and P+N+K were applied. A significant increase in yield was also obtained with N application but not with K. P or P+N promoted spike development and hence, increased seed production. N+P+K improved the quality of seeds, and N, P and K content of seed increased by 18.5%, 18.4% and 8.1%, respectively, compared with the zero fertilizer treatment. This study highlights the compensation effect of improved soil fertility for the efficient use of limited water in dryland spring wheat production.

Key words: Spring wheat, inorganic nutrition, compensation effect, water use efficiency, grain yield.

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1 Introduction

Water shortage is one of the main constraints to grain productivity in the semiarid areas of the world. In most cases, however, these limited water resources are inefficiently used, and actual crop yield is lower than the potential yield estimated by precipitation (Howell, 2001). Although lack of water is the primary cause of drought, there are a large number of factors that exacerbate and intensify the effects of lack of water. If these factors are adequately managed, many of which have little to do with water per se, the consequences of the lack of water can be greatly reduced (Makcamob, 1985; Turner, 1990; Richards et al., 2002). The hilly loess region of Northwest China is a typical semiarid area with severe soil erosion and soil fertility problems (Wei et al., 2000). Geomorphology and topography are highly variable. Sloping land constitutes 80% of the total cultivable area (Shan and Chen, 1998).

Spring wheat is one of major crops in the semiarid area of the world and occupies a large portion of the cultivated land. In order to increase its productivity, experimental work should be conducted to identify the optimum crop management practices for this area. Most of the research conducted in the past to improve yield has concentrated on fertilizer and plant density (Welch et al., 1962; Harmsen et al., 1983; Korentajer and Berliner, 1988). Under such water limited conditions, improvement of crop WUE is very important (Shan and Deng, 2000). However, most past studies on fertilizer and crop density were conducted separately, and rarely linked with the relationship between fertilization and crop WUE (Welch et al., 1966; Stockle and Campbell, 1988). Furthermore, N, P and K are essential elements for plant growth and their contents in the soil directly influence the growth and development of crops and, hence, determine their yields, quality and WUE (Gupta et al., 1992). Unfortunately, the effects of these inorganic nutrients on crop WUE in semiarid conditions are still not fully understood.

The objectives of this study were to clarify the relationship between fertilizer and plant density, to determine effects of N, P and K application and their combined application on spring wheat growth, yield and seed quality in the semi-arid hilly region of the Loess Plateau. Crop yield, yield components and WUE under different fertilizer and planting density conditions were studied to provide a theoretical basis for rational use of fertilizer and limited water resources in the area. The results will provide important information about the use of limited water resources for sustainable agricultural development under semiarid conditions.

2 Materials and methods

Two experiments were conducted from October 1989 to July 1991 at the Guyuan Ecological Station located in the semiarid region of the Loess Plateau, in western China. The experimental site is 1,765m above sea level with aridity index of 1.55. The average annual temperature is 6.9?C and frost-free period is 152 days. The annual precipitation in 1990 and 1991 was 389.6 and 430mm, respectively. The experimental field was level and no run-off occurred. No organic manure had been applied to the field for several years. The soil type was loess soil with the texture of fine silt and soil fertility was low**.** The spring wheat Hongmang (*Triticum aestivum* L. Var. Hongmang) was used in this study.

2.1 Experiment 1

The experimental plots had previously been planted to flax. The treatments were as follows: 1. Fertilization 5 levels: 0, 25, 50, 75, and 100g/m^2; 2. Planting density 4 levels: 300, 500, 700, and 900 seeds/m^2.

The factorial treatment combinations were arranged in a randomized complete block design with five replicates. Plot size was 3.2 m^2. A Japanese compound fertilizer containing 12% N, 18% P_2O_5 and 16% KCl was used. Spring wheat was sown on March 17—18th. First, a hoe was used to dig furrows of 10 cm depth in the plots. Secondly, fertilizer was drilled into the furrows, covered with a 3—4 cm layer of soil, and then pressed with a small stone-roller. Finally, the seeds were sown at a depth of 6—7 cm and the furrows were filled until the soil was level. Seedlings started to emerge on April 8-11, and more then 50% of the seedlings had emerged by April 12-15.

Crop growth and development measurements were made when the wheat reached boot stage (June 11-18). Selected root growth measurements were made at the same time. A root sample collector (20 cm long, 16 cm wide and 10 cm high) was used. Selected plots were sampled at both the row and inter-row position, including Planting density of 500 seeds/m^2 with five fertilizer treatments and fertilizer level of 50g/m^2 with four Planting density levels. Sampling depth was from 0 to 60 cm. Six samples were collected at each point. Root samples were washed and measured by the lattice method and then dried in an oven. Total root length and weight of each plot were calculated.

In each plot, the total yield and yield components were determined from a net harvested area of 50 cm wide and 80 cm long (16 cm × 5 rows). Plant numbers, cauline numbers, spike number, grain weight, biomass, plant height, spike length, fertile spikelet numbers and seed numbers per head were determined. Soil moisture content (0—200 cm) was determined for each plot at both sowing and harvest. Soil moisture content of each 10 cm depth was calculated from the fresh and dry weights of the samples.

2.2 Experiment 2

The preceding crop was soybean. The nutrient treatments are shown in Table 1. Each plot area was 3.2m^2 and the treatments were arranged in a randomized complete block design with five replicates. In October of the previous year, the fertilizer was broadcast uniformly onto the plots and then ploughed in to a depth of 15-17cm. The field surface was leveled in mid-December. Wheat (cv. Hongmang, a strong drought resistant cultivar in the region) was sown on March 17th each year with a seeding rate of 500 seeds per m^2. Seeds were planted at a depth of 5~6cm. Row spacing was 16.5cm. The crop was harvested on 24 July, 1990 and 27 July 1991. In each plot, an area of 1 m^2 was harvested for estimation of yield and determination of morphological traits. Seeds and shoots were ground for N, P and K analysis.

Table 1. Experiment 2 Nutrient Treatments

Treatment	N?P_2O_5?K_2O (Kg/ha)	Treatment	N?P_2O_5?K_2O (Kg/ha)
NPK	135?135?135	PK	0?135?135
0	0?0?0	N	135?0?0
NP	135?135?0	P	0?135?0
NK	135?0?135	K	0?0?135

3 Results

3.1 Effects of Fertilizer and Plant Density on Grain Yield and Components (Experiment1)

The result showed that maximum yield of 2483 kg/ha was attained under the highest input of both fertilizer and planting density (Table 2). Grain yield of was lowest (825 kg/ha) in the maximum plant density and no fertilizer input treatment. The analysis of variance showed that fertilizer level significantly affected grain yield. The effect of planting density on grain yield was not significant however. Grain yield and fertilizer showed a high positive correlation ($r = 0.959^{**}$), but planting density showed a poor correlation with grain yield. Under high yield conditions, optimum-planting density was 500 seeds/m^2.

Table 2. Effects of planting density and fertilizer on grain yield (kg/ha)

Planting density (seeds/m^2)	Fertilizer level (g/m^2)					
	0	25	50	75	100	Mean (S.E ±)
300	951	1625	1850	2358	2378	1832±264
500	1196	1730	2187	2363	2412	1977±230
700	1035	1493	1905	2268	2424	1806±261
900	825	1398	1880	2250	2483	1786±293
Mean (S.E ±)	1002±78	1561±73	1955±78	2310±29	2424±22	

Grain yield varied under different planting densities. Effects of both low and high planting densities on yield showed a closer relation with fertilizer levels, indicated that there were no significant differences in grain yield between planting densities of 300 and 900 seeds/m^2 at the 75g/m^2 and 100g/m^2 fertilizer levels. However, there were significant differences in grain yield between planting densities 300 and 500 seeds/m^2 at the 25g/m^2 and 50 g/m^2 fertilizer levels (Table 2). Under the 75 and 100 g/m^2 of high fertilizer levels, slight increases in grain yield were obtained with increasing planting densities. Under these farming conditions, considering save fertilizer and sowing seeds economically, better grain yields could be obtained at a planting density of 500 seeds/m^2 and a fertilizer level of 50g/m^2 which occupied 88% of maximum yield and save 50% fertilizer input and 44% sown seeds input respectively.

Among yield component parameters, spike number per m^2 seeds per spike and kernel weight were significantly ($p < 0.01^{***}$) affected by fertilizer and planting density (Table 3). Seed number per spike and kernel weight increased with the increase in fertilizer level, but decreased as planting density increased. The seed number per spike was significantly affected by planting density, the lowest planting density had more seeds per spike than the highest density (Table 3). Spike number per m^2 was affected insignificantly by the levels of fertilizer input, but increased obviously with the increase in plant density levels. So Spike number per m^2 increase with increase in plant density was able to compensate for decreasing in seeds per spike caused by increasing planting density.

Although the fertilizer treatments significantly increased number of seeds per spike as compared with the no fertilizer treatment, differences among fertilizer levels were not significant. It is clear that under conditions where soils suffer from severe nutrient deficiency, soil fertility is the major factor that affects number of seeds/spike. Kernel weight was significantly ($p< 0.01$***) affected by both fertilizer and planting density. The highest kernel weights were obtained at lowest planting density and highest fertilizer level.

Table 3. Effects of fertilization and planting density on yield components

Fertilizer level (g/m^2)	Planting density (seeds/m^2)									
	300		500		700		900		Mean (S.E±)	
	SPS	KW	SPS	KW	SPS	KW	SPS	KW	SPS	KW
0	9.0	35.5	8.9	33.7	7.3	32.2	4.8	31.0	7.5±1.0	33.1±1.0
25	14.8	38.2	11.7	36.4	8.8	35.1	7.4	34.0	10.7±1.6	35.9±0.9
50	16.0	40.0	13.8	37.4	10.1	36.0	9.4	35.3	12.3±1.6	37.2±1.0
75	19.9	40.8	14.8	38.4	11.4	37.1	10.7	36.5	14.2±2.1	38.2±1.0
100	21.3	38.9	15.2	39.2	12.0	38.0	11.6	37.4	15.0±2.3	38.4±0.4
Mean (S.E±)	16.2±2.2	38.7±0.9	12.9±1.2	37.0±1.0	9.9±0.9	35.7±1.0	8.8±1.2	34.8±1.1		
Fertilizer level (g/m^2)	Planting density (seeds/m^2)									
	300		500		700		900		Mean (S.E±)	
	SN	HI	SN	HI	SN	HI	SN	HI	SN	HI
0	297	0.26	391	0.30	427	0.25	521	0.20	409±46	0.25±0.02
25	288	0.30	401	0.29	475	0.29	537	0.24	425±54	0.28±0.01
50	290	0.32	422	0.34	517	0.32	559	0.25	447±60	0.31±0.02
75	290	0.30	414	0.33	531	0.30	571	0.27	452±63	0.30±0.01
100	286	0.35	402	0.35	530	0.33	572	0.30	448±65	0.33±0.01
Mean (S.E±)	290±2	0.31±0.01	406±5	0.32±0.01	496±20	0.30±0.01	552±10	0.25±0.02		

Notes: SPS = Seeds per spike, KW = Kernel weight (g/1000 seeds), SN = Spike number per m^2, HI = Harvest index.

3.2 Effects of fertilizer and plant density on biomass and root growth

The highest biomass, 8400 kg/ha was achieved for the highest planting density (900 seeds/m^2) and fertilizer rate (100 g/m^2), whereas the lowest biomass, 3645 kg/ha, was obtained under the lowest density and no fertilizer input (Table 4). Results showed that both planting density and fertilizer significantly affected biomass, but the effect of fertilizer was more pronounced than that of planting density. Results also indicated that under 0 and 25g/m^2 fertilizer levels, biomass was not significantly affected by planting density.

Fertilizer significantly increased total root dry weight, total root length and thick root length in the 0—60 cm soil layer compared with the no fertilizer treatment (Table 5). There were no differences in total root dry weight among the treatments that received fertilizer. The ratio of total root length to thick root length, however, decreased with an increase in fertilizer level. This is because that fertilizer enhanced secondary root number by 1.8—2.9, resulting in an increase in the number of total root per plant.

Table 4. Effects of planting density and fertilizer on wheat biomass (kg/ha)

Planting density (seeds/m^2)	Fertilizer levels (g/m^2)					Mean
	0	25	50	75	100	
300	3645	5385	5745	7860	6870	5901±713
500	4050	6015	6375	7215	6960	6123±560
700	4140	5175	5970	7485	7410	6036±645
900	4095	5715	7500	8385	8400	6819±838
Mean	3983±114	5573±185	6398±390	7736±253	7410±350	

Table 5. Effects of fertilizer on growth of wheat roots

Root growth	Fertilizer level (g/m^2)					
	0	25	50	75	100	Mean (S.E ±)
Total root dry weight (g)	2.92	3.42	3.63	3.60	3.70	3.45±0.14
Total root length (m)	260	298	257	256	300	274±10.
Thick root length (m)	49.6	60.0	57.7	66.7	86.6	64.1±6.3
Total root length/thick root length	5.23	4.98	4.45	3.82	3.45	4.39±0.34
Seminal roots number	4.79	5.52	4.69	5.02	4.97	5.00±0.14
Secondary root number	4.13	5.94	6.51	6.73	6.59	5.98±0.48
Root number per plant	8.82	11.4	11.2	11.7	11.8	11.0±0.56

This evidence suggests that fertilizer improved growth and development of secondary roots. This caused an increase in number of secondary roots and fully-fledged thick root length elongated. So effective absorption of soil storage water and nutrients was possible.

Figure 1 also showed that fertilizer promoted root growth mainly at the depth of 0—20 cm, the root growth below 35 cm was similar for all treatments.

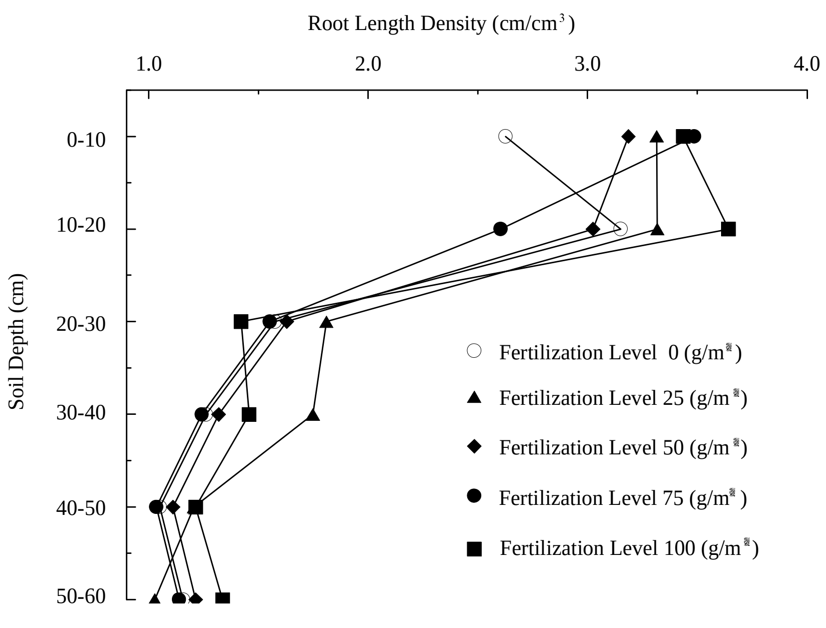

Figure 1. Effects of fertilizer on the root length density and distribution of spring wheat.

3.3 Effects of fertilizer and planting density on crop water use

Crop evapotranspiration (ET) was closely correlated with soil fertilizer (Table 6). At the highest fertilizer level, total ET (average 275 mm) was significantly higher than under other fertilizer levels (227—234 mm) irrespective of planting density, indicating that the 100 g/m^2 fertilizer level increased crop water use and induced the largest amount of soil water depletion.

Fertilizer was positively correlated with WUE and the correlation was highly significant (r=0.894), however, the effect of planting density on WUE showed a negative correlation(r=0.894) (Table 7).

Table 6. Effects of fertilizer and planting density on total ET (mm)

Planting density (seeds/m^2)	Fertilizer level (g/m^2)					Mean (S.E.±)
	0	25	50	75	100	
300	221	238	243	230	261	239±7
500	230	233	236	238	283	244±10
700	234	243	231	233	279	244±9
900	223	217	224	223	275	232±11
Mean (S.E.±)	227±3	233±6	234±4	231±3	275±5	

Table 7. Effects of fertilizer and planting density on WUE (kg/mm.ha)

Planting density (seeds/m^2)	Fertilizer level (g/m^2)					Mean (S.E.±)
	0	25	50	75	100	
300	4.30	6.83	7.61	10.3	9.11	7.62±1.02
500	5.20	7.42	9.27	9.93	8.52	8.07±0.83
700	4.42	5.75	8.25	9.73	8.69	7.37±0.99
900	3.70	6.88	8.39	10.09	9.03	7.62±1.11
Mean (S.E.±)	4.41±0.31	6.72±0.35	8.38±0.34	10.00±0.11	8.84±0.14	

WUE was lowest (4.41 kg/ mm.ha) in the plots that received no fertilizer. In the fertilizer range of 25 to 75 g/m^2, as fertilizer level gradually increased WUE was enhanced by 52.4%, 24.7% and 19.3%, respectively. At the 100g/m^2 fertilizer level, WUE was not enhanced but reduced. These results indicate that only optimal levels of fertilizer can enhance WUE. Over fertilizer could have a depressing effect on WUE.

3.4 Effects of N, P and K on Yield and Grain Quality of Spring Wheat (Experiment 2)

As previously mentioned, Experiment 2 was conducted in a level field; no water ran onto or off of the field during the growing season. At sowing time soil water content at the depth of 0—200 cm was 280.9 mm, and precipitation during wheat growing season (from March 17th to July 27th) was 171.9 mm.

Wheat yield and biomass increased significantly when P or N was applied, indicating that the soil is deficient in both P and N (Table 8). The positive effect of N, however, was smaller than that of P. In contrast, the application of K had no significant effect on grain yield and biomass.

Table 8. Effects of N, P, K and their combinations on grain yield and biomass (kg/ha)

Treatment	Grain yield	% increase over control	Treatment	Biomass	% increase over control
NPK	1935a	55.4	NPK	6095a	48.6
NP	1890ab	51.8	NP	6060a	45.3
P	1800bc	44.6	PK	5640b	35.3
PK	1755c	41.0	P	5565b	33.5
N	1395d	12.0	N	4710c	12.9
NK	1350de	8.4	NK	4665c	11.9
K	1260de	1.2	0	4170d	0.0
0	1245e	0.0	K	3960d	-5.3

Means followed by the same letters are not statistically significantly different according to t-test at p=0.05.

Table 9. Effects of N, P, K and their combinations on yield components

Treatment	Fertile spikes per m^2	Treatment	Fertile spikelets per spike	Treatment	1000-kernel wt (g)
NPK	459a	NP	10.2a	PK	31.5a
NP	452a	P	10.2a	P	31.4ab
P	449ab	NPK	9.6ab	NPK	30.2ab
PK	431bc	NK	9.4ab	NP	30.1bc
N	427cd	PK	9.2b	K	29.8bc
NK	425cd	N	9.0b	0	29.6bc
K	410d	0	8.7b	N	29.0bc
0	409d	K	8.6b	NK	28.8c

Means followed by the same letters are not statistically significantly different according to t-test at p=0.05.

The number of fertile spikes per m^2 and fertile spikelets per spike increased significantly when P was applied (Table 9). The effects of both N and K on these parameters were not significant.

Nutrient analyses showed that N and P contents of seeds were 4.56 and 9.71 times higher than that of shoots, respectively. However, K content in seeds was only 32.2% of that in shoots (Table 10). This suggests that both N and P uptake by roots is mainly used for seed formation. N application significantly increased the N contents in both seeds and shoots while it increased the P content in the shoots only (Tables 11 and 12). We also noticed that the percentage increase in the N content of shoots was greater than that of seeds when no P was applied, indicating that P-deficiency inhibited the transportation of N from shoots to seeds.

Table 10. Effects of N, P, K and their combinations on N, P and K contents in seeds and shoots

Treatment	Seeds			Shoots		
	N (%)	P_2O_5 (%)	K_2O (%)	N (%)	P_2O_5 (%)	K_2O (%)
NPK	2.44?0.11	0.272?0.042	0.267?0.027	0.540?0.084	0.027?0.006	0.914?0.102
0	2.12?0.06	0.244?0.025	0.275?0.023	0.450?0.023	0.024?0.002	0.800?0.042
NP	2.51?0.09	0.264?0.013	0.297?0.016	0.297?0.016	0.027?0.005	0.876?0.161
NK	2.42?0.05	0.232?0.011	0.294?0.007	0.600?0.078	0.027?0.003	1.040?0.088
PK	2.07?0.06	0.239?0.017	0.272?0.010	0.414?0.011	0.022?0.004	0.922?0.064
N	2.39?0.09	0.240?0.015	0.284?0.016	0.596?0.064	0.031?0.006	0.928?0.045
P	2.13?0.15	0.240?0.018	0.273?0.006	0.404?0.035	0.022?0.003	0.798?0.029
K	2.08?0.06	0.251?0.018	0.283?0.008	0.283?0.008	0.024?0.003	0.864?0.025

Table 11. Effects of N, P, K and their combinations on total N, P and K contents in seeds

Treatment	Total N (%)	Increment (%)	Treatment	Total P (%)	Increment (%)	Treatment	Total K (%)	Increment (%)
NP	2.51a	18.5	NPK	0.272a	11.3	NP	0.297a	8.1
NPK	2.44ab	15.4	NP	0.264ab	8.4	NK	0.294a	6.8
NK	2.42ab	14.4	K	0.251ab	3.0	NPK	0.287ab	4.2
N	2.39b	12.8	0	0.244bc	0.0	N	0.284ab	3.2
P	2.13c	-0.6	P	0.240bc	-1.5	K	0.283ab	3.0
0	2.12c	0.0	N	0.2408c	-1.8	0	0.2750b	0.0
K	2.13c	-1.9	PK	0.239c	-2.2	P	0.273b	-0.6
PK	2.07c	-2.5	NK	0.232c	-5.3	PK	0.272b	-1.0

Table 12. Effects of N, P, K and their combinations on total N P K contents in shoots

Treatment	Total N (%)	% Increase over control	Treatment	Total P (%)	% Increase over control	Treatment	Total K (%)	% Increase over control
NP	0.600a	33.3	N	0.0308a	27.3	NK	1.040a	30.0
N	0.596a	32.4	NPK	0.0272ab	12.4	N	0.928b	16.0
NPK	0.540ab	20.0	NK	0.0272ab	12.4	NPK	0.914b	14.2
NK	0.530b	17.8	NP	0.0270ab	11.6	NP	0.876bc	9.5
K	0.452c	0.4	0	0.0242bc	0.0	K	0.864bc	8.0
0	0.450c	0.0	K	0.0240bc	-0.8	PK	0.808bc	0.0
PK	0.414c	-8.0	PK	0.0220c	-9.1	0	0.808bc	0.0
P	0.404c	-10.2	P	0.0216c	-10.7	P	0.798c	-0.3

The same letters in parenthesis indicated no statistical difference between treatments with t-test at 0.05 level.

These results indicate that P or N application significantly increased yield of spring wheat, whereas no significant increase in yield occurred when K was applied. N and P+N combinations improved yields remarkably. The results also showed that the soil is deficient in both P and N. Specifically, P is considered as a major bottleneck for spring wheat production in this semiarid area. Application of P with K improved accumulation of photosynthetic matter and its transport to seeds. Combined application of N, P and K can significantly increase number of fertile spikes; and it is important to maintain the nutrient balance in the soil that will improve seeds quality as well as yield of spring wheat.

4 Discussion

Suitable soil management is a very important approach for improving wheat WUE in water limited conditions (Hatfield et al., 2001). Spring wheat in semiarid regions is usually grown under nutrient deficient conditions due to loss of fertile surface soil by erosion (Richardson et al., 1969; Williams, 1981; Bilbro, 1987; Wei et al., 2000). Under such low soil fertility conditions, application of limited irrigation is ineffective for improving grain yield and WUE. To improve spring wheat productivity in this area, increasing soil fertility plays an important role (Deng et al., 2002). Results in this study indicate that fertilizer was positively correlated (r = 0.959) with grain yield of spring wheat. Planting density, however, showed poor correlation with grain yield of spring wheat. High planting density resulted in a relatively low yield that was not compensated for by increasing fertilizer. Under these semiarid conditions, a 2250 kg/ha yield could be achieved by adding 90 kg N and 135kg P_2O_5 per ha with a planting density of 500 seeds/m^2. Yield components such as fertile spikelets number, kernels per spike and kernel weight were influenced by both fertilizer and planting density (Kiniry, 1988; Pecetti et al., 1992). Increasing fertilizer level significantly increased fertile spikelets number, kernels per spike and kernel weight. These components were decreased with high planting density. The number of fertile spikelets was sensitive to fertilizer, whereas kernel number and weight was mainly affected by plant density.

Fertilizer improved the development of the root system in spring wheat and especially enhanced root growth in the cultivated (0-20 cm) layer. This resulted in an improvement in crop water use and nutrient absorption and hence, crop yield and WUE also increased (Williams, 1976; Merrill and Upchurch, 1994). Crop WUE was positively correlated (r = 0.894), with fertilizer of spring wheat but poorly correlated with planting density. WUE increased with the addition of fertilizer (Cooper et al. 1987), however, the response of WUE to the additional amounts of fertilizer gradually declined. At the 75-g/m^2

fertilizer level, crop WUE was in the range of 9.73—10.25 kg/mm.ha, and a further increase in the fertilizer level was not accompanied by an increase in WUE.

Results of a two-year field nutrient experiment in a semiarid area showed that the grain yield of spring wheat increased by 44.6% and 55.4%, respectively, when P and P+N+K were applied. N+P+K improved the quality of wheat seeds and the content of N, P and K in seed increased by 18.5%, 18.4% and 8.1%, respectively, compared with no nutrient treatment. A significant increase in yield was obtained with N application but not with K, suggesting that the soil is deficient in both P and N. P is considered as a major bottleneck for spring wheat production in this semiarid area.

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Comparison of root strength of different plant species

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Abstract

Slope-stability is investigated from a biological perspective, associated with capability of roots to achieve soil stabilisation. Four levels of soil-stability were identified for plant roots, through experimental determinations made using various plants. Results revealed that various roots have different tensile strengths. Values of 85, 27.3, 24.6, 24.5, 19.7, 19.2, 17.5 and 13.5 MPa, respectively, were found for maximum tensile strength of Vetiver grass (*Vetiveria Zizanioides*), Common Cetipede grass (*Eremochioa ophiuroides hack*), White Clover (*trifolium repens*),Late Juncellus (*Juncelles serotinus*), Dallis grass (*paspalum dilatatum poir*), Bahio grass (*paspalum notatum flugge*), Manila grass (*Zoysia matrella merr*) and Bermuda grass (*Cynodon dactylon*). Differing tensile strengths of various plant roots and their soil stabilisation capabilities are concerned with their inherited structures and various tissues. Knowledge of plant soil stabilisation properties affords a rational biological approach that may substitute or combine with engineering measures for natural slope protection or restoration, in Chinese primary construction projects.

Key words: Bio-engineering approach, root network, mechanics, soil stabilisation, tensile strength, root-soil compounds; grasses.

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1. Introduction

1.1 General

In comparing constructional and biological methods of erosion control, benefits of the latter have included rainfall infiltration and interception to prevent soil detachment and movement; decreased surface-flow thereby preventing erosion; protection against erosion associated with traffic and wind; root anchors and buttresses. To realize physiological and ecological functions, roots should remain active and should combine fully with the clay particles, colloids, organisms, minerals and microorganisms. Generally, the deeper and the more extensive the area covered, then the stronger is the root's soil-reinforcement performance.

Conditions and growing surroundings are mainly emphasized in general agro-forestry production (Jackson, 1996; Gale and Grigal 1987; Lyr, 1967; Coile, 1936; Li Peng, 2002). Some study in this field is fairly rich and ripe, but the study of reinforcement of soil by root is by far ignored or less at least. For example, silt deposition, runoff, runoff coefficient, erosion modulus are much stressed on, as far as soil and moisture are concerned, but the study is less stressed on the micro mechanisms of reinforcement of soil by roots in the contact area of organisms.

Reinforcement of soil by roots includes: the ability of its mechanics and the compound integral performance of organisms between root and soil. Although the research is reported much, it lacks a systematic approach, furthermore, less is made the study of performance of root reinforcing soil by root. It is reported that the tensile strength of roots are as follows: willow (*Salix*), 9～36 MPa; Poplars (*Populus*), 5～38 MPa; Alders (*Alnus*), 4～74 MPa; Douglas fir (*Pseudotsuga*), 19～61 MPa; Silver maple (*Acer sacharinum*), 15～30 MPa; Western hemlock (*Tsuga heterophylia*), 27 MPa; Huckleberry (*Vaccinum*), 16 MPa; Barley (*Hordeum vulgare*), 15～31 MPa; Moss, 2～7 kPa; Grass, 2～20 MPa; Vetiver, 40～180 MPa. Some researchers have studied the effects of vegetation on slope-stability, including hydrologic mechanisms and mechanics. Mechanical factors indicate that plant growth increases soil load, and root function increases soil adherence (Diti, 1999). The study attempts to find the differences in strength between different plant roots in reinforcing soil.

1.2 Mechanical model of soil reinforcement by roots

The function of root enforcing the resistance to impact, corrosion resistance is considered by many learners (Kazuroki, 1990). After observing the physical relation of man-planted pine root and soil, Li Yong believes that the physical effective relation of effective root density (<=ф1mm tiny root) contacts closely with the effectiveness of soil-change physically, which can obviously increase soil-stability in water, ratio of macro-tube in soil, and increase the contents of organism in soil, decrease the density and weight of soil. In this way, it has revealed performance of soilimpacting resistance enforced by root (Li Yong, 1993). Liu Guobing (1996) made a further study to distinguish the function of reinforcement of soil by root into three ways: function of series root network, function of root-soil cement and sticking, root biochemical function. On the basis of these, the tissue structure's function of root itself should be considered well so that mechanical model of root network would be constituted to the fourth function (See Fig 1).

1.3 Four sorts of mechanical model of reinforcement of soil by roots

1.3.1 Mechanics of roots

Mechanics of roots can be defined as the characters of the root function formed against outer force from outside during its growing and developing, and determined by some factors, such as: tensile strength, performance of shear force. Inherited, constructive discrepancy of various roots constitutes distinctive chemical and physical characters of mechanism.

1.3.2 Linking and force conveying function of root system network

Root in any direction composes root system network, with which the performance and ability connected between networks are good to the connection of root network and soil network.

1.3.3 Integrated function of root-soil adhering and cementing acting as a compound power

On the surface where root and soil contact each other, the organic compound performs and acts as cementing and sticking substances: such as cellulose, protein, polysaccharides, fat, wax and substance from micro organism and the alike.

1.3.4 Biochemical function of root-soil

In the course of constituting organic compounds, some chemical and biochemical action take place in root-soil system, organic substances, such as polysaccharides, radical–OH, proton–H, act with oxygen on the surface of clay grains and the molecules of organic matters can be combined or connected by polyvalent cation, such as Fe^{3+}, Ca^{2+}, Al^{3+} to form a bridge from a organic body to another, so the root-soil compound can be aggregated and perform a compound root-soil system.

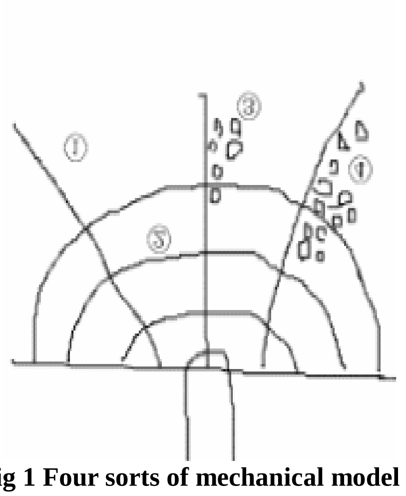

Fig 1 Four sorts of mechanical model of reinforcement of soil by roots

1.4 Soil reinforcement by root

Theoretically the power produced on the root mainly includes: extrusion force of crowding out by every root contributed from the top plant weight, adsorptive power of moisture molecular adhering to the surface of root, sticking and cementing power between root and soil, expanding and tensile force of interaction in the root network, frictional resistance between the movement of root and soil, shear and tensile force to the root turned out in the soil sliding, upward force of outtake and uptake substances from outside to inside of plant root. Therefore, the extrusion press transformed from weight, power of moisture uptake between root and soil, binding and cementing power, frictional force, tensile force of interaction in the root network and resistance against outside force of root, shear force above build up the soil reinforcement mechanics, so, when we judge the mechanic performance of reinforcement of soil by root, all the above should be considered as key elements.

Since less are the reports on mechanical performance of herb root of, and the research methods of herb root are simpler comparing with those of trees, we take for example, the mechanic performance of several kinds of herbs mainly as follows so as to confirm the mechanic performance of root.

2 Materials and methods

Vetiver, grass was obtained from the nursery of Nanchang Water Conservancy and Hydropower College, on May. 6, 2001while Common Cetipede grass, Bahio grass, White Clover and Dallis grass were obtained from the Experimental Station of Forage and Livestock of Jiangxi Province, on Jun. 5, 2001. The experiment was carried out according to that introduced by Diti (1997). Maximum strength was measured using a tensile spring dial gauge and the diameter of root was measured by using a caliper rule when failure took place. The tensile strength was calculated according to $P=4F/\pi D^2$; F-maximum tensile force; D-the root diameter at failure, and every sample of herb root experiment was repeated 20-28 times.

3 Results and discussion

3.1 Mechanical properties of grass roots

Table 2 indicates that roots are different because of their different structures. The mechanical strength of Vetiver reaches 85 MPa; Common Cetipede grass 27.3 MPa; White Clover 24.6 MPa; Late Juncellus 24.5 MPa; Dallis grass, 19.74MPa; Bahio grass, 19.2 MPa; Manila grass, 17.6 MPa; Bermuda grass, 13.5MPa (Cheng Hong, 2002). Other studies show that root of certain trees have an elastic failure typically when they are cut by pulling, such as that of *Populus purdomii, Abies Fabri*, whi l e *Rhododendron spp* displays a brittle failure (Zhu Qingke, 2002). So the differences of plant variety decides the mechanical performance.

3.2 Mechanics of reinforcement of soil by grass root in network

Grasses have no main strong roots, compared with trees. Herbs mainly have fibrous roots or tiny roots (**ϕ**<= 1mm), such as Vetiver, which of **ϕ**<= 1mm constitute 50-66% (Cheng Hong, 2002). In this way, roots can connect fully with soil, withstand uptake power of water, sticking and cementing power of organisms, frictional force produced from the sliding between roots and soil, moreover, roots can withstand shear turned out from the movement of soil and resistance produced from inside and outside.

Table 1. Tensile strength of Vetiver

Diameter/ mm	Maximum of tensile force/kg	Maximum of tensile strength/MPa	Diameter/ mm	Maximum of tensile force/kg	Maximum of tensile strength/MPa
0.20	0.60	186.7	0.63	2.73	85.6
0.35	1.20	121.9	0.62	2.80	71.4
0.38	1.50	129.2	0.65	2.73	63.3
0.40	1.33	103.4	0.65	2.70	76.7
0.40	1.50	116.7	0.66	2.74	78.2
0.45	1.38	97.1	0.62	2.53	81.9
0.48	1.75	93.5	0.67	2.68	74.3
0.55	2.23	91.7	0.62	2.63	85.2
0.57	2.62	100.3	0.65	2.56	75.4
0.60	2.61	90.2	0.60	2.15	74.3
0.63	2.66	83.4	0.70	2.95	74.9
0.62	2.63	85.1	1.30	4.90	36.1
0.61	2.30	76.9	1.50	5.10	28.2
0.62	2.48	79.0	1.70	5.30	22.9

Table 2. The resisting force, diameter and tensile strength of root of various herbs

Sorts	Average diameter of root/mm	Average resistance/n	Average tensile strength/MPa
Late Juncellus	0.38±0.43	2.66±0.47	24.50±4.20
Dallis grass	0.92±0.28	12.98±0.35	19.74±3.00
White Clover	0.91±0.11	12.80±0.59	24.64±3.36
Vetiver	0.66±0.32	24.89±1.08	85.10±31.2
Common Cetipede grass	0.66±0.05	9.56±1.33	27.30±1.74
Bahio grass	0.73±0.07	8.99±1.99	19.23±3.59
Manila grass	0.77±0.67	8.84±1.25	17.55±2.85
Bermuda grass	0.99±0.17	10.49±2.65	13.45±2.18

3.3 Root strength of different plants

The data in Table 2 indicates that with a root strength of 85 MPa, Vetiver has the highest strength of all the herbs being researched. This explains why Vetiver system is used widely and quickly for highway embankment stabilisation, river banks and coastal protection, sandy dune stabilization and restoring vegetation as a very effective bioengineering means throughout South China. Knowledge of plant soil stabilization properties affords a rational biological approach that may substitute or combine with engineering measures for natural slope protection or restoration, in Chinese
primary construction projects.

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Compensatory effects of water stress on maize

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Abstract

Compensatory effects of water stress on maize were studied by pots and farm experiments. Results indicated that both stage of exposure and severity of water stress affected compensatory effects. Water stress in the seedling stage could increase root activity both during the stress period and after re-watering, as well as delaying caducity of leaves in the filling stage. Higher rates of photosynthesis and areas of green leaves were observed for maize subjected to stress in the seedling stage, by comparison with values under full irrigation. Slight stress in the early jointing stage could improve root activity in some cases while severe stress had adverse effects. Compensatory effects might explain a slightly higher grain yield of maize under stress.

Key words: Maize, water stress, compensatory effects.

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1 Introduction

Deficit Irrigation (DI) is increasingly the only choice due to increasing shortage of irrigation water. Much effort has been made to investigate effects of water stress on growth, water consumption and crop yield. However there is limited knowledge of after effects and compensatory effects of water stress. In most cases water stress can be damaging, but in some instances, there might be compensatory effects on crops which counteract adverse effects to some extend. This might be the reason why crops under deficit irrigation (DI) could produce fairly high grain yields. This paper describes an investigation of compensatory effects on water stress applied to maize by pot and field experiments to better understand the theory of DI.

2 Materials and methods

2.1 Pot experiment

Pot experiments were conducted in 1998 at the Key Laboratory of Agricultural Soil and Water Engineering in Northwest Sci-Tech University of Agriculture and Forestry in Shaanxi Province. Seeds of local maize cv. SZ-9 were planted in plastic pots of 15 cm diameter and 20 cm length. About 3 kg dry loam soil was put into these pots. The field capacity and bulk density of soil were 26%, on a gravimetric basis, and 1.02 g/cm^3, respectively. Five seeds were planted in each pot on 20^{th} May, with only two seedlings similar being retained at the 3-leaf-stage. All other agricultural treatments were kept same except for the maintained level of soil moisture (SM).

Seedlings were divided into two groups, A and B. Each group was divided into four sub-groups, to be compared with a control treatment which was fully irrigated. Seedlings in the A and B groups were subjected water stress in seedling stage and jointing stage, respectively. The seedlings in each sub-group were subjected to different lengths and severity of stress as shown in Table 1. Seedlings in group A were subjected to water stress from the 5-leaf-stage (21 days after planting) and group B from 7-leaf-stage (28 days after planting, early period of jointing stage) respectively. There were 10-12 pots or more of seedlings in each sub-group as replicates.

Table 1 Stress conditions of maize pot experiment

Treatment	Control	A1	A2	A3	A4	B1	B2	B3	B4
Stress time (d)	—	7	7	14	14	7	7	14	14
Severity	—	SL	SE	SL	SE	SL	SE	SL	SE
Stress period		Seedling stage				Jointing stage			

Note: SL and SE represent slight and severe stress; with corresponding SM ranges of 40-50% and 50-60% of field capacity, respectively.

Seedlings in pots were put in a green house only on rainy days. Different degrees of water stress were controlled by regulating the water supply. SM was measured daily by weighing at 8:00 am. Slight and severe levels of stress were identified as SM contents of 50-60% and 40-50% of field capacity, respectively. Root lengths were measured by a ruler attached under a piece of glass while activity was determined by TTC measurement (Staff room notes, 1987). Shoots and roots were washed out and dried in an oven maintained at 70^{0}C. Leaf area was measured by delta area system while photosynthesis rate, stomatal resistance and internal CO_2 concentration were measured by portable CID-301P system.

2.2 Field experiment

Field experiments were performed in Hongdong county, Shaanxi Province, China. A local high production cultivar named Danyu-13 was used as the source of maize seed. Seeds were planted on 1st June and harvested on 28th September, 1998. The test plot dimensions were 20m×3m. All other agricultural practices were kept the same except for the lower limit of SM. The field was not irrigated until SM reached the lower limit. The soil texture was loam with a field capacity of 24.5% (w/w) and having medium fertility. The groundwater level was 15m deep.

Treatments were divided into two groups, C and D, subjected to slight and severe water stress in the seedling and jointing stages, respectively. A control plot was fully irrigated. Each group consisted of two sub-groups, C1 and D1 subjected to slight stress (the lower SM limit was 60% of field capacity) while C2 and D2 were subjected to severe stress (lower limit 50% of field capacity), as shown in Table 2. Different degrees of stress were achieved by restricted watering. All treatments were fully irrigated after stress ended. SM was measured by neutron probe every 4-5 days. Root length, leaf area, root activity, photosynthesis rate, stomatal resistance and internal CO_2 concentration was measured by the same methods mentioned above.

Some 47.3 mm of effective rainfall occurred during the stressed seedling stage of which 37.4 mm was received within 7 days of planting. Only 21.5 mm of rain fell in the jointing stage during stress period. Each treatment reached its design lower limit of moisture. The depth of soil wetting was 60 cm in the seedling stage and 100 cm in later stages.

Table 2 Lower limits of % field capacity during maize growth stages

Treatment	Growing and developing stage			
	Seedling	Jointing	Ear-filli ng	Filling maturity
Con-trol	70	70	75	70
C1	60	70	75	70
C2	50	70	75	70
D1	70	60	75	70
D2	70	50	75	70

Note: All treatments were restored to a full irrigation regime similar to the control after stress period.

3 Results

3.1 Compensatory effects of water stress on growth of root

Table 3 shows that dry matter accumulation declined with water stress, while root/shoot ratio increased remarkably with increasing severity and duration of stress. A reduced photosynthesis rate caused the reduced dry matter accumulation. On the other hand, an increased root/shoot ratio indicated that stress could simulate transfer of material in maize from shoot to root and so improve drought-resistance.

Table 3 Effects of water stress in seedling stage on root and shoot dry matter accumulation

Treat-ment	Weight of root (g/plant)	Weight of shoot (g/plant)	Root/ shoot ratio	Time after stress
Control 1	0.510	0.962	0.380	7 days
A1	0.433	0.795	0.545	
A2	0.380	0.537	0.721	
Control 2	0.751	2.35	0.318	14 days
A3	0.624	1.51	0.412	
A4	0.520	1.00	0.518	

Note:1.Water stress in 5-leaf-period,late period of seedling stage

2. Control 1, A1, A2 were measured 28 DAP and Control 2, A3, A4 measured 35 DAP.

3.All treatments were measured just after stress without re-watering.

4. Weight of shoot and root were dry weights.

Relative growth rate (RGR) of root and shoot dry matter were higher, under slight stress, than under severe stress or with full irrigation. When comparing slight stress and the control, compensatory RGR of shoots was more evident. RGR of shoots under severe stress was higher than the control but root RGR was reduced compared with the control. This suggested that appearance of compensatory effects of water stress were conditional and depended on severity of stress. Severe stress would inhibit recovery of growth after re-watering, as shown in Table 4. Due to the severe inhibition of growth during the stress period, accumulation of shoot and root dry matter under severe stress was lower than the control despite any compensatory effects. This indicted that compensatory effects were limited and no over-compensation was apparent under water stress.

Table 4 RGR of root and shoot after e-watering (%)

Treat-ment	Root	Shoot	Treat-ment	Root	Shoot
Control 1	3.84	5.69	Control 2	3.36	3.71
A1	3.60	5.51	A3	2.91	3.79
A2	4.39	7.03	A4	3.34	5.30

Note:1. RGR of Control 1, A1, A2 were the average relative growth rates between 28-60 days after planting; RGR of A3, A4 were average relative growth rates between 35-60 days after planting. 2.RGR were measured 60 days after planting and all treatment were re-watered.

Table 5 Root and shoot parameters of maize after re-watering

Treat-ment	Weight of root (g/plant)	Weight of shoot (g/plant)	Root/shoot ratio
Control	1.741	5.94	0.293
A1	1.371	4.63	0.296
A2	1.548	5.09	0.304
A3	1.292	3.90	0.331
A4	1.198	3.77	0.321

Note: Measured 60 days after planting

Table 6 Root form and TTC induced capacity under stress at seedling stage

Treatment	Control 1	A1	A2	Control 2	A3	A4
Overall root length (cm/plant)	387	390.5	339	453	443	375
Number of roots per plant	16.5	14	12	15.8	14.5	12
Average root length (cm)	25.8	27.8	28.3	28.7	30.5	31.3
TTC capacity (before re-water)	0.109	0.112	0.140	0.108	0.128	0.138
TTC capacity (after stress)	0.088	0.106	0.112	0.088	0.107	0.132

Note: 1.TTC capacity of Control 1, A1, A2 and Control 2, A3, A4 were measured on 28 and 35 DAP before re-watering respectively. 2. Other physiological properties were measured 60 days after planting.

Water stress at different growth stages had different effects on the root/shoot ratio. The ratio under stress at the seedling stage was higher than that at the jointing stage, indicted that seedling stage was a better stage to regulate root activity by water stress.

Water stress could not increase overall length and number of roots per plant but increased average length of root, as shown in Table 4. Maize roots were more slender, longer and had more fibrils in roots under stress, as shown by Table 6. The longer roots could absorb more water and fertilizer from deeper soil. More fibrils per root could increase the contact area with soil grains and be good for absorption. Table 6 shows that, apart from increased root/shoot ratio and improved root form, water stress could also increase root activity. The table shows that TTC induced capacity of roots under stress was higher than the control and positively correlated with increased severity of water stress.

Before full irrigation was re-established, results in the tables above suggest that the TTC induced capacity had already risen quite remarkably with the increase of severity and exposure time of water stress in the seedling stage. The compensatory effect was caused by the stress itself during stress period rather than being an effect of recovery of full irrigation. This suggests that water stress could change the internal physiological and physic-chemical reactions of maize and improved adaptability to drought might appear at a later stage

When compared to maize roots under full irrigation, the TTC induced capacity of stressed roots remained higher for a long time after re-watering as shown in Table 6. There was a positive correlation with severity of stress, indicating that water stress had after-effects on the compensatory effects. The higher level of root activity could improve fertilizer and water uptake and stimulate more assimilate to move from leaves to grain in the filling stage, resulting in higher relative grain yield (Guo, 2000; Dong, 2001).

Jointing stage water stress also had a compensatory effect on root activity. TTC capacity, under slight jointing stage stress, remained higher after full irrigation for 18-25 days compared with the control. Table 8 also implies that stress at the early jointing stage could be used to regulate root activity for drought tolerance. The difference was that only slight, when comparing stressed root activity in the jointing and seedling stages. Short-time stress could increase TTC induced capacity. While severe or slight stress for long periods would suspend root activity both during and after stress period, resulting decrease of drought-resistance ability.

Slight stress for 14 days in the jointing stage did not increase root activity. This might be due to the limited resistance to stress in the late jointing period. So a reasonable combination of stress severity and stage are important to regulate root activity and drought resistance, otherwise root activity might be inhibited.

Table 7 Effects of water stress in jointing stage on root and shoot

Treat ment	Weight of root (g/plant)	Weight of shoot (g/plant)	Ratio of root versus shoot	TTC capacity (mg/g/h)
Control 1	0.751	2.35	0.318	0.108
B1	0.585	2.05	0.292	0.122
B2	0.525	1.60	0.382	0.085
Control 2	1.104	3.31	0.324	0.102
B3	0.650	2.07	0.313	0.108
B4	0.730	1.72	0.353	0.082

Note: Control 1, B1, B2 were investigated 35 DAP and Control 2, B3, B4 were investigated 42 DAP just at the end of stress in jointing stage.

3.2 Compensatory effects on leaf physiological properties

Field experiment data showed that plant leaf area was seriously inhibited and positively correlated with severity of stress in seedling stage. Leaf extension recovered soon after stress ended and relative growth rate of leaf area was higher than the control due to compensatory effects. As a result, differences at ear filling stage, between stressed treatments and the control, were reduced. However, compensatory effects were limited and the compensatory growth could not completely offset the inhibition of vegetative growth. So maximum leaf area in ear filling stage remained less than the control, suggesting that inhibition was the major effect despite existence of some compensatory effects.

Table 8 Root parameter of maize after re-watering

Treat ment	Weight of root (g/plant)	Weight of shoot (g/plant)	Root/ shoot ratio	TTC capacity (mg/g/h)
Control	1.74	5.94	0.293	0.104
B1	1.82	5.98	0.309	0.115
B2	1.60	5.17	0.332	0.085
B3	1.48	4.98	0.303	0.102
B4	1.53	4.84	0.312	0.086

Note: All treatments were measured 60 DAP

In the filling stage, rate of leaf senescence seemed slower than the control, for plants stressed in seedling stage. This was evidenced by a reduction of numbers of dead and yellow leaves in lower layers, greater green leaf area and deeper green colours as shown in Tables 9 and 10 and Figure 1.

Table 9 Leaf area under stress at different stages in 1998 (cm^2/plant)

Treat-ment	Seedling (1/7)	Ear filling (8/8)	Filling (26/8)
Control	2317	9015	7244
C1	1770	8503	7814
C2	1312	8296	8063

Table 10 Relative growth rate of leaf area under different stress in 1998 (%)

Treat-ment	Jointing-filling stage	Filling mature stage
Control	3.58	-1.22
C1	4.13	-0.47
C2	4.85	-0.16

Control **C1** **C2**

Figure 1 Leaf appearance under different degrees of stress in seedling stage

Note: Photographs on 28th August, 1998; C1 was irrigated 32 DAP and C2 was irrigated 38 DAP.

Water stress in the seedling stage had after effects on physiological properties besides leaf area and leaf form. Leaf photosynthesis rate was also lower than the control after restored irrigation and was positive correlated with severity of stress. The inhibition could last quite a long time. Photosynthetic rate under slight stress did not reach that of the control until ear filling stage. So non-stomatal factors were major reasons for the inhibition of photosynthesis (Xu, 1997). But in the filling stage, leaf photosynthetic rate was higher than the control and positively correlated with severity of seedling stage stress. This similar to the leaf area effects indicting that water stress in seedling stage could delay leaf senescence and improve its physiological properties, as shown in Figure 2

The filling stage is an important stage for the forming of grain of maize. Vegetable growth stops at this stage and photosynthate begins to transfer mainly to the ears. Higher photosynthetic rate and leaf area implies that leaves can produce more assimilate. There is also evidence that higher root activity in later stages might improve assimilate transfer from leaves to grains (Dong, 2001). The above factors might be the main causes of relatively higher grain yield for maize under seedling stage stress.

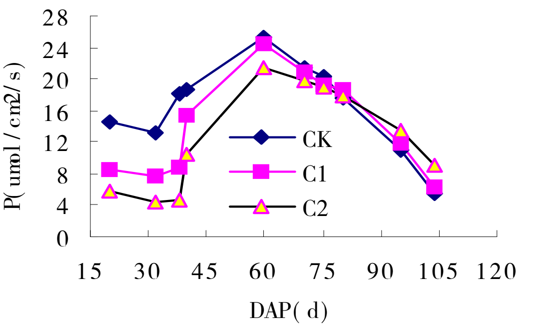

Figure 2 Photosynthesis rate of different treatments

3.3 Jointing stage stress effects on leaf area and physiological properties

Stress at the jointing stage badly suspended vegetative growth of leaves resulting in an evident decrease of leaf area as shown in Table 12. Relative leaf-area growth-rate was also lower than the control after re-watering without any evident compensatory growth. The maximum leaf area, which occurred during the ear filling stage, was less than the control. The degree of inhibition was in positively correlated to severity of stress.

Similar to the tendency of leaf area, jointing stage stress inhibited physiological properties rather than creating compensatory effects. After restoring irrigation, photosynthetic rate of leaves stressed in the jointing stage remained lower until the filling stage, as compared with the control. This was positively correlated with severity of stress as shown in Figure 2. The decline of leaf area and photosynthesis might be the reason for the lower dry matter accumulation and grain yield. Figure 3 shows that that internal CO_2 concentration of leaves (C_I) increased while photosynthesis rate declined, implying that non-stomatal factors inhibited photosynthesis after re-watering.

Table 12 Leaf area of maize under stress in jointing stage in 1998

Treat ment	Seedling stage (07－20)	Jointing stage (08－15)	Ear filling stage (08－26)	Filling stage (09－15)
Control	2145	7260	8670	6836
D1	2250	6537	7196	6148
D2	2327	5923	6936	5742

Note: 20-30 plants were measured for each treatment by area measurement system.

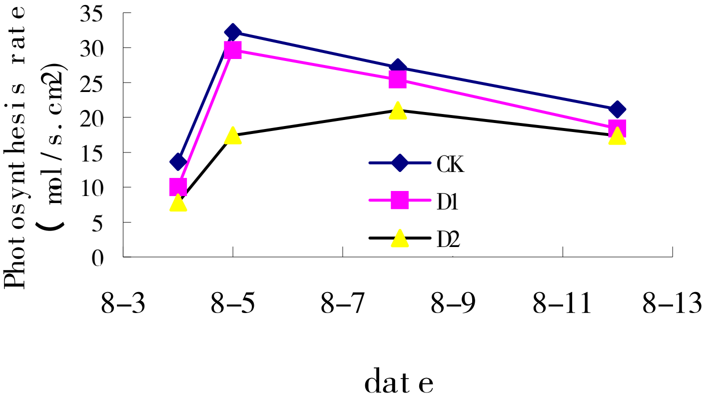

Figure 3 Photosynthetic rate of leaves under stress at jointing stage

Note: Measuring time 9:38-16:28, after re-watering

4 Conclusions

Both stage of exposure and severity of water stress affected compensatory effects. Compensatory effects caused by water stress in seedling stage were more evident than those in the jointing stage. Examples include the increase of root activity, improvement of root absorption range and physiological activity in later stages. Compensatory effects were positively correlated with severity of seedling stage stress. Only slight and short-term stress at the jointing stage would improve root activity while severe and long-term stress would decrease root activity in later stress periods. Physiological activity in filling stage might also be inhibited.

Compensatory effects improved physiological activity of plant tissue. Root activity and photosynthetic rate improved while accumulation of dry matter of root, overall root length and number of root per maize deceased. Increase of root activity appeared in stress periods and was caused by the changes of biochemical and physiological reaction affected by water stress and could last for quite a long time. While the delay of senescence and improvement of photosynthesis appeared only after stress, suggesting water stress had after-effects.

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Effect of fertigation depth on corn root morphology and NO_3^- uptake

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Abstract
Influence of nitrate fertigation depth was determined for maize root weights (RW), root density (RLD) and distribution. Relationships were established for root morphology vs. nitrate uptake and localized nitrate supply vs. sprouting or elongation of fine roots. At depths of 20, 30 and 40 cm, the localized nitrate supply by fertigation encouraged distribution of roots in deeper soil, greatly increasing RLD and encouraging subsoil penetration. RLD was closely related to nitrate uptake ($r^2 = 0.950$). So localized supplies of nitrate stimulate fine root growth, with RLD increasing quickly and allowing further nitrate absorption.

Key words: Fertigation depth; localized supply; nitrate; maize; root morphology; uptake.

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1 Introduction
The pattern of crop roots in soil is not only related to the availability of soil nutrients but also to the spatial distribution of soil nutrients (spatial availability). Crop root distribution is affected by the pattern of nutrients in soil. Then crop root distribution affects crop uptake and use nutrient use, thereby changing the distribution of nutrients.

There is limited data on effects of localized NO_3^- on crop roots' growth and distribution as there are many experimental report or research paper on how the localized fertilization affect the growth and distribution of crop roots. Some research into NO_3^- uptake of crop also examines the relationship between crop uptake of NO_3^- and root formation. Since nitrate pollution becomes more serious so better understanding of localized NO_3^- uptake and spatial root distribution becomes important.

2 Materials and methods
Experiments were conducted at the irrigation station of the Northwest Sci-Tech University of Agriculture and Forestry. Corn was planted in PVC pipes, of 11cm diameter and 67 cm length. Pipes were split lengthwise then joined again using water-proof adhesive plaster, for ease of soil sampling. Two "tee" piece ports were fitted on either side of the pipe at 20, 30 and 40 cm depths, relative to the soil surface. Ports were 1 cm diameter and contained a fine tube of 1 mm diameter, through which nutrient solutions could be introduced to different rooting depths. Sieved soil was used to fill each pipe with soil being packed in accordance with the natural field soil profile. Soil water content was arrived at 75%.

Maize *(Zea mays L.*) seeds were germinated on June 7th, 2000, then transplanted into PVC pipes when they had grown 3 leaves, using one plant per pipe. Maize roots were sampled at different soil depths at the end of the experiment, to determine root weight and root density. There were 4 localized NO_3^- treatments, with fertigation at the soil surface (FD_0), at 20 cm depth (FD_{20}), at 30 cm depth (FD_{30}) and at 40 cm depth. Amounts of irrigation and fertilization were the same, with 4 repetitions. Amounts of water supplied were decided based on idealized soil water contents for different grow stages. Fertigation was applied 3 times during the period from jointing to booting stage, using 2.465g KNO_3 each time. The control (CK) for each treatment consisted of copied fertigation applications to pipes with no maize plant, with 3 repetitions.

Amounts of NO_3^- taken from each depth were calculated from comparison of each treatment and its control. Change of NO_3^- for each treatment is given by: NO_3^- uptake + transportation + transformation changes. If the control (CK) changes in NO_3^- represent transportation and transformation changes, then NO_3^- uptake can be determined from relative change of NO_3^- between a treatment and its control.

3 Results
3.1 Effect of localized NO_3^- on morphology of maize roots
Figures 1 and 2 give % root weight and length in different soil layers.

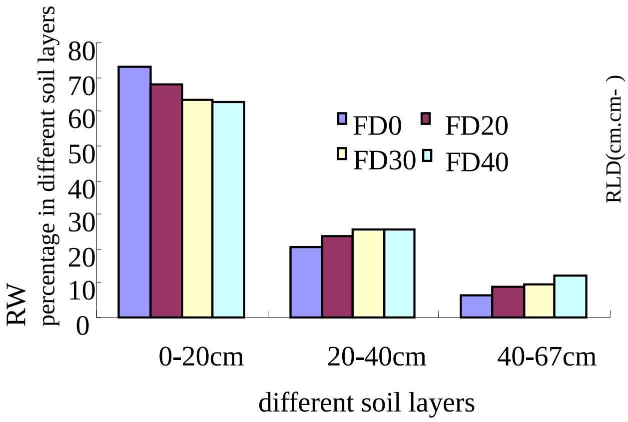

Fig. 1. RW in different soil layers

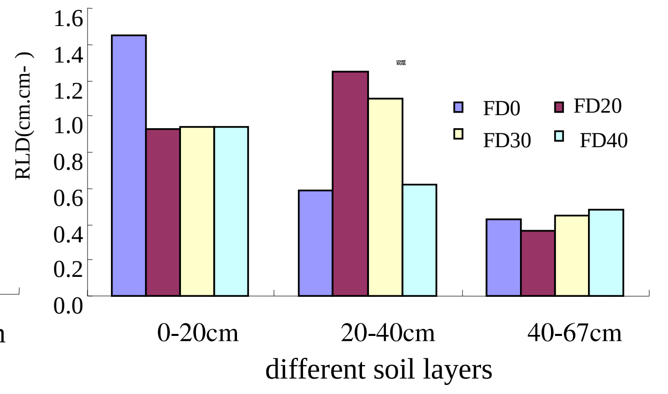

Fig.2. RLD in different soil layers

For the FD_0 treatment soil water and nutrients mainly existed in the topsoil. So, many roots densely distributed in the same depth of soil. When NO_3^- was fertigated from subsoil (FD_{20}, FD_{30}, FD_{40}), more soil water and nutrients relayed near the same depth of fertigating NO_3^-. So, roots distributed near the fertigation depth exceeded those at the same depth when fertigating with NO_3^- at the surface (FD_0). Root length density and % root weight both for different soil depths and the whole profile could prove this. Maize roots of the FD_0 treatment are most dense at 0-20cm depth, and there was a significant difference in root length density (RLD) between FD_0 and other fertigation depth treatments (FD_{20}, FD_{30}, FD_{40}). RLD of FD_0 for the 0-20cm depth was 2.48 times that at 20-40cm and 3.40 times that at 40-67cm. Also, RLD of FD_0 at 0-20 cm was higher than the RLD of FD_{20}, FD_{30} and FD_{40} in the same soil layer by 55.6%, 54.4% and 53.8%, respectively. The FD_{20} and FD_{30} layers had the largest RLDs, being higher than that of the FD_0 by 114% and 88%, respectively. However they were less than the largest RLD of FD_0 for 0-20cm.. RLD of FD_{40} was far smaller than that of FD_{20} or FD_{30} but still larger than that of FD_0 by 6.2%, and its RLD at 40-67cm depth was larger than any other treatment.

Fertigation depth affected RLD pattern more than RW distribution. Examining the relationship between RLD and RW for 20-40cm in the FD_{20}, FD_{30} and FD_{40} treatments, RW was notably smaller while RLD was larger than at 0-20cm. So smaller RW is linked with larger RLD since many thin fine roots had grown at 20-40cm. Although this kind of fine roots was light, the total length was very large. So fertigation with NO_3^- in subsoil (20-40cm) created longer roots without strongly changing the root weight, resulting in finer roots.

To a great extent, development of plant roots was decided by availability of soil mineral nutrients and their spatial distribution(Zhang H. M. etal.,2000). Fine roots appeared and grew vigorously in nutrient-rich zones(Layser, O., 1998). This kind of phenomenon was happened, on different extent, among many kinds of plant species and it was meaningful for individual plant' ability to compete limited soil nutrients with other individual plants in near.

3.2 Morphology of maize roots and NO_3^- uptake

RLD of the FD_{20}, FD_{30} and FD_{40} treatments at 20-40 cm were much greater than the RLD of same layer for the FD_0 treatment. Figure 3 shows that change was closely related with NO_3^- uptake in NO_3^- rich zone near fertigation depth. The relationship between RW and NO_3^- uptake quantity was similar to that of RLD and NO_3^- uptake. NO_3^- uptake quantity increased with increased RW and RLD, and vice versa. NO_3^- uptakes in the 20-40 cm soil layer of the FD_{20}, FD_{30} and FD_{40} treatments were larger than that of FD_0 treatments by 111%, 118% and 42% respectively. While NO_3^- uptakes in the 40-67cm soil layer of the FD_{30} and FD_{40} treatments were larger than that of the FD_0 treatment by 14% and 30%, respectively. So NO_3^- uptake accorded with the soil RLD distribution.

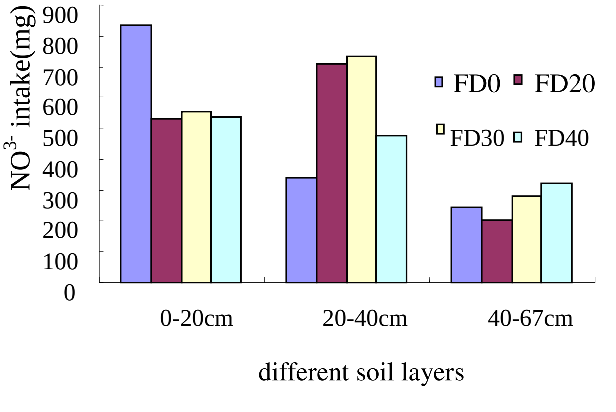

Fig. 3. Effect of fertigation depth on NO^{3-} intake

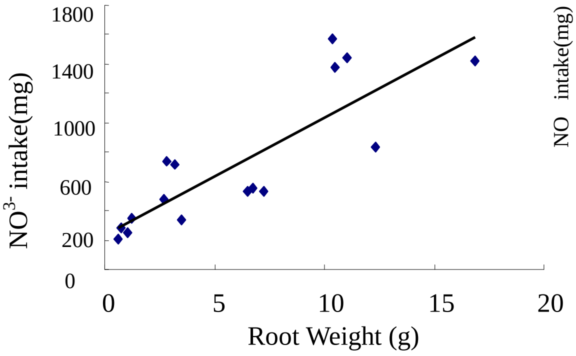

Fig.4. Effect of RW on NO^{3-} intake

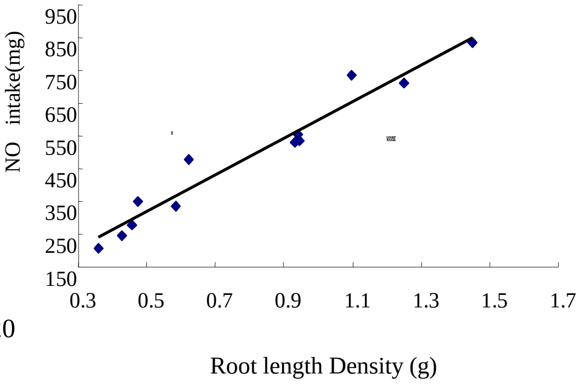

Fig.5. Effect of RLD on NO^{3-} intake

Figures 4 and 5 show that both RW and RLD affected the NO_3^- uptake of corn, but the influence differs slightly. The correlative coefficient of NO_3^- uptake and RW in different soil layers is only 0.705 while that of NO_3^- uptake and RLD is 0.951. NO_3^- uptake quantity is closely correlated with RLD, being similar to previous research results(Wiesler F, W. J. Horst,1994; Robinson D, etal., 1994).

4 Discussion

A typical experiment to investigate stimulation of fine roots by nutrition was conducted with barley (*Hordeum vulgare*) [8 ~ 10]. Drew and his cooperators found that fine roots could be stimulated to grow in nutrient rich zones when NO_3^-, NH_4^+ and mineral P_i were supplied locally. This stimulating effect was directly or indirectly related to the nutrient value of the characteristic of ions[11,12]. Those plant parts where NO_3^- was assimilated induced an increase in plant hormones to stimulate the growth of fine roots in this zone.

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Effect of growth, water use efficiency and pH value in xylem sap of alternate split-root osmotic stress on maize

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Abstract
The growth, water use efficiency and pH value in xylem sap were researched with alternate split-root osmotic stress on maize seedlings in Hoagland solution. Half of the roots were exposed to Hoagland+PEG, then after a certain time, the half roots in Hoagland+PEG were placed in Hoagland, while the other roots were changed from Hoagland to Hoagland+PEG. Results showed that the stress had a significant compensatory effect on growth and can increase water use efficiency. The pH value of xylem sap increased under osmotic stress, especially under alternate split-root osmotic stress, suggesting there is a correlation between the increase and amount of amino acid, K^+ and NO_3^- concentrations.

Key words: Alternate split-root osmotic stress; water use efficiency; xylem sap; pH value.

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1 Introduction

Research into root signals is more and more significant in recent years. At the same time, some water-saving actions were identified based on the theory and provided practical benefit. But, there are still some problems on the essence of root signals. Some papers have demonstrated that ABA is a kind of root signals, yet whether it is the only signals or not and how it acts are still urgent problems to be solved.

Some studies had been carried out under the green house and field conditions on the alternate split-root irrigation—a kind of new irrigation, which showed that irrigation can decrease crop water use but not yield.

In this experiment, we researched the seedling growth, water use efficiency and xylem sap pH under alternate split-root osmotic stress through solution culture, and we expected to explain those changes.

2 Materials and methods

2.1 Plant growth and treatments

The experiment was carried in Key Laboratory of Agriculture Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest Sci-Tech University of Agriculture and Forestry. Seeds of maize (Zea mays L. ShanDan9 cv) (pretreated with 0.2% $Hgcl_2$ for 25 min) were germinated in moist vermiculite at 26-30ºC. When the root length was 1cm height, Hoagland solution was used to water the seedlings.

Treatment was applied when the xylem appeared. In the stress treatment, half root bundles were immersed in half strength Hoagland solution containing polyethylene glycol (6000) (PEG6000). This gives a –0.2MPa or –0.5MPa solution water potential and the other half bundle was immersed in half strength Hoagland solution. After a certain time, all roots were rinsed with water then root bundle positions were reversed. Every treatment had four replicates and each replicate had four to six seedlings. Seedlings were also grown under well (untreated) water conditions and with ½ Hoagland+PEG but without any split root treatment. Seedlings were grown in the 10×6×8 cm^3 boxes, for the split-root treatment, two identical boxes were bound together so that each box had a half root bundle. Solutions were ventilated every day and added solutions to corresponding treatments to supply the loss water via transpiration or evaporating from time to time, and changed solutions every there days, so that roots grew well.

2.2 Materials and methods

Leaf water potential was measured use a pressure chamber (Model 3005, Soil Moisture Equipment Co., USA). Excised leaves were immediately placed into the chamber and pressurized to the balance pressure (Liang and Zhang, 1997).

Relative growth rate (RGR) was calculated according $RGR=L/L_0 \times dl/dt$, L_0 is the height of seedling before treatment, dl/dt is the increased height each day. The seedling height was measured every day.

Photosynthesis (Pn) and transpiration (Tr) were measured with a photosynthesis meter (Model CID-301PS, USA). Xylem sap was collected with a pressure chamber, a pressure 0.2MPa above the balancing pressure (Liang and Zhang, 1997) was always applied. The first two droplets of the xylem sap were discarded to avoid any contamination from injured cells at the cut stumps. The sap was collected in 1.5cm^3 Eppendorf tubes every 5-7 min and all of xylem sap samples were immediately frozen at –20ºC until analysis.

The value of xylem sap pH was measured use a pHS-3C digital meter. K^+ was measured with a flame spectro-photometer and NO^-_3 with a spectrophotometer. The amount of amino acid was obtained with a Amino acid meter (Beckman 121MB, USA).

3 Results

3.1 Effect on RGR of alternating split-root osmotic stress

Figure 1 shows that no matter whether split or not, the RGR of all treatments decreased remarkably under the PEG treatment. When re-supplied with water, RGR resumed at a different rate. Compared with no split-root treatment, the resumed rate was larger under the alternating split-root stress. Obviously, there was a compensatory effect, especially under –0.5MPa stress, and the effect was more remarkable with the increase of alternating frequency.

3.2 Effect on leaf water potential of alternating split-root osmotic stress

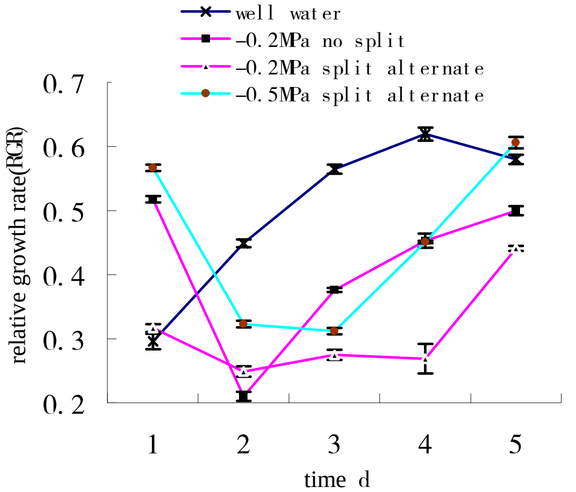

Fig.1 Relative growth rate under split-root osmotic stress on maize.Vertical bars are standard errors of means.

Table 1. Effects of alternating split-root osmotic stress on leaf water potential of maize (MPa)

	Well water	stress12h	water12h	stress12h	water12h
Well water	-0.4	-0.4	-0.4	-0.5	-0.4
-0.2MPa no split	-0.4	-0.9	-0.4	-0.9	-0.5
-0.2MPa split	-0.4	-0.8	-0.4	-0.8	-0.4
-0.5MPa split	-0.4	-1.2	-0.6	-1.1	-0.5

Table 2. Changes of photosynthesis(Pn)?transpiration(Tr) and (Pn/Tr) in alternating split-root osmotic stress on maize

Treatments	Item	Well water	stress12h	water12h	stress12h	water12h	water24h
	Pn	1.88	1.63	1.91	1.81	1.55	1.95
Control	Tr	0.577	0.472	0.605	0.693	0.400	0.638
	Pn/Tr	3.258	3.453	3.157	2.162	3.875	3.056
	Pn	3.55	2.48	2.24	2.04	2.27	2.99
-0.2MPa	Tr	0.764	0.660	0.458	0.486	0.463	0.815
no split	Pn/Tr	4.647	3.758	4.891	4.198	4.903	3.669
	Pn	3.34	2.71	2.99	2.34	3.38	5.38
-0.2MPa	Tr	0.456	0.434	0.815	0.483	0.291	0.569
split	Pn/Tr	7.325	6.242	3.669	4.485	11.615	9.455
	Pn	2.09	1.74	2.05	1.91	2.04	2.24
-0.5MPa	Tr	0.428	0.485	0.475	0.370	0.475	0.458
split	Pn/Tr	4.883	3.588	4.316	5.162	4.294	4.891

Pn-μmol·m^{-2}·s^{-1}:Tr-mmol·m^{-2}·s^{-1}:Pn/Tr-CO_2μmol·m^{-2}·s^{-1}/H_2O mmol·m^{-2}·s^{-1}

We conclude from Table 1 that the leaf water potential always changed under –0.4MPa or so for the untreated water treatment, yet water potential changed greatly under stress. Leaf water potential was higher under split-root treatment (-0.2MPa) than without splitting, which showed that although half root bundles were subjected to osmotic stress, the other half roots provided enough water to avoid serious water deficit. Compared with –0.2MPa treatment, the leaf water potential was lower under –0.5MPa stress, which told us that we should choose proper stress or drought times according to seedling age in practice.

3.3 Effect on photosynthesis, transpiration and water use efficiency of alternating split-root osmotic stress

Table 2 told us that no matter whether roots were split or not, all the leaf Pn and Tr decreased under osmotic stress. But when eliminated stress was eliminated Pn and Tr resumed to some degree. In fact the different degrees lead to different water use efficiencies (Pn/Tr) and the difference was most noticeable with increase of alternate split-root treatment. As a whole, water use efficiency increased under the alternate split-root stress, but changed little with well water. Similar to the water potential, the change of Pn, Tr and Pn/Tr were lower under –0.5MPa treatment than –0.2MPa.

3.4 Change of xylem sap pH, K^+, NO^-_3 concentration and amount of amino acid under alternating split-root osmotic stress

Figure 2 shows that, although the change was not remarkable under –0.2MPa or –0.5MPa stress, the value of xylem sap increased than well water treatment, the value was higher by 2.4 and 2.6% under –0.2MPa and –0.5MPa alternate split-root stress, respectively. Comparatively, the value changed little under stress with no splitting.

Table 3 was the change of amino acid in xylem sap. We concluded that the amount of acidic amino acid decreased with the increasing of stress, being 81% and 71% lower under alternate split-root stress (12h) and well water, respectively. On the contrary, the amount of basic amino acid increased, especially under alternating split-root stress, the amount was higher 271% and 198% under –0.2MPa and –0.5MPa (12h) than

Table 3. Changes of amino acid in xylem sap in alternating split-root osmotic stress on maize (mg/100ml)

	CK	-0.2MPa no split 6h	-0.2MPa no split 12h	-0.5MPa no split 6h	-0.5MPa no split 12h	-0.2MPa split alternate 6h	-0.2MPa split alternate 12h	-0.5MPa split alternate 12h
acidic amino acid	30.23	33.76	18.80	10.42	20.24	28.93	5.84	8.76
neutral amino acid	1.85	1.62	0.61	0.88	1.17	1.71	0.38	0.75
basic amino acid	0.84	0.39	0.43	1.47	2.1	1.37	3.12	2.50

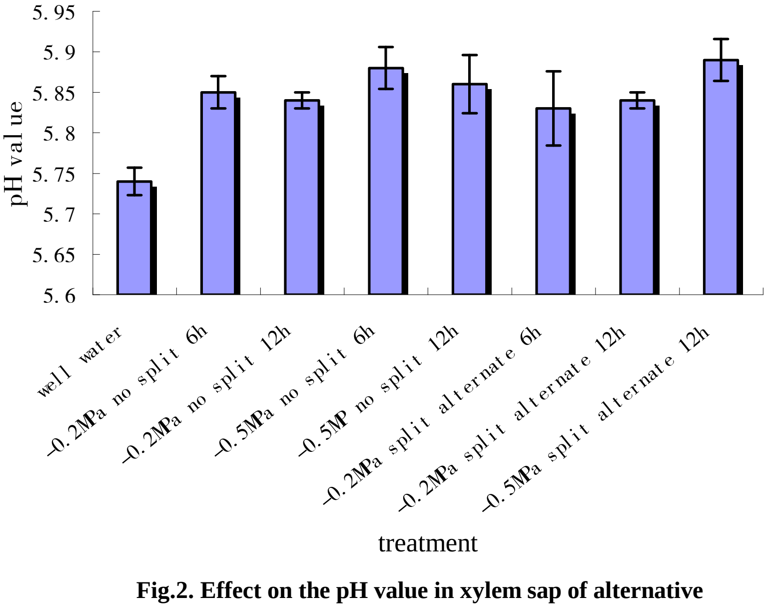

Fig.2. Effect on the pH value in xylem sap of alternative split-root osmotic stress on maize.Vertical bars are standard errors of means

well water. The amount of neutral amino acid nearly kept steady. Amounts of acidic and base amino acids kept step with the pH change in the xylem sap, showing that there was a correlation between them.

Table 4 gives the change of K^+ and NO^-_3 concentration in xylem sap under stress. The change of K^+ concentration was similar to the base amino acid, and NO^-_3 to the acidic amino acid. Under the alternate split-root osmotic stress, the change was more obvious, for –0.2MPa K+ concentration was higher 91% than well water, and for –0.5MPa stress was 75% higher. It also showed that the imbalance of K^+ and NO^-_3 could a reason for increased xylem sap pH.

Table 4. Effect of alternate split-root osmotic stress on concentration of K^+ and NO_3^- in xylem sap on maize

mg/ml

	CK	-0.2MPa no split 6h	-0.2MPa no split 12h	-0.5MPa no split 6h	-0.5MPa no split 12h	-0.2MPa split alternate 6h	-0.2MPa split alternate 12h	-0.5MPa split alternate 12h
K^+	15.55	20.15	23.95	21.05	24.10	25.80	29.65	27.20
NO_3^-	4.904	6.186	1.346	0.320	0.577	1.154	3.686	2.628

4 Discussion

Drought is a major reason of crop production decrease, but proper water deficit would improve the crop growth and development and increase yield. Deng and Shan (1999) thought that compensatory effects, produced by the drought treatment may be an adaptive mechanism formed by crops during evolution.

A theoretical foundation is the root signal theory (Davies and Zhang, 1991), when part roots are subjected to water deficit then signals are produced and transferred to shoots through xylem sap to control the stomatal aperture. As a result, transpiration decreases and water absorbed by the roots is used most efficiently. Thus, water is saved, yet crop yield does not decrease.

Davies and Zhang (1991) believe that ABA is a kind of root signal, but other scientists (Wilkinson and Davies, 1997) have shown that pH or protein may act as a signal associated with ABA. So we researched xylem sap pH.

Our experiment demonstrated that there were compensatory effects on maize growth. If leaf water potential was not sufficient to cause damage, then water use efficiency was also higher, giving benefits to maize growth and development under alternating split-root osmotic stress. With the serious stress, the pH value, K^+ concentration, basic amino acid in xylem increased, but NO^-_3 concentration, acidic amino acid changes were reversed under alternating split-root stress. We concluded that there were a correlation between pH increase and change of K^+, NO^-_3 concentration and amino acid amount.

Acknowledgements

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Section II

Agronomic Technology and Plant Improvement for Water-Saving

Spatio-temporal analysis of water productivity to explore water saving strategies in agriculture

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Abstract
The objective of this paper is to present a spatio-temporal analysis of water productivity to explore water saving strategy in agriculture. The method was to apply crop growth simulation models at the regional scale to study the productivity potentials of selected crops and delineate the effects of some agro-hydrological variables like effective rainfall and nitrogen (N) to the yield to infer their contributions in saving water for agriculture.
The study was conducted in Laoag river basin located in Ilocos Norte, Philippines. Three crops were considered in the analysis: rice, maize and peanut. Simulations were done for both existing and potential agricultural areas. The potential productions of the selected crops from October 1996 – September 1997 were used as bases in determining water productivity for the three cropping seasons being considered in the study. Water-limited productions were simulated for each of the crops, for each of the cropping seasons in the basin. A marginal productivity analysis was done to determine the potential of water for crop production in the basin. The significance of irrigation was emphasized in the analysis when availability of water, and the combination of water and N are limiting, respectively. Results showed that the spatio-temporal analysis of water productivity could be used to explore water saving strategies in agriculture.

Keywords: water productivity, simulation models, water saving, GIS

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1 Introduction

Water scarcity is a matter of concern in the near future (see Seckler *et al.*, 1999). To minimize this problem, a rational use of water among the multiple water users is important. Irrigated agriculture, being the major user of water, is worth studying in this regard.

There is really a need to study the efficiency of water used in irrigated agriculture because (i) the supply of water available for agriculture may not increase further in the future - due to competing demands, economic, social and environmental constraints, and the possibility to reallocate some portions of this supply to other water users; and (ii) the fact that agriculture is still committed to produce more food for the growing population. The question then of how to produce more crops with lesser water is a research dilemma that needs to be addressed in crops and water research.

To address this problem, water saving in agriculture has been proposed (Seckler, 1996) and a measure of which has been associated to water productivity (Molden, 1997).

It has been known also that the spatial and temporal attributes of water productivity could reveal better clues on how to save water for agriculture (Ines *et al.*, 2002).

In this paper, a spatio-temporal analysis of water productivity is presented using a GIS and crop growth simulation models. It also aims to present the impacts of several agro-hydrological variables to water productivity and how they can be inferred to explore water savings in crop production.

2 Methodology

2.1 Description of the study area

The study was conducted in Laoag River basin in Ilocos Norte, Philippines, which is geographically located between latitudes 17°45’ and 18°15’ N and longitudes 120°30’ and 121°00’ E. The basin drains an approximate area of 1,331 km^2 at the South China sea.

The climate in the basin is characterized by two seasons, the wet, during May to October and dry season, during November to April. Average annual rainfall is approximately 2,000 mm of which 97% is concentrated in the wet season.

Approximately 50% of the basin is mountainous while the 50% of the remaining area is considered arable. Rice is the primary crop grown in the basin cultivated at a maximum of three times a year in the irrigated areas and once in the rainfed areas. In some areas of the basin, diversified cropping is also practiced, where cash crops such as maize, peanut, vegetables, tobacco etc. are planted. Irrigation from the surface water is mostly supplemented by groundwater even in the irrigated areas under the National Irrigation Administration (NIA). Majority of the irrigation systems in the basin are of run-off the river type.

2.2 Water productivity

One of the primary objectives in defining water productivity is to set a more tangible term(s) in measuring water use efficiency in crop production. They have been associated since then to water savings in agriculture. Water productivity, PW (kg m^{-3}), can be quantified at different levels such as those proposed by Molden (1997):

$PW_{inflow} = C$ yield/net inflow (1)

$PW_{depleted} = C$ yield/depletion (2)

$PW_{process} = C$ yield/process depletion (3)

where yield is the economic yield of the crop (kg ha^{-1}), net inflow is the difference between the gross inflow and storage in the water balance equation (mm), depletion is the evapotranspiration, ET (mm), process depletion is the transpiration alone, T (mm) and *C* is a constant equal to 0.10 (ha mm m^{-3}).

Droogers and Kite (2001) later introduced in their studies another level called $PW_{irrigated}$ defined as:

$PW_{irrigated} = C$ yield/irrigation (4)

where irrigation is the total amount of irrigation during a cropping season (mm).

The water productivity levels mentioned above can evaluate the present state of the productivity of water but could not to show how to save water in a system. This weakness stems from their inability to delineate the effects of agro-hydrological variables that could impact to crop production because of their generality in form. As such Ines *et al.* (2002) proposed $PW_{irrigation}$ where the marginal analysis of productivity can be done. This index, in general, can be defined as follows:

$PW_{irrigation} = C$? yield/? depletion (5)

? yield = potentialYield – waterlimitedYield (6)

? depletion = potentialET – waterlimitedET (7)

where ? yield is the incremental yield (kg ha^{-1}), ? depletion is the incremental water requirements (mm), potentialYield is the potential production (kg ha^{-1}), waterlimitedYield is the production under limited water condition (kg ha^{-1}), potentialET is the atmospheric demand (mm) and waterlimitedET is the actual evapotranspiration (ET) under limited water condition (mm).

Delineating the production hierarchy in defining water productivity is vital in analyzing water saving strategy in agriculture. If we can delineate the effect of rainfall to yield, effect of N to yield, etc. then better understanding of the opportunities to save water in agriculture can be done. This level of water productivity is discussed in this paper.

2.3 Spatio-temporal analysis

Since this paper aims at exploring the spatio-temporal attributes of water productivity for water saving in agriculture, the analyses were done at the river basin level.

Spatial analysis was done in a GIS; spatial database of soils, crops, weather, etc. were developed for the basin for the qualitative and quantitative analyses in this study. A land suitability analysis for the selected crops, rice, maize and peanut was done to delineate the computational units for the quantitative analysis where the productivity potentials of the selected crops were studied.

Temporal analysis was done using the crop growth simulation models in DSSATv3.0 (Tsuji *et al.*, 1994). Ceres-rice, Ceres-maize and CROPGRO were used to simulate the potential and water limited productions under optimum nitrogen (N) and without N conditions in rice, maize and peanut, respectively in the basin. The cultivars used in the analyses were IR-64 for rice, PIO 3541 form maize and TAMNUT for peanut. The simulation period is 1996-1997; cropping seasons October 1996 - January 1997 (CS 1), January - May 1997 (CS 2) and May - September 1997 (CS 3).

3 Results and discussion

3.1 Potential productions

The weather conditions in the basin during the simulation period were assumed homogenous because of the limited number of available weather stations to interpolate weather variables. This assumption may be acceptable for some weather variables but might caused some significant errors to rainfall.

Table 1. Climate during the study period, 1996-1997

Climatic Variables	CS 1	CS 2	CS 3
Rainfall (mm)	556.8	171.4	903.4
SRAD (MJ m^{-2} d^{-1})	16.8	20.8	17.5
TMAX (^{o}C)	31.9	33.0	32.5
TMIN (^{o}C)	20.8	20.7	24.2

SRAD-solar radiation; TMAX, TMIN-maximum and minimum temperature

Year 1996 was a wet year with a total rainfall of 2844 mm while 1997 was relatively dry with a total rainfall of 1170 mm; CS 1 can be considered as relatively wet because of the rainfall of October and November 1996, CS 2 falls to the dry period of the year while CS 3 falls to the wet season. CS 1, 2 and 3 had a rainfall of 557, 171 and 903 mm, respectively (Table 1). The rainfall in CS 1 occurred only during the first 45 days while in CS 2 it occurred only during the month of May and was more uniformly distributed during CS 3.

Potential production is the level of yield that a crop can achieve under optimal environmental conditions, basically, only temperature, solar radiation and crop properties are affecting the yield levels. Figure 1 shows potential productions of the selected crops for three cropping seasons. It is clear that potential production is not changing in space because of the assumption that weather is homogenous in the basin but it is changing in time and peaks during CS 2 due to higher solar radiation. These productivity values were used as bases in estimating water productivity at different CS in the basin.

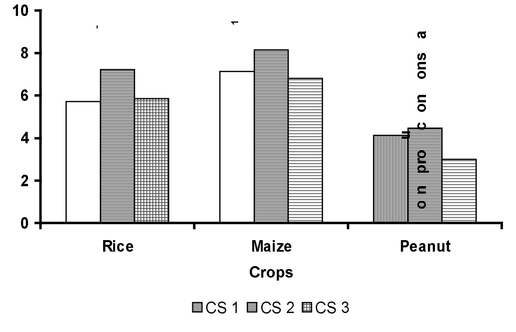


Figure 1. Potential productions of the selected crops in the basin

3.2 Water limited productions

Water limited production is the level of yield that a crop can achieve when water is limited, in this paper this is attributed to rainfed production. A general term, however, of the level of yield with limited water, nutrients etc. is called limited production. In this paper, two water limited conditions are discussed: (i) water limited condition with optimum N and (ii) water limited condition without N applications. Tables 2 and 3 show the results of simulations under these conditions.

Table 2. Water-limited productivity with ptimum N

	CS 1			CS 2			CS 3		
Stat.	Rice	Maize	Pean.	Rice	Maize	Pean.	Rice	Maize	Pean.
Ave	1.06	6.38	1.37	1.19	1.15	0.02	5.50	6.79	2.93
SD	0.35	0.62	0.51	0.33	1.28	0.06	0.25	0.07	0.04
Max	1.92	7.14	2.95	1.93	5.25	0.28	5.81	6.82	2.99
Min	0.57	5.14	0.70	0.54	0.04	0.00	4.87	6.59	2.85

Note: in tons ha^{-1}

Table 3. Water limited productivity without N

	CS 1			CS 2			CS 3		
Stat.	Rice	Maize	Pean.	Rice	Maize	Pean.	Rice	Maize	Pean.
Ave	0.63	0.94	0.45	0.09	0.36	0.02	1.56	1.29	0.66
SD	0.34	0.64	0.31	0.17	0.11	0.04	0.97	0.64	0.24
Max	1.67	2.74	1.34	0.51	0.61	0.15	3.84	2.91	1.19
Min	0.12	0.20	0.14	0.00	0.23	0.00	0.08	0.36	0.18

Note: in tons ha^{-1}

During CS 1, the water-limited yield of rice with optimum nitrogen requirements varied from 0.6 to 1.9 tons ha^{-1}. Although rainfall in this season is 557 mm, the levels of yield still imply that the crop suffered significant water stress, which obviously occurred during the critical periods of crop growth. The timing of rainfall is the major factor that influenced the level of yield. The same is true with peanut; water stress was significant, the yield varied from 0.7 to 2.9 tons ha^{-1}. However, maize is an exception, the average yield in the basin was 6.4 tons ha^{-1} with minimum and maximum yields of 5.1 and 7.1 tons ha^{-1}, respectively. This performance of maize is attributed to its rooting depth.

During the dry period of the year (CS 2), where rainfall is 171 mm for four months, the selected crops did not perform well. Average yields of rice, maize and peanut in the basin were 1.2, 1.1 and 0.02 tons ha^{-1}, respectively. The effect of higher solar radiation is observed in the yield levels. Rainfall only occurred during the month of May and for the first three months of growth, the only source of water for the plants was the soil water available. The soil water was at its upper limits when sowing commenced. For maize, the effect of rooting depth is still prevalent in some land units. For peanut however, there was almost no yield achieved in most of the suitable land units in the basin.

With a rainfall of 903 mm for the whole of CS 3, fairly uniformly distributed, resulted to the excellent crop yield. Most of the suitable land units achieved potential productions of maize and peanut. The maximum yield achieved by rice was 5.8 tons ha^{-1} while maize and peanut have 6.8 and 2.9 tons ha^{-1} achieving their full potentials. The yields did not vary greatly from each of the suitable land units.

The consequence of nitrogen deficiency in crop growth when water is limited is evident (Table 3). There were certain levels of yield realized during CS 1 and 3, however, crop growth during CS 2 is almost not possible. Unusual results occurred to some land units during CS 2 where the yield of maize when water and N are limited increased compared to the case with optimum N. This may be the limitation of the model under extreme environmental stress.

3.3 Water productivity

The productivity of water was determined by defining two differential variables i.e. incremental yield (? yield) and incremental water requirements. The greater the incremental yield, the lower the actual production.

Table 4. Ave. incremental yield

	CS 1			CS 2			CS 3		
Due:	Rice	Maize	Pean.	Rice	Maize	Pean.	Rice	Maize	Pean.
Irrig.	4.67	0.75	2.76	6.03	7.00	4.45	0.36	0.03	0.06
N	5.09	6.19	3.67	7.14	7.79	4.45	4.30	5.53	2.33

Note: in tons ha^{-1}

Table 5. Incremental water requirements

	CS 1			CS 2			CS 3		
Stat.	Rice	Maize	Pean.	Rice	Maize	Pean.	Rice	Maize	Pean.
Ave	400.4	123.6	228.3	674.4	229.4	445.9	220.6	70.1	103.7
SD	33.9	22.8	22.9	32.9	35.7	44.5	25.3	10.8	11.9
Max	453.0	166.7	266.4	747.2	331.3	517.1	280.4	83.6	130.2
Min	318.7	78.2	167.3	601.4	196.6	353.4	182.8	41.6	77.6

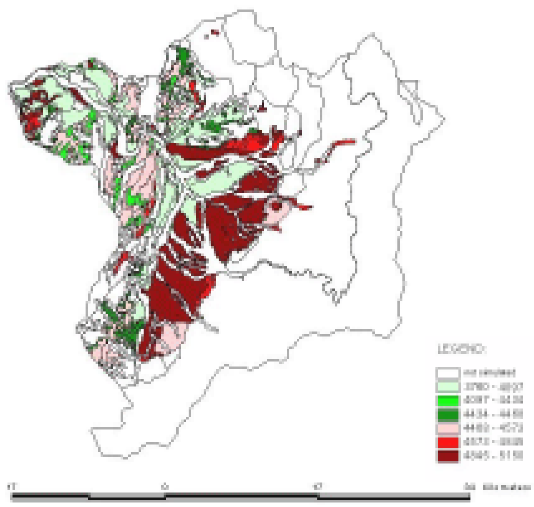
Note: mm

Table 4 shows that when water is limited, the yield gap is high and much more when nutrient is deficient in the soil. When rainfall is adequate and fell uniformly distributed during the growing season, the yield gap can be minimal. Water is needed in nutrient dynamics hence the process is hampered when water is limited. Figures 2a - c show the spatial distributions for rice in the basin.

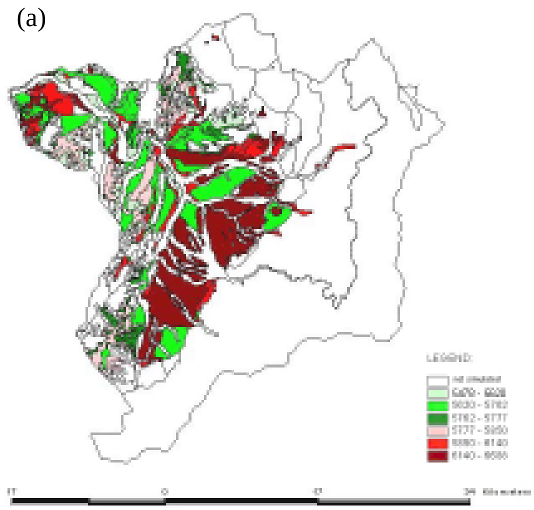
Generally, it was observed that with optimum nitrogen supply, the crops are more active to extract water from the soil throughout the growth process. During development and midseason stage, plants are so demanding with water that they attempt to satisfy this requirement. Given the condition where water is applied or present in the soil, water use is tremendous. On the other hand, plants with deficiency of nitrogen are less active and more sensitive to water stress. Crops ended with premature growth or even death if water is not enough to support their physiological needs. Usually, this happened during CS 2 (see Table 3). Maize is an exception because of its rooting depth; it can extract soil water redistributed in the soil profile.

Table 5 shows the incremental water requirements of the selected crops in different cropping seasons. The table only presents the differential requirements with optimum N as it emphasizes the significance of irrigation more. The greater the difference means the lesser the actual crop evapotranspiration.

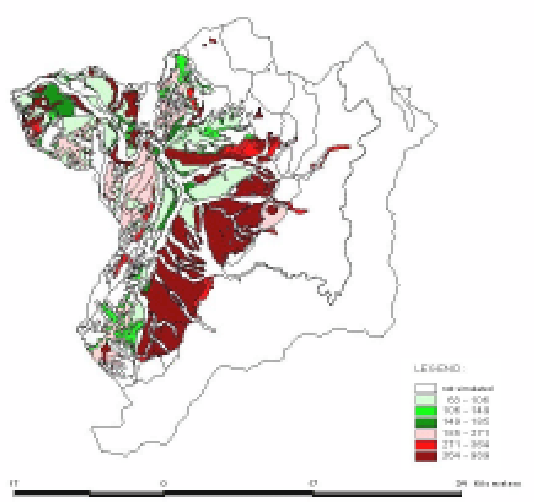
Timing of rainfall is significant in all cropping seasons. In CS 1, where the total rainfall was 557 mm, still water stress exists, especially to the shallow rooted crops. Most of the rainfall in this season fell during the first 45 days after sowing. The plants were stressed during midseason to maturity stage of the growth process. There were



(a)



(b)



(c)

Figure 2. Incremental yield (kg ha^{-1}) of rice due to irrigation during (a) CS 1, (b) CS 2 and (c) CS 3

higher requirements during the dry period and lesser in the wet season. Interestingly, land units that achieved the production ceiling when water was adequate have still incremental water requirements. This is attributed to the non-beneficial loss of water from evapotranspiration, i.e. the soil evaporation (E_{soil}).

Table 6. Water productivity ($PW_{irrigation}$) in the basin

	CS 1			CS 2			CS 3		
Stat.	Rice	Maize	Pean.	Rice	Maize	Pean.	Rice	Maize	Pean.
Ave	1.17	0.54	1.20	0.89	3.12	1.01	0.15	0.04	0.05
SD	0.04	0.39	0.14	0.01	0.74	0.10	0.08	0.09	0.04
Max	1.29	1.19	1.39	0.92	3.94	1.26	0.35	0.30	0.11
Min	1.11	0.00	0.70	0.88	1.29	0.86	0.02	0.00	0.00

Note: in kg m^{-3}

Table 6 shows the water productivity in the basin. On the average, during CS 1, this index was on the order of 1.2 kg m^{-3} for rice and peanut while maize had 0.5 kg m^{-3}; during CS 3, the marginal benefit was minimal. CS 2 has an interesting implication; previous analysis shows that crop production during this season is the highest because of higher solar radiation. But the reward is expensive as it entails larger water quantity because of higher water demand. For rice and peanut, an average of 675 and 446 mm water only yielded to 0.9 and 1.0 kg m^{-3}, respectively. For maize, with 229 mm water it had a return of 3.1 kg m^{-3}. This is interesting to scrutinize because this gives a glimpse on how water use should be planned and managed in crop production. This performance of maize is attributed to its properties as a C4 crop, cultivar characteristics and rooting depths. A caution though should be considered in the analysis because a zero value does not imply that there is no need to apply water.

This water productivity index indicates the significance of irrigation during a cropping season. If it is less likely that irrigation is desired because rainfall is adequate for the crops, the available water could be saved and allocated to other purpose. Unfortunately in this basin, there is no storage dam available. The index also implies the effective use of the water available in the soil profile.

3.4 Benefit of irrigation

The law of the minimum is the driving force in DSSAT models when crop growth is source limited. When water availability determines crop growth, the benefit of irrigation dominates the total benefit; the same is true when N availability limits the growth. Using Table 4, the estimates of irrigation and N benefits were derived. N benefit is estimated by getting the difference between the two incremental productivity terms. Irrigation is beneficial during CS 1 and 2 while it is marginally beneficial during CS 3. Maize and peanut during CS 1 and 2 gives a good example on crops responses to their environment. For maize, only 11% of the benefit is contributed by irrigation while 76% by nitrogen. There was lesser importance of irrigation because of its rooting depth. For peanut, most of the benefit comes from irrigation (99.5%) because the crop can synthesize its own N requirement from atmospheric nitrogen through their root nodules (Table 7). CS 3 has clearer implication, the marginal benefit from irrigation is low, which means that the expected level of yield is high with the available rainfall as long as the N requirements of the crops are met.

Table 7. Average benefit of irrigation and N

Cropping season	Benefit of Irrigation			Benefit of N application		
	Rice	Maize	Peanut	Rice	Maize	Peanut
CS 1	81.6	10.5	66.9	7.4	76.2	22.1
CS 2	83.5	85.9	99.5	15.3	9.7	0.0
CS 3	6.2	0.4	1.9	67.2	80.7	76.0

Note: in %

4. Conclusions

This paper presented an example of a spatio-temporal analysis of water productivity using a combination of GIS and crop growth simulation models. The combination of the two enabled a more effective analysis because the spatial and temporal dimensions are studied at once, hence, broader understanding about the implications of the indices under study.

The concept of production hierarchy can be used to delineate the effects of water and N in a growing period, which could be repeated along the cropping seasons to explore water saving strategy in agriculture. The spatial differences can be accounted for in a GIS, which enables one to see the *where* and *what* of the water productivity in the study area.

The water productivity level developed here is aimed to evaluate the significance of irrigation in a cropping season. This is a strong index because the value of irrigation is evaluated prior to the cropping season.

In this study, the water productivity (irrigation) was found to be low during the wet season, further analysis showed that the expected level of yield is high as long as the N requirements of the crops are fully met. Rainfall could be adequate to support the water requirements of the crops for the growing season.

Deficit irrigation could be an alternative to save water in water scarce areas. Water stress during non-critical periods of crop growth does not impact significantly to the yield.

To save water in agriculture, take advantage of the rainfall, adjusting the cropping calendar could be of advantage. In this case, careful planning and scheduling of the water releases from the storage facility could save significant volume of water for other purpose. Water harvesting at the on-farm level is another strategy of saving water for other use. Also, the antecedent soil moisture is a potential resource in agriculture. This should be taken into consideration. And last but not the least, the selection of crops or varieties of crops. Drought resistant crops could be planted during the dryer periods. Deep-rooted crops could also be selected to take advantage of the antecedent soil moisture.

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Predicting photosynthetic water use efficiency of crops under climate change

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Abstract

Water use efficiency (WUE) is a critical factor in the determination of adaptation and productivity of crops in water-limited areas, either under the present climate or future global change. Data on WUE are often highly variable and a unifying and quantitative approach is needed to analyze and predict crop WUE for different environments. Hsiao (1993) proposed a set of paradigm equations based on leaf gas exchange for this purpose, calculating WUE relative to the WUE for an arbitrarily chosen reference situation. The key parameters in the equations are water vapor (W_a) and CO_2 concentration (C_a) in the air surrounding the foliage, intercellular CO_2 concentration (C_i) relative to air CO_2 concentration (C_a), and intercellular water vapor concentration (W_i) as calculated from foliage temperature. This study tests the validity and applicability of these equations to cotton, sweet corn and sunflower populations growing in the open field, with WUE measured as the ratio of canopy CO_2 assimilation to evapotranspiration (ET). The Bowen ratio/energy balance /CO_2 gradient technique was used to measure crop ET and downward CO_2 flux from the atmosphere into the canopy. By confining the study to periods when canopy fully covers the soil, ET is assumed to be all due to transpiration. Canopy CO_2 assimilation was calculated as the sum of the downward CO_2 flux plus the measured CO_2 efflux from the soil. Canopy temperature and vapor pressure and CO_2 concentration of the air surrounding the canopy were monitored continuously. The rates of CO_2 assimilation and transpiration were used to calculate measured photosynthetic WUE. After choosing the measured photosynthetic WUE at a particular time as the reference, photosynthetic WUE for other times were predicted using the equations and the measured values of C_a, W_a, canopy temperature, and the assumed ratio of C_i to C_a based on leaf gas exchange data. Provided stomatal response to humidity as it affected C_i/C_a ratio was accounted for, the equations predicted accurately the moment by moment changes in canopy WUE of cotton over daily cycles, and it also predicted the variation in WUE from day to day over a period of over 45 days. The prediction for sunflower over diurnal cycles was also quite accurate. The prediction for sweet corn was good for most parts of the day except early in the morning. Possible causes of the differences between predicted and measured WUE are discussed. Overall, the results also demonstrate clearly the importance of stomatal response to humidity in determining photosynthetic WUE.

Keywords: transpiration ratio; photosynthesis; stomata; canopy; cotton; sweet corn; sunflower.

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1 Introduction

In water-limited environments, plant productivity is determined jointly by the amount of water available and the efficiency by which the water is used by the plant. With the continuous rise in atmospheric CO_2 and global climate change, to predict the associated changes in productivity and distribution of plant species, it is essential to know how water use efficiency (WUE) of different species would change with the environment. At the physiological level, WUE may be defined as the ratio of photosynthesis to transpiration, also referred to in the literature as transpiration efficiency. Photosynthetic WUE is difficult to monitor over long periods, however. More conveniently and for agronomic assessment, WUE has been expressed as the ratio of biomass produced to water consumed, referred to as biomass WUE. Biomass WUE is known to be relatively constant for a given crop under the prevailing air CO_2 concentration and a given climate (Hanks, 1983). For different climates, biomass WUE is conservative only if normalized for the given evaporative demand (de Wit, 1958). Because increases in air CO_2 concentration generally enhance photosynthesis and reduce stomatal opening, WUE, either in terms of photosynthesis or biomass accumulation, is expected to increase with rising levels of CO_2 in the atmosphere, as is almost universally observed. The increases in WUE for a given increase in CO_2, however, are highly variable among different studies (Eamus, 1991; Morison, 1993; Hsiao and Jackson, 1999). In view of the varied responses, a systematic and conceptual approach is needed to analyze the experimental results and to quantify and predict the impact of environmental changes.

Such an approach, general and not restricted to a given species and accounting for all the important variables affecting WUE, was proposed by Hsiao (1993) as a set of paradigm equations. The equations are simple, based on the fundamentals underlying leaf gas exchange, and express WUE under new sets of conditions relative to WUE under a set of reference conditions. Of the environmental factors, temperature, humidity, and air CO_2 concentration are accounted for explicitly, and radiation and wind are accounted for implicitly. In this study, we tested the validity of the equations on cotton, sweet corn and sunflower growing in large fields as environmental factors varied naturally through the diurnal and seasonal course. This paper reports the first set of the apparently promising results.

2. Conceptual Framework

The basic unit of photosynthesis and transpiration is the single leaf and the two processes are well described by gas exchange equations. In the framework proposed by Hsiao (1993), the complexity of metabolic processes underlying photosynthesis, lumped together as mesophyll resistance (r'_m) or conductance (g'_m) in the gas exchange equation, was by-passed by considering the rate of CO_2 transport from the bulk air only to the leaf intercellular space, which equals the rate of CO_2 assimilation (A) under steady state conditions. Transpiration shares that segment of transport pathway with CO_2, but with water vapor going the opposite direction, from the intercellular space to the bulk air. Consequently two equations of identical form may be written, one for photosynthesis (A) and one for transpiration (T):

$$A ? \frac{1}{r'_a ? r'_e}(C_a ? C_i) ? \frac{1}{r'_a ? r'_e} ? C \tag{1a}$$

$$T ? \frac{1}{r_a ? r_e}(W_i ? W_a) ? \frac{1}{r_a ? r_e} ? W \tag{1b}$$

where the resistance to gas transport of air boundary layer and leaf epidermis are denoted respectively by r_a and r_e, with r_e being the resistance made up by two parallel resistances, that of the stomata and of the cuticle. The resistances for CO_2 are indicated by a prime, and for water vapor, without the prime. Due to its lighter molecular mass, water vapor diffuses faster than CO_2 and encounters a lower resistance in the diffusion path, with r = 0.625 r', for both boundary layer and epidermal parts of the pathway (Farquhar and Sharkey, 1982). The driving force for A and T is, respectively, the difference in CO_2 concentration (? C) between the bulk air (C_a) and the intercellular space (C_i), and the difference in the water vapor concentration (? W) between the intercellular space (W_i) and the bulk air (W_a). The impact of metabolism on A is not dealt with directly but is reflected in the value of A, C_i, and C_a relative to C_i. Because leaf intercellular space is essentially saturated with water vapor and saturation water vapor pressure is a function of temperature, leaf temperature must be measured or calculated in order to calculate W_i and hence ? W. Since only physical processes are involved in the gaseous phase, all terms in Eq. 1a and 1b are well defined and can be experimentally determined for single leaves.

Hsiao (1993) proposed that when conditions change, WUE under the new set of conditions (WUE_n) be evaluated in relation to the WUE under the original or reference conditions (WUE_o). Expression photosynthetic WUE as the ratio of A (Eq. 1a) to T (Eq. 1b), the ratio of the new WUE to the reference WUE then becomes

$$\frac{WUE_n}{WUE_o} ? \frac{A_n}{T_n} \Big/ \frac{A_o}{T_o} ? \frac{?C_n}{?C_o}\frac{?W_o}{?W_n} \tag{2}$$

Eq. 2 is fundamental and holds regardless whether the plant is C_3 or C_4, with or without a change in leaf photosynthetic capacity, whether the leaf is under high or present level of CO_2, under low or high temperature, and well watered or is affected by stresses.

As environmental conditions vary, C_i tends to remain constant at a given C_a (Wong et al., 1979). As C_a changes, C_i tends to change in proportion. That is, the ratio of C_i to C_a, designated as ?, is nearly constant. This conservative behavior of C_i and ? appears to hold, within limits, for variations in photosynthetic active radiation (PAR), temperature, and leaf age (Hsiao and Jackson, 1999). The exception is variations in humidity. In plants with stomata which respond to humidity, (more specifically, to ?W), C_i tends to decrease linearly with increases in ?W (Morison, 1987).

In view of the conservative nature of ?, it is advantageous to express the relative changes in WUE in terms of ?. Thus, to evaluate changes in WUE due to changes in C_a, Eq. 3 is rewritten in terms of C_a by recognizing that C_i = ?C_a,

$$\frac{WUE_n}{WUE_o} ? \frac{(1 ? ?_n)}{(1 ? ?_o)}\frac{C_{a,n}}{C_{a,o}}\frac{?W_o}{?W_n} \tag{3}$$

Eq. 3 shows that as C_a rises or falls, relative WUE would change in proportion to the C_a ratio modified by the (1-?) ratio and ?W ratio. In cases where ? does not change with the changes in conditions, $?_n$? $?_o$, and the change in relative WUE would be the product of the C_a ratio by ?W ratio:

$$\frac{WUE_n}{WUE_o} ? \frac{C_{a,n}}{C_{a,o}} \frac{?W_o}{?W_n} \qquad (4)$$

Theoretically, it is the ratio of C_i to CO_2 concentration at the leaf epidermal surface (C_e) that behaves conservatively (Ball and Berry, 1982), and the ratio C_i/C_a is an approximation of the ratio C_i/C_e. This would be true if the air is highly turbulent and r_e>>r_a. To arrive at Eq. 4 from Eq. 3, however, it is not necessary that ? remains constant as long as $?_n$? $?_o$.

3. Materials and Methods

3.1 Plants Grown in Environment Chambers

To determine the basic gas exchange parameters of single leaves, cotton (cv. Acala GC 510), sweet corn (cv. Silverrado F1, Harris Moran Seed Co.). amd sunflower (cv. Hybrid 6482, Pioneer Seed Co.) were grown in cylindrical tubes 7.4 x 10^{-3} m^3 in volume) in a well-fertilized Yolo clay loam soil/peat moss (2:1 by volume) mixture in controlled environment chambers under nominally 360 and 720 ppm of CO_2 and 14-h photoperiod (750 to 820 ?mol m^{-2} s^{-1} of PAR) for about 1.4 month. Pots were watered to a predetermined weight daily. Day/night temperatures and relative humidities were, respectively, 29/20^{o}C and 45/80%.

One or two pots were taken from the growth chamber on measurement days to determine photosynthetic response of recently matured leaves to C_a, PAR and ?W in a steady-state open gas exchange system detailed earlier (Bolaños and Hsiao, 1991). Humidity response curves were obtained by varying W_a of the incoming air and adjusting air flow rate into the chamber. C_i and related gas exchange parameters were calculated according to von Caemmerer and Farquhar (1981).

3.2 Canopy photosynthesis, evapotranspiration, and water use efficiency

In the field cotton (cv. Sure-grow 404) was grown in 1997 and sweet corn (cv. Silverrado F1, Harris Moran Seed Co.) and sunflower (cv. Hybrid 6482, Pioneer Seed Co.) in 1998 in a soil of high fertility (Yolo silty clay loam) and well fertilized with nitrogen (200 kg ha^{-1}), in large fields (3 to 6 ha) to provide a fetch of more than 130 m in the prevailing wind directions. The downward flux of CO_2 to the canopy and the upward flux of water vapor (evapotranspiration, ET) were measured simultaneously with a Bowen ratio/energy balance/CO_2 gradient (BREB+) system (Held et al., 1990) capable of resolving the fluxes for 5-min intervals (Steduto and Hsiao, 1998a). The BREB+ with its data logger measured, once per second, air temperature, W_a, and C_a at two heights above the canopy, and net radiation and soil heat flux, and averaged the measurements over each 5 min interval and stored the averages. Also measured and logged were PAR (LI-191SB, LI-COR) and wind velocity (cup anemometer) about 2 m above the canopy. The drift in the null point of the IRGA (LI-6252 or 6262, LI-COR, Lincoln, NE, USA) used for measuring CO_2 in the BREB+ method was corrected for by automatically stopping the measurements every half of an hour for 5 min to determine the IRGA zero. Thus, every sixth data point involving CO_2 presented in the figures was interpolated from the two adjacent points. Efflux of CO_2 from the soil was measured periodically at four locations of the field by placing a large stirred chamber over the soil for less than 1 min and measuring the rate of increase in chamber CO_2, as described by Steduto and Hsiao (1998a). Net canopy assimilation was calculated as the sum of CO_2 fluxes into the canopy from the atmosphere and from the soil. Photosynthetic WUE was calculated as the ratio of canopy assimilation to ET. The data presented were taken after canopy had closed, so the soil was mostly shaded and not receiving much energy from radiation. Hence, most of the ET was attributable to transpiration, and soil evaporation was slight and hence assumed to be negligible.

3.3 Determination of CO2 and water vapor profiles, C_a, W_a, and W_i

To predict WUE under different environmental conditions using Eq. 3 or 4, CO_2 and water vapor pressure data of the air surrounding the canopy are required. CO_2 and water vapor profiles within and above the canopy were measured simultaneously with a multiport air sampling apparatus (Xu, et al., 1999) that provided 5-min mean C_a and W_a of five 8-s measurements spaced 1 min apart for each height. Six heights were measured, in the cotton field of 1997 they were 0.6, 1.3, 1.65, 2.55, 3.4 and 4.4 m, and in the sweet corn field of 1998 they were 0.3, 0.9, 1.65, 2.4, 3.3, and 4.5 m. Canopy C_a and W_a used in calculation were taken as the average of three heights where most of the active leaves were distributed. These were 0.6, 1.3 and 1.65 m for cotton with the canopy height of 1.4 m, and 0.9, 1.65 and 2.4 m for sweet corn with a canopy height of 2.4 m. W_i was calculated from the measured canopy surface temperature (T_c) by assuming water vapor saturation of the intercellular space. T_c was monitored continuously using an infrared thermometer with a viewing angle of 15? (Model 4000BL, Everest Interscience, Fullerton, CA), positioned toward the north at an angle of approximately 30? from the horizontal, and viewing the upper part of the canopy.

3.4 Calculating and predicting photosynthetic WUE using Eq. 3 and 4

When ? was not known but expected or assumed to be constant and WUE was known for a reference situation (WUE_o), WUE for a new situation (WUE_n) was calculated with Eq. 4 from WUE_o using C_a, W_a, and W_i of the reference and the new situation. The reference situation chosen for each case are given in the legend of the figures. When ? was not constant but changed with ?W, an empirical linear relationship between ? and ?W was obtained from the humidity-response curves measured with the steady-state gas exchange system, and Eq. 3 was used in the calculations. Although Eq. 2, 3, and 4 were derived for single leaf gas exchange, they were used to calculate WUE for canopies of the crops consisted of a population of plants in the open field without modification.

4 Results

4.1 Constancy and variability of Ci/Ca ratio

Knowing under what conditions ? remains constant and when and how it varies is pivotal to the application of the model. Under conditions favoring good rates of photosynthesis, C_i increased linearly with increases in C_a,in cotton, sweet corn and sunflower regardless whether the plants were grown under ambient (360 ?mol mol^{-1}) or 2 x ambient (720 ?mol mol^{-1}) C_a in the growth chamber. Long-term acclimation to elevated C_a did not alter significantly the slope of C_i vs. C_a (?). Values of ?, obtained by linear regression of the data (not shown), were found to be 0.61 and 0.33 for cotton and maize, respectively, similar to values published by Wong et al. (1979) and Morison (1987).

The response of C_i to PAR was also assessed for cotton and sweet corn (data not shown). C_i for both remained essentially constant, at about 230 ?mol mol^{-1} for cotton, and 110 **?**mol mol^{-1} for maize, over a wide PAR range (0.5 to 2.0 mmol m^{-2} s^{-1}). C_i rose as PAR fell below approximately 0.5 mmol m^{-2} s^{-1} for sweet corn, and 0.3 mmol $m^{-2}s^{-1}$ for cotton. Because the PAR response curves were determined with C_a held constant, it is deduced that ? remained constant over the PAR range where C_i remained constant.

Fig. 1 shows the relationship between ? and ?W for cotton and sweet corn. ? decreased linearly with increasing ?W for cotton (Fig. 1a), but showed no obvious trend for sweet corn (Fig. 1b). The results indicate that maize stomata did not close significantly in response to increases in ?W. Others (Held, 1991; Dai et al., 1992) have reported a similar lack of response for maize.

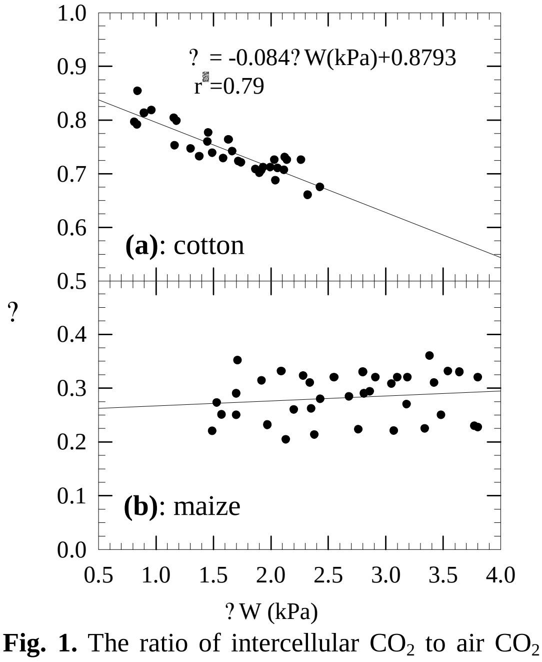

Fig. 1. The ratio of intercellular CO_2 to air CO_2 concentration (C_i/C_a = ?) as related to the water vapor pressure difference between the intercellular air space and bulk air (?W) for leaves of cotton (a) and maize (b). Plants were grown in nominally 360 or 720 ppm of CO_2, day/night temperature of 27/20°C, and 770 ?mol m^{-2} s^{-1} PAR (14 h light period). Data represent six leaves in (a) and seven leaves in (b).

4.2 Prediction of WUE for single leaves

WUE of single leaves of cotton and sweet corn were measured under a range of C_a and ?W in a gas exchange chamber, taking the ratio of CO_2 assimilation to transpiration (A/T) as measured WUE. The results are compared in Fig. 2 with the WUE predicted by Eq. 3 for cotton and Eq. 4 for maize under the various levels of C_a and ?W. WUE_o used for the calculation was determined under C_a of 360 ?mol mol^{-1} and ?W of 1.8 kPa. The comparison shows a near 1:1 relation between the predicted and the measured WUE over the wide range of C_a and ?W. The slopes of the predicted values vs. measured values were not significantly different from 1.0 for both cotton and sweet corn .

4.3 Prediction of WUE of crops in the open field over diurnal cycles

Strictly speaking, the paradigm equations are for single leaves and upscaling may be necessary for application to the canopy made up of numerous leaves from a population of plants. Nonetheless, we tested the paradigm equations for predicting canopy photosynthetic WUE of the three crops in the open field. C_a and W_a surrounding the canopy were measured as given under Materials and Methods. Canopy temperature continuously sensed with an infrared thermometer, was used to calculate W_i and hence ? W.

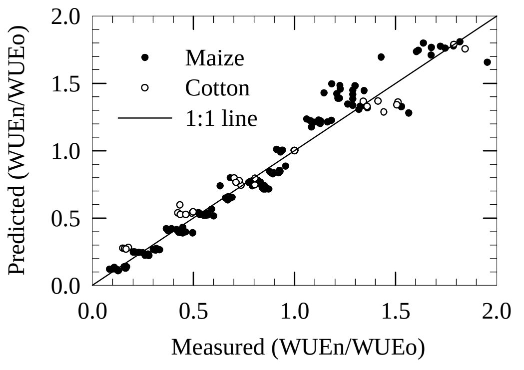

Fig. 2. Comparison of measured changes in relative photosynthetic WUE of cotton and sweat corn leaves as affected by changes in C_a and ? W with that predicted using Eq. 3 for cotton and Eq. 4 for sweet corn. WUE was calculated as the ratio of photosynthesis rate to transpiration rate. Reference WUE (WUE_o) is that measured under C_a of 360 ? mol mol^{-1} and ? W of 1.8 kPa.?

Measured WUE of cotton was compared with predicted WUE over two diurnal cycles in Fig. 3 and 4. The trends in mean C_a and W_a surrounding the canopy are also given, as well as PAR and temperature of the air above the canopy measured by the upper Bowen unit.

On 3 September 1997, with the sky clear all day, measured WUE (Fig. 3b and c) declined from early morning to midday, then remained nearly constant until mid-afternoon, before increasing slightly toward sunset. WUE predicted by Eq. 4, given in the Fig. 3b, is much higher than the measured value in the early morning, very similar around midday, and slightly lower than the measured value in the afternoon. Eq. 4, however, is derived by assuming ? to be constant. Since stomata of cotton respond to humidity and ? changes with ? W (Fig. 1a), the change in ? needs to be taken into account. The value of ? was calculated from ? W as derived from canopy temperature and W_a using the linear regression equation of ? vs. ? W (Fig. 1a). Based on these changing values of ?, WUE was then predicted using Eq. 3. The results (Fig. 3c) show that the predicted WUE now matched the measured WUE very closely. Not only was the difference between the measured and predicted values for the morning period in Fig. 3b essentially eliminated, the difference in the afternoon was also reduced to a minimum. Remarkable is the fact that the function of ? vs. ? W used in the calculation was not based

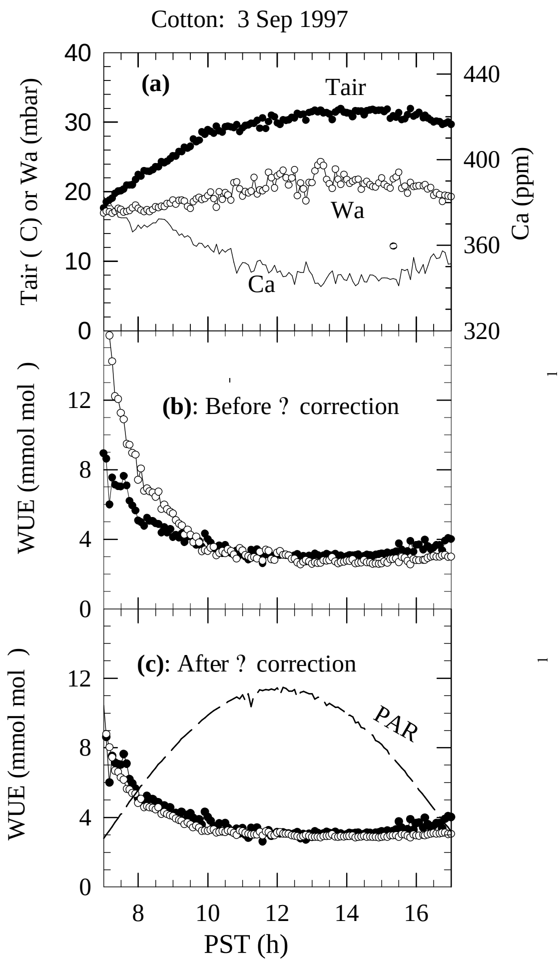

Fig. 3. Comparison of measured canopy photosynthetic WUE with that predicted using Eq. 4 (b) or Eq. 3 (c), and the air temperature (T_{air}) C_a, and W_a (a) and PAR (c) over a diurnal cycle for cotton (LAI = 5.8) in the open field on a clear day (3 September 1997). Time given is Pacific Standard Time (PST). Reference for this and the next three figures (Fig. 4, 5 and 6) was chosen as the mean value (for WUE_o, C_{ao}, ? W_o and ? ?) for the 11:30 to 12:30 midday period.

on measurements made on field-grown plants, but measurements made on plants grown in growth chambers.

The data in Fig. 3 were collected on a clear day (3 September 1997). On the day before (2 September 1997) radiation was highly variable, with periods of sunshine alternating with periods of clouds. The clouds cut radiation and PAR by a half or more (Fig. 4c) and caused the canopy (not shown) and air to cool (Fig. 4a). Measured WUE (Fig. 4b and c) was again higher in the morning and lower in the afternoon. As clouds obscured the sun, measured WUE usually increased noticeably.

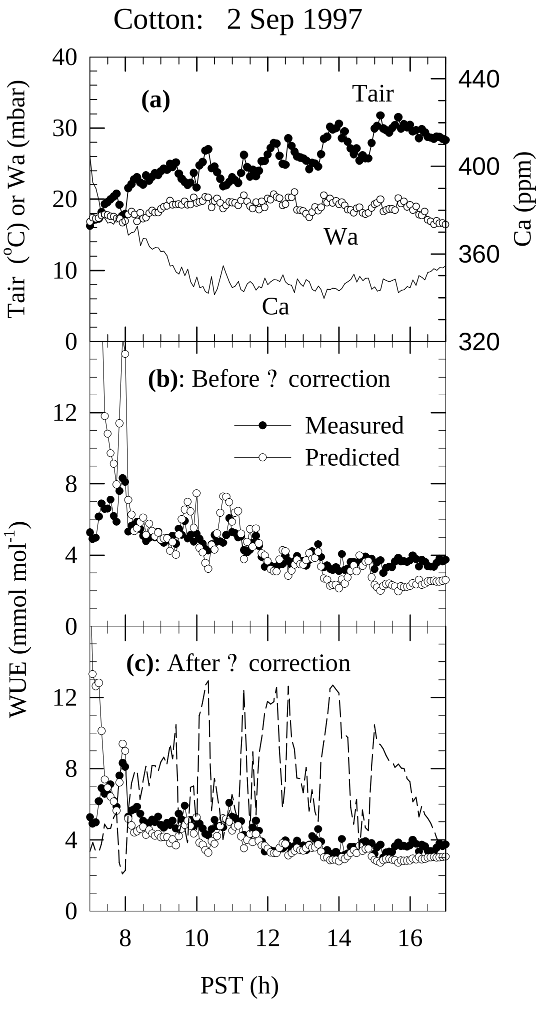

Fig. 4. Comparison of measured canopy photosynthetic WUE with that predicted using Eq. 4 (b) or Eq. 3 (c), and the air temperature (T_{air}) C_a, and W_a (a) and PAR (c) over a diurnal cycle for cotton (LAI = 5.8) in the open field on a day with variable clouds (2 September 1997). Reference chosen was the mean value for the 11:30 to 12:30 midday period.

Both CO_2 assimilation and transpiration were reduced markedly by the clouds, but the proportion of reduction was apparently larger for transpiration, causing WUE to rise.
WUE predicted by Eq. 4 (Fig. 4b) was again higher in the morning and lower in the afternoon than measured WUE. The prediction was also improved substantially by treating ? as a variable dependent on ?W and using Eq. 3 (Fig. 4c). Notable is the fact that the increase in measured WUE during the cloudy periods was well predicted most of the time.
Between 7:00 and 7:30 the measured WUE was much lower than the value predicted by Eq. 3. This was likely the result of measurement errors. Accuracy of the BREB+ technique is substantially less for the time shortly after sunrise and before sunset, particularly for the measurement of CO_2 assimilation in comparison to the measurement of ET (Held et al., 1990). On both 2 and 3 of September, due to stable atmospheric conditions at night, C_a started out high in the morning (approximately 400 ?mol mol^{-1} for 2 September) and depleted to 345 ?mol mol^{-1} at midday (low wind both dates). The predicted changes in WUE with time would have been poor had the changes in C_a not been taken into account.

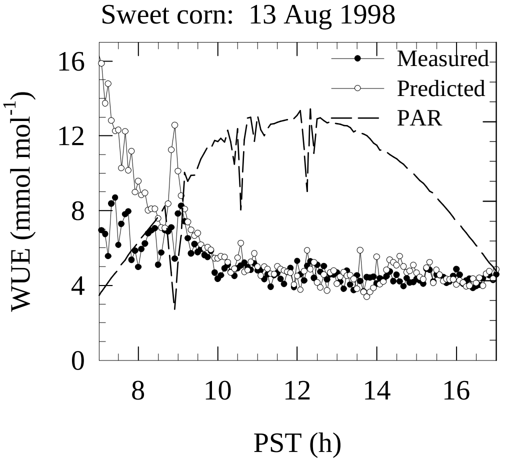

Fig. 5. Comparison of measured canopy photosynthetic WUE with that predicted using Eq. 4, over a diurnal cycle for sweet corn (LAI = 4.7) in the open field on a day with occasional clouds (13 August 1998). Reference chosen was the mean value for the 11:30 to 12:30 midday period.

WUE of sweet corn was also measured over diurnal cycles and compared with the predictions made by the paradigm equation. An example is given in Fig. 5, for 13 August 1998. Since stomata of sweet corn exhibited minimal or no response to ?W (Fig. 1b), WUE was simply with Eq. 4. The predicted WUE was in good agreement with the measured WUE for most of the day, except for the period before 9:00. At 7:00 the difference between the predicted and measured WUE was very large, and decreased with time until 9:00. These deviations might have been the result of ? (assumed to be constant in calculating the predicted WUE) varying with PAR and temperature when both were low in the morning, and will be discussed later.

?

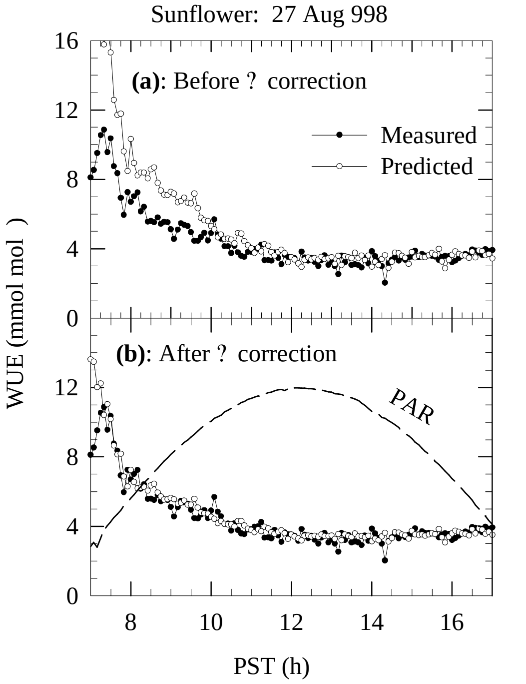

Fig. 6. Comparison of measured canopy photosynthetic WUE with that predicted using Eq. 4 (a) and using Eq. 3 (b), over a diurnal cycle for sunflower (LAI = 4.8) in the open field on a clear day (27 August 1998). Reference chosen was the mean values for the 11:30 to 12:30 midday period.

Fig. 6 presents a comparison of the measured and predicted WUE for a sunflower crop on 27 August 1998. Using Eq. 4 (Fig. 6a), the predicted WUE was too high in the morning. After accounting for the change in ? with ? W (Fig. 6b), the prediction was brought very close to the measured values, except for the early morning before 7:30.

The results on other days are consistent with those shown and indicate that early in the morning and near the end of the day, the predicted WUE could deviate considerably from the measured values. A part of this deviation may be attributable to errors in the BREB+ measurements, which are known to be larger at low radiation levels, i.e., early morning and late afternoon (Pruitt et al., 1987; Held et al., 1990).

4.3 Prediction of WUE of crop canopies in the open field over many days

Data were obtained for the three crops at the full canopy stage spanning many days, but on some days the canopy photosynthesis data were reliable only for the midday period of few hours due to the particularity of the BREB+ technique. It was decided to compare measured and predicted WUE of cotton over a long period using only the mean midday values (Fig. 7). The references chosen were those measured at midday (mean of 11:30 to 12:30) on 16 September 1997. As can be seen in Fig. 7, after accounting for the variations in ? with changes in ? W from day to day, over a 47-day period the predicted midday WUE followed the measured values well except for small deviations on some dates. In Fig. 8, the predicted WUE was plotted against the measured WUE. The slope of the linear regression line is 0.85 with an r^2 of 0.60 at 0.05 confidence interval.

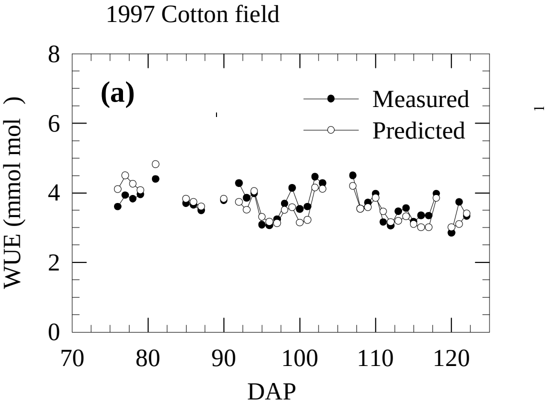

Fig. 7. Comparison of measured canopy photosynthetic WUE at midday (mean of 11:30 to 12:30) for a cotton crop in the open field with that predicted using Eq. 3, over the season when canopy cover was complete and before senescence. Reference chosen was the mean values for the midday period of 16 September 1997.

For sweet corn, the comparison between measured and predicted midday WUE over a 44-day period when the canopy was complete and before senescence also showed close agreement, with the slope of the linear regression line being 1.18 and an $r^2$of 0.76 at 0.05 confidence interval (data not shown). Since ? ?? f sweet corn did not show a clear response to humidity (Fig. 1b), the predication was made using Eq. 4 assuming ? to be constant. A similar comparison was made for sunflower using Eq. 3 with ? varying according to ? W. The results (not presented) show good agreement for the latter half of the season, but not for the first half. The ? vs. ? W regression was obtained on sunflower late in the season. It is possible that this relationship might have been different early in the season, causing the deviation between the measured and predicted WUE values.

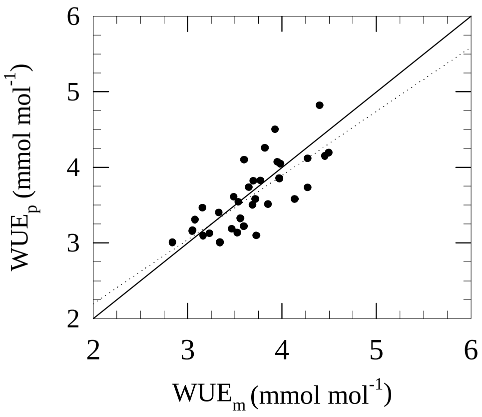

Fig. 8. Regression of midday canopy photosynthetic WUE of a cotton crop predicted using Eq. 3 (WUE_p) with the measured values (WUE_m) over a period of 47 days in 1997. Solid line is the 1:1 relationship and dashed line represents regression. Same data as those in Fig. 7.

5. Discussion

Modeling of canopy photosynthesis and transpiration based on characteristics of CO_2 assimilation and stomatal conductance of single leaves (DePury and Farquhar; 1997; Wang and Leuning, 1998) is not straightforward due to nonlinearity in the scaling up processes (Fannigan and Raupach, 1987; Baldocchi, 1993). Equally difficult has been the modeling of plant water use efficiency for conditions of elevated CO_2 and climate change scenarios (Eamus, 1991; Morison, 1993; Hsiao and Jackson, 1999). This paper reports the results of experimental tests of the WUE paradigm equations of Hsiao (1993). While the validity of the model at the leaf level (Fig. 2) was fully expected because it is based on the fundamental equations for gas exchange of single leaves, good agreement between predicted and measured WUE for whole plants and population of plants in the field over diurnal and long term courses was surprising when the model was directly applied to the canopy. The data described here point to the exciting possibility that the equations, without any explicit upscaling, may be applicable to whole plants and crop canopies in open fields of many species over the period of late morning to mid to late afternoon, when most of the CO_2 is assimilated and the water transpired. The reason for not needing upscaling may be the use of a reference and the expression of WUE of the new situation relative to that for the reference situation. Since the upscaling is likely not to change for the new situation relative to the reference situation, calculating WUE relative to a reference situation allows one to bypass upscaling.

The usefulness of the equations is dependent on the constancy or orderly and regular variations of ?, the ratio of C_i to C_a, with environmental factors. Early work showed that CO_2 assimilation is apparently well coordinated with stomatal behavior so that C_i is commonly constant for a give C_a and changes in proportion to changes in C_a. Wong et al. (1979) demonstrated near constant values of C_i over a range of CO_2 assimilation rates for a number of C_3 and C_4 species, under varied level of PAR, nitrogen and phosphorus nutrition, and slowly imposed water stress, when C_a was held constant. They also showed that ? remained virtually constant as C_a was varied to obtain different assimilation rates for *Eucalyptus pauciflora* and maize.

Another variable that has little effect on C_i at a given C_a appears to be leaf age. C_i apparently remains relatively constant (200 to 230 ?mol mol^{-1}) under ambient CO_2 level for cotton leaves of different ages (Constable and Rawson, 1980). C_i of tomato remained within the narrow range of 225 to 238 ?mol mol^{-1} over a period of 50 days, from the time of rapid leaf expansion to the time just before senescence (Bolaños and Hsiao, 1991). Similar results were obtained with maize leaves of different ages in the field over a wide range of ?W (Xu, L.-K. and Hsiao, T.C., unpublished). It seems obvious that insensitivity of C_i and ? to leaf age is a prerequisite for the equations to predict accurately changes in WUE over many days of the crop's life cycle, as they did for cotton (Fig. 7). In addition to leaf age, there is substantial variation in temperature, wind, humidity and C_a from day to day. Apparently Eq. 3 is adequate to take all there variables into account, as judged by the fairly accurate predictions made for cotton over many days (Fig. 7).

Regarding temperature, earlier Björkman (1981) showed that C_i of *Larrea divaricata* remained almost constant between 25 and 43º C, but rose gradually when temperature dropped below 23? C, and more sharply when temperature increased beyond 45? C. Sage et al. (1990) found that at a constant C_a, C_i of *Chenopodium album* remained essentially constant over a temperature range of 15 to 34º C. We do not know for certain if ? of sweet corn responds to temperature in a similar way. Preliminary results we obtained do indicate, however, that sweet corn ? may be substantially higher at low temperatures. If that is the case, the substantial negative deviation of predicted WUE from the measured WUE of sweet corn (Fig. 5) could be the result of higher ? at lower temperatures.

One environmental variable, ?W, is exceptional in that it alters ? of many species.

Ball and Berry (1982) found ? to decrease linearly with increases in ?W for *Geraea canescens* and *Perityle emoryii*. Morison and Gifford (1983) demonstrated similar linear relationship for two C_3 (rice and phalaris) and two C_4 (maize and paspalum) species. For maize grown in the field under the high radiation environment of Davis, however, there is minimum or no stomatal response to ?W (Held et al., 1991; Dai et al., 1992), as confirmed by the results obtained on sweet corn in this study (Fig. 1b).

The importance of knowing the value or the behavior of ? as environmental conditions change is clearly demonstrated in the results on cotton presented in Fig. 3 and 4. By assuming ? to be constant for the whole day and using Eq. 4, the predicted WUE was much higher than the observed WUE early in the morning (Fig. 3b). When the change in ? in response to ?W was taken into account (using Eq. 3 instead of Eq. 4), the difference between the predicted WUE and the observed WUE virtually disappeared (Fig. 3c). It is important to note that ? was not actually measured on the crop in the field, but derived from the function of ? vs. ?W in Fig. 1a.

Using the same function for ?, the pattern of WUE for cotton was also predicted quite well for a day of fluctuating radiation caused by moving clouds (Fig. 4). How WUE may change between alternating sunny and cloudy periods is not intuitive or can be simply deduced. The fact that Eq. 3 predicted most of the measured slight increases in WUE during the cloudy periods can be taken as evidence for the validity of the approach. It is important to note that radiation is not directly accounted for by the paradigm equations.

6. Acknowledgements

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Integrated drought prevention and control system and its application for winter wheat in North China

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Abstract

The mechanisms, characteristics and operation of drought prevention and control techniques were investigated for winter wheat during 1996~1998, to improve agricultural production and resist agricultural drought in North China. A wheat drought monitor and forecast technique, a straw mulching technique, scientific use of available soil moisture at planting (ASW_p), limited water stress, deep tillage and multi-functional drought-resistant agents were used. These individual techniques were also synthesized to achieve integrated prevention and control effect for winter wheat. During the winter wheat growth season with severe drought in 1998-1999 and 1999-2000, the integrated technique system was demonstrated and applied in Zhengzhou (Henan), Gucheng, (Hebei), Taian (Shandong) and Feicheng (Shangdong). Trials indicated that the drought resistance and increased production effects were very significant. Winter wheat yield increased by 24.6%, while water use decreased by 8.3% giving a 32.2% improvement in water use efficiency. The input output ratio was 1:3.2, with a net income of 845 yuan/ ha.

Key words: Agricultural drought, integrated prevention and control effect, application.

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1 Introduction

In China, the arid and semi-arid climatic region accounts for about 2/5 of total land. Even in humid and semi-humid area, drought disaster takes place frequently. According to statistical data from 1950 to 1998 (Liu, 2000) drought affected 20.8 million ha of land per year on average. The annual area experiencing some loss amounts to 8.5 million ha. Drought affected areas and damaged area accounted for 15% and 7% of total cultivable land respectively. The Huang-Huai-Hai Plain is the most seriously damaged region in China, where the drought affected area and damaged area account for more than 40% of the total affected and damaged area. Next in importance is the middle and lower reaches of the Yangtze River, where the drought affected area and damaged area account for 20.7% and 18.8% respectively. In northeast, northwest, southwest and south region of China, the drought affected areas account for 12.4%, 10%, 10% and 5.6% in turn, and drought damaged area account for 12.3%, 12%, 9.5%, and 4.6% in turn. Drought damage was relatively small in the 1950's, whereas in the 1960's, the damaged area increased by 54%, and increased by 46% in 1970's compared with 1960's. In 1980's, the drought-damaged area decreased by 6% and maintained the same level in 1990's.

The planting area of winter wheat in North China is about $1.1?10^{7}$ha, accounting for 40% of the total wheat planting area in China. The yield in North China is about 48% of the total wheat yield in China. But precipitation during the wheat growth season is only about 1/3 of wheat water demand, and much less in dry year. Wheat production is often water limited in North China. In a severe drought year, it is impractical to prevent drought only by irrigation. Integrated drought resistance practices are an effective measure to prevent severe drought. Many foreign countries pay attention to integrated drought prevention measure. For instance, America, Australia and India have developed dryland farming systems related to common local farming practices, and maintained sustainable agricultural development (Abrol, 1988; McWilliams, 1988; Stewart, 1988). Integrated drought prevention and control techniques have been developed according to agricultural characteristics and farming practices in North China. Integrated drought prevention and control techniques consist of three subsystems: 1) agricultural drought monitoring and forecasting subsystem; 2) soil water reservoir and plant water regulation subsystem; 3) limited irrigation subsystem (Figure 1). Application of these techniques in several demonstration regions

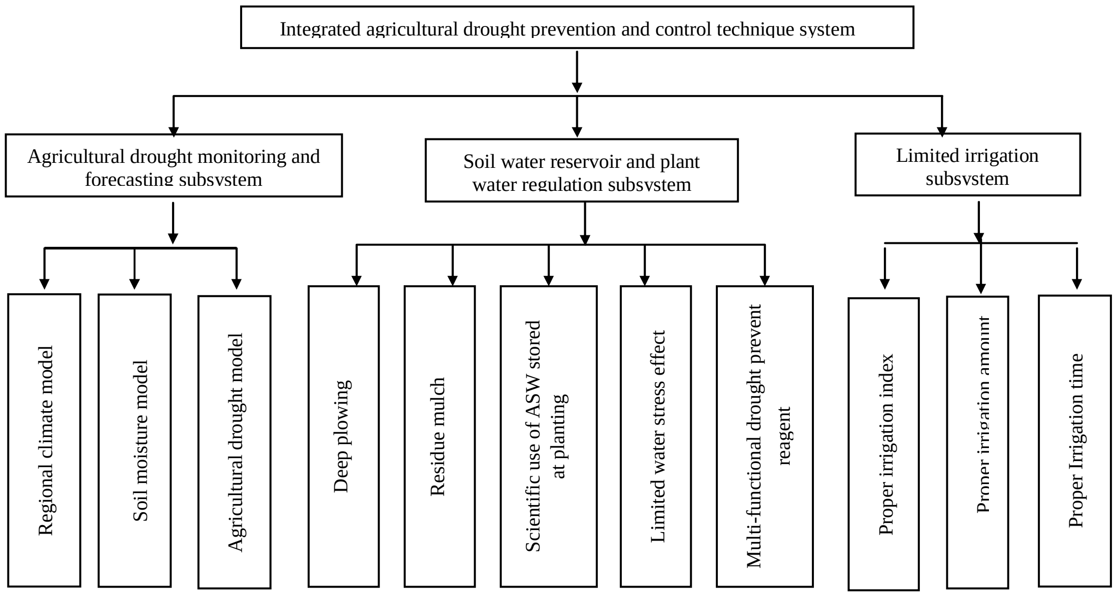

Figure 1. Integrated agricultural drought prevention and control system

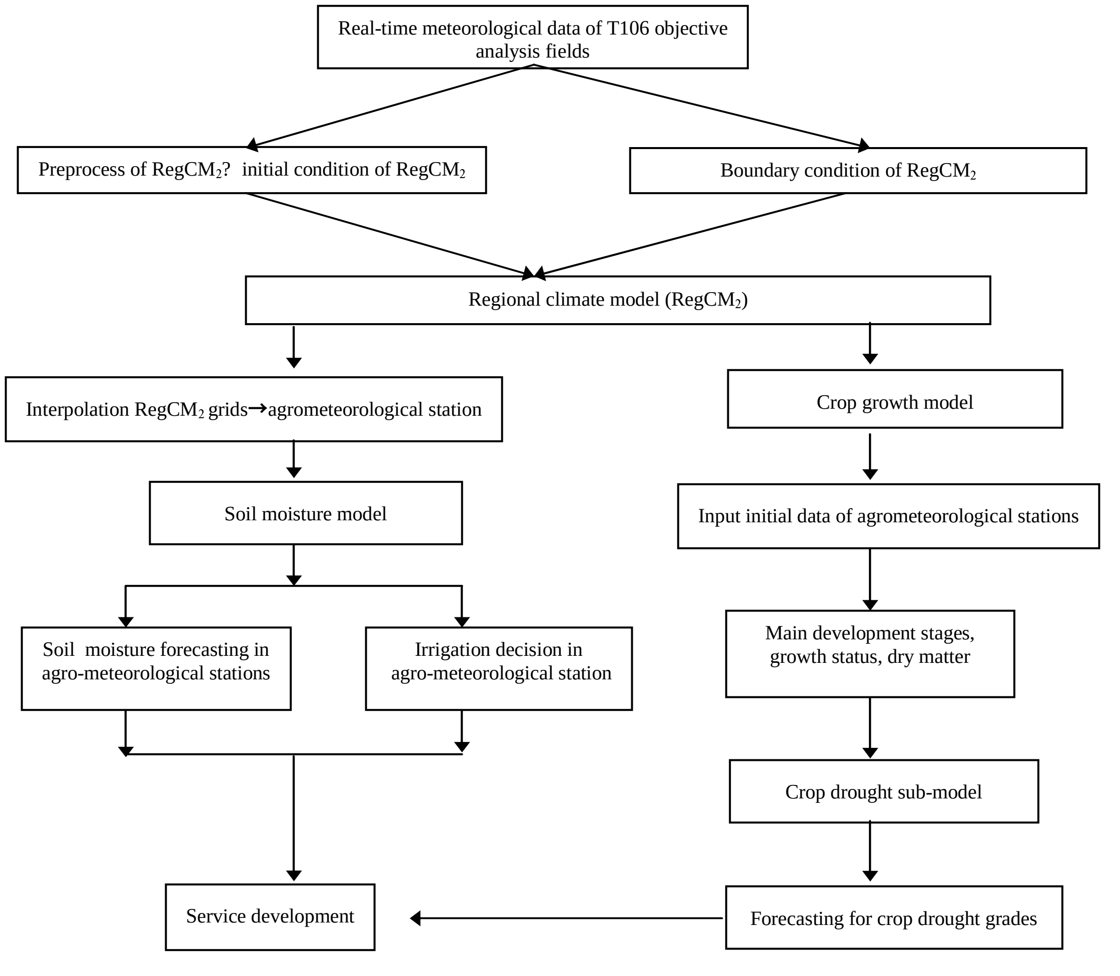

Figure 2. Soil moisture, drought, and irrigation forecasting by regional climatic and agrometeorological model

indicates that the system was effective in resisting severe drought.

2 Materials and methods

2.1 Agricultural drought monitoring and forecasting subsystem

Agricultural drought monitoring and forecasting technique is related to weather forecasts, crop growth conditions, soil water simulation and management practice. The CCM_3 and GENESIS models were used to get numerical forecasts of meteorological factors in the next 10 days, 1 month, and even 3 months. Crop growth stages, leaf area index and biomass were obtained by linking output data with crop growth models, and predictions of actual evapotranspiration. Soil water at different rooting depths is estimated by linking output data with a soil water simulation model. Soil water content and water shortage at any crop growth stages is forecast by linking a drought index with an irrigation management model, which recommends optimal irrigation time and amount (Figure 2).

2.2 Soil water reservoir and plant water regulation subsystem

2.2.1 Mulching effects in wheat fields

Experiments were carried out using straw and residue mulching for different soil moisture, mulching amounts and times at Zhengzhou agro-meteorological experimental station.

2.2.2 Available soil water use at planting (ASW_p)

The available soil water at planting (ASW_p) has an influence on wheat yield. Two years of experiments on ASW_p in winter wheat field were carried out at Gucheng Agrometeorological Experimental Base to quantify these effects. A consumption ratio (Rc,%) was defined as

$$Rc \ ? \ (\frac{Ac}{ASW}) \ ? \ 100$$

where *Ac* is the amount of ASW_p that is consumed (mm), and ASW_p is available soil water stored at planting (mm). Rc was determined for each layer in the soil profile. Amounts of water used in non-irrigated wheat fields, supplied by both ASW_p and precipitation (Ac), were calculated by:

$$Ac = ET - P$$

$$ET \ ? \ ? \ Pa \ ? \int_0^h (?_2 \ ? \ ?_1) dh$$

The study was intended to determine the duration and use of ASW_p without irrigation and precipitation. This may provide some information about soil water use under extreme drought conditions. The ASW_p ranged from 65-75% within a 2 m depth at planting, which represents the normal conditions in North China. This is seldom judged adequate in farming practice.

2.2.3 Water stress effects on winter wheat

During 1997~1998, experiments were carried out in Tai'an and Gucheng on different water stress levels and durations in winter wheat fields. The water stress levels were ?45%, 45~50%, 51~55%, 56~60%, and 60~80% of field capacity (FC) at the returning-green and jointing stages, respectively. Three stress durations of 10 (T1), 20 (T2) and 30days (T3) were identified for each water stress level. The control was represented by 60~80% of field capacity.

2.2.4 Deep tillage operations

Deep tillage operations at 45cm soil depth and 30cm were carried out in Gucheng. Surface soil tillage was designed as the control.

3 Results

3.1 Mulching

Results indicated that the water dynamics and aerodynamic conditions in surface soil had been changed with wheat straw or maize residue mulching. After mulching, the turbulence exchange coefficient, sensible heat flux, and temperature at 5 cm soil depth in wheat field were increased, while latent heat flux and soil heat flux was decreased (Figures 3 and 4). Soil evaporation was decreased due to reduced latent heat flux (Figure 5). In addition, separate estimates of evaporation and transpiration were obtained. Transpiration is a function of leaf area index, potential evapotranspiration and soil moisture. An equation was developed to describe this:

$$Tr \ ? \ 0.234758(LAI \ ? \ 1)^{1.51445} *$$
$$ETp^{0.481815} * (\frac{SWe}{SWt})^{0.16849} \ ? \ 1$$

where Tr is plant transpiration, LAI is leaf area index, ETp is potential evapotranspiration, SWe is actual soil water content in rooting depth, and SWt is maximum soil water content in rooting depth.

Observations showed that mulching can make best use of soil water for wheat by reducing soil water evaporation in early growth stages, then allowing savings to be used for transpiration in later growth stages (Figure 6). So soil water was used for transpiration instead of evaporation, improving water use efficiency.

Mulching amounts, timing and soil moisture at mulching had different effects on wheat dry matter, leaf area, transpiration rate, yield and water use efficiency. The optimal mulching time was the day on which wheat stopped growing before winter, with an optimal mulching amount

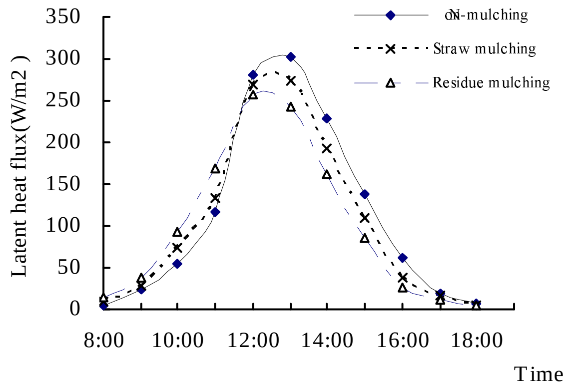

Fig. 3. Diurnal change of latent heat flux in wheat field

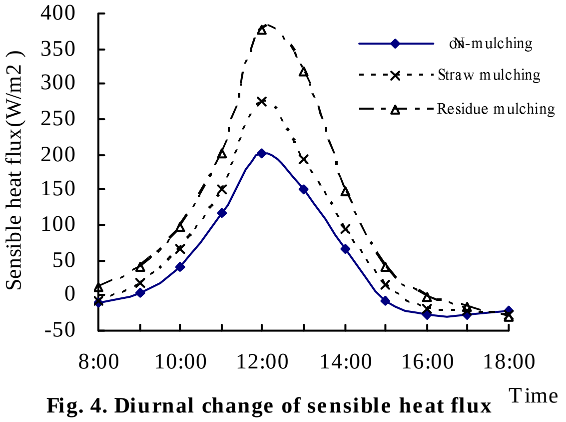

Fig. 4. Diurnal change of sensible heat flux in wheat field

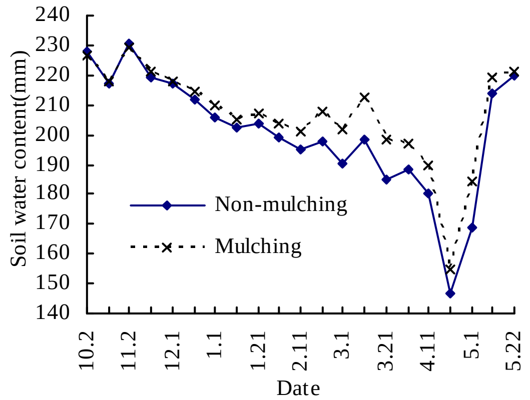

Fig.5. Soil water content in 0-100cm layer under mulching and non-mulching treatment in 1998

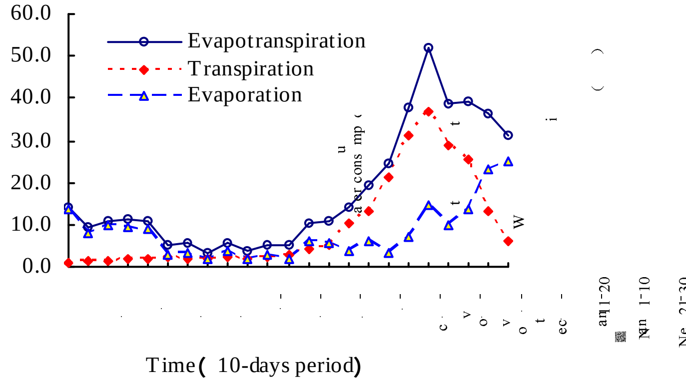

Fig.6 Transpiration, evaporation and evapotranspiraion in mulching wheat field during 1998-1999

of 4.5~6 ton/ha, and at a soil moisture content of 55~70% FC. Under favourable mulching conditions, wheat yield can be increased by 18.5%, and water use efficiency was improved by 22.1%.

3.2 Available water

3.2.1 Results with no rainfall

Table 1 shows water use and consumption ratios of the winter wheat plots for 0-2 m, 0-0.5 m, 0.5-1m, and 1-2 m depths. There were slight differences in ASW_p of the five plots. In general, Ac increased with ASW_p and Rc ranged from 60% to 72%, averaging 67.6% in the 0-2 m layer. Equivalent averages were 88.8%, 57.6% and 58.8% for the 0-0.5 m, 0.5-1m and 1-2 m depths respectively. In sum, Rc in the 0-0.5 m depth was higher than that in layers below 0.5 m, resulting from the higher wheat root density and higher evaporation under drought conditions. Rc also varied with different wheat growth stages. Table 2 shows that in each soil layer, water consumption at jointing-maturing was lower than that at planting-jointing due to water shortage.

3.3.2 Results with rain

The five levels of ASW_p were 348.3, 320.0, 282.3, 278.8 and 244.3 mm in the top 2 m of the soil profile at planting. Growing-season precipitation was 70.6 mm. In Table 3, Ac and Rc in the 0-2 m layer increased with ASW_p. Ac in 0-2 m ranged from 98.2-226.8 mm in 5 levels, and Rc in 0-2 m ranged from 40.2-65.0%. In addition, it can be seen that: (1) Except Rc in the 0-0.5 m layer, Ac and Rc in each soil layer also increased with ASW_p. Rc in the 0-0.5 m soil layer was just about 90%, whereas in the deeper soil profile, Rc decreased with the deepening soil. (2) In all of the 5 ASW_p levels, Ac were the highest in the upper soil profile (0-0.5 m), and accounted for 70.5-89.6% of total Ac (0-2 m). This ratio decreased in the upper soil profile (0-0.5 m) with the increase of ASW_p, whereas it increased in deeper soil profile. (3) In the lower ASW_p level, Rc below 0.5 m was less than 2.6%, which showed that in the dry farming wheat field with insufficient ASW_p and low precipitation, use of ASW_p was inefficient, resulting from unsuccessful root development.

Table 1. Consumption ratio (Rc) of winter wheat plots that only had stored soil water

Soil layer	Items	Plots					
		1	2	3	4	5	Average
0-2 m	ASW_p (mm)	294.5	269.3	318.9	292.7	301.9	295.5
	Ac (mm)	186.0	161.6	220.7	209.3	214.3	198.4
	Rc (%)	63	60	72	72	71	67.6
0-0.5 m	ASW_p (mm)	79.6	76.3	82.9	83.0	86.0	81.6
	Ac (mm)	71.4	68.4	73.1	75.2	75.1	72.6
	Rc (%)	90	89	88	90	87	88.8
	Ratio of total Ac in 0-2 m layer (%)	38	43	34	36	35	37.2
0.5-1 m	ASW_p (mm)	60.5	46.8	86.7	63.9	66.3	64.8
	Ac (mm)	33.0	24.1	56.1	32.2	43.6	37.8
	Rc (%)	54	52	66	50	66	57.6
	Ratio of total Ac in 0-2 m layer (%)	18	15	26	15	20	18.8
1-2 m	ASW_p (mm)	153.4	146.2	149.3	146.8	150.6	149.3
	Ac (mm)	81.6	69.1	90.9	101.9	95.6	87.8
	Rc (%)	53	47	61	70	63	58.8
	Ratio of total Ac in 0-2m layer (%)	44	42	40	49	45	44

Table 2. Consumption ratio (Rc) of wheat plots at different growth stages with water supplied only by ASW_p.

Soil layer	0-0.5 m	0.5-1 m	1-2 m	0-2 m
Planting-jointing	66	60	50	60
Jointing-maturing	21	6	13	11

Table 3. Amount (Ac) and consumption ratio (Rc) of wheat plots that had both ASW_p and precipitation

		ASW_p levels				
		I	II	III	IV	V
0-2 m	ASW_p (mm)	348.3	320.0	282.3	278.8	244.3
	Ac (mm)	226.8	193.2	177.0	145.2	98.2
	Rc (%)	65.0	60.2	62.7	52.1	40.2
	Ratio to total Ac in 0-2 m layer (%)	100	100	100	100	100
0-0.5 m	Ac (mm)	159.0	142.2	133.4	122.1	88
	Rc (%)	90	87	90	90	90
	Ratio to total Ac in 0-2 m layer (%)	70.5	73.6	75.4	84.1	89.6
0.5-1 m	Ac (mm)	34.9	19.7	17.0	8.6	4.7
	Rc (%)	33	32.8	16.8	4.6	2.6
	Ratio to total Ac in 0-2 m layer (%)	15.4	10.2	9.6	5.9	4.8
1-2 m	Ac (mm)	32.0	31.3	26.6	14.5	5.5
	Rc (%)	20.2	14.7	12.4	4.2	1.2
	Ratio to total Ac in 0-2 m layer (%)	14.1	16.2	15.0	10.0	5.6

Table 4 shows Rc for different growth stage at 3 ASW_p levels. At all three ASW_p levels and in each soil layer, Rc at planting-jointing stage was higher than that at jointing-maturing stage. Rc in 0-0.5 m was also highest for the whole soil profile. At the planting-jointing stage, Rc in 0-2 m was positively correlated to ASW_p, but negatively correlated in 0-0.5 m. Rc was 14.3% for 1-2 m in the higher ASW_p level, whereas very little water use occurred in the lower ASW_p level below 0.5 m. At the jointing-maturing stage, Rc in 0-0.5 m layer ranged from 12.7-20.4%, and was positively correlated to ASW_p. But for deeper soil layers, Rc was less than 10% with the exception of the higher ASW_p level. In this case, wheat plants with better shoot growth and deeper rooting system in the higher ASW_p level could absorb more ASW_p in 1-2 m, until the late growth period.

Table 4. Consumption ratio (Rc) at different growth stages in wheat plots that had both ASW_p and precipitation

Level of ASW	Growth stage	Soil layer (m) 0-50	50-1	1-2	0-2
80%-85%	Planting-jointing	69.6	22.5	14.3	59.0
	Jointing-maturing	20.4	10.5	5.7	6.2
70%-74%	Planting-jointing	72.8	17.8	6.0	51.5
	Jointing-maturing	17.2	6.9	1.4	5.2
60%-64%	Planting-jointing	87.3	2.8	1.2	36.2
	Jointing-maturing	12.7	1.1	0.0	4.8

So winter wheat could resist drought to some extent. Under the normal ASW_p condition with 65-75% of FC or 270-330 mm of available water in 0-2 m, ASW_p alone could supply about 200 mm water for winter wheat until the late grain filling stage. Then the winter wheat yield was about 1.16 ton/ha. If winter wheat has a water supply of over 360 mm of ASW_p, or 80% of FC in 0-2 m and 70.6 mm of rainfall, it can yield about 3.25 ton/ha. Dryland conditions correspond to ASW_p ranging from 60-70% or about 240-300 mm of available water. With 70.6 mm of precipitation, the effect of every 10 mm ASW_p on wheat yield was an increase of 0.37 ton/ha and water use efficiency increased from 0.31 to 1 kg m^{-3}. When ASW_p ranged from 70-80% or about 300-360 mm of available water, the effect of every 10 mm ASW_p on wheat yield was an increase of 0.11 ton/ha and water use efficiency increased slightly. An optimal ASW_p for 0-2 m depth was 80-85% under dryland conditions in North China (An, 2003).

3.3.3 Limited water stress effects on winter wheat

Table 5 shows that appropriate water stress indices at the returning-green stage and jointing stages were 50% and 55%, respectively. The irrigation guided by the index in wheat field showed that the wheat yield was increased by 3~7.7% and water use efficiency was increased by 9~20%.

Table 5. Effects of limited water stress on winter wheat yields

	Soil moisture	Ratio of ear numbers to Control T_1	T_2	T_3	Grain number per ear T_1	T_2	T_3	1000 grain weight (g) T_1	T_2	T_3	Yield increase (decrease) (%) T_1	T_2	T_3
1997	<45%	0.85	0.81	0.81	25.4	23.6	24.5	33.3	35.6	33.2	-13.1	-17.5	-19.9
	45%-50%	0.95	0.87	0.95	25.8	25.8	25.0	31.6	34.3	32.5	-6.0	-8.3	-6.4
	51%-55%	0.94	0.93	0.95	26.7	25.8	24.8	33.1	34.4	34.7	0.2	-0.3	-1.6
	56%-60%	0.94	0.98	0.93	27.9	27.8	27.7	32.4	31.9	32.7	2.6	-0.2	1.3
	60%-80%	1.00			25.8			32.2			0.0		
1998	51%-55%	1.01	0.96	0.96	54.1	53.9	52.2	34.5	32.9	32.7	0.0	-8.9	-10.4
	56%-60%	1.06	1.00	1.01	54.0	53.5	54.2	33.8	33.4	35.4	6.9	-0.3	0.1
	60%-80%	1.00			54.1			34.9			0.0		

3.3.4 Deep tillage technique

Results showed that deep tillage operations encourage breaking up any restrictive soil layers that may prevent root extension. With tillage at 45 cm depth, soil bulk density in the 0~10, 10~20, 20~30, 30~40, and 40~50 cm depths was reduced by 0.7%, 2.7%, 0.6%, 3.4% and 0.8%, respectively. Soil moisture was increased by 8.6% and 2.7%, respectively, with tillage at 45 cm and 30 cm depths. For 20~30 mm of rain, the water infiltration depth following deep tillage operations was increased by 10 cm. Deep tillage favored root development and water use in 1~2 m soil layer. Under tillage at 45 cm and 30 cm depths, the root length was increased by 3.0% and 9.4%, and root dry matter was increased by 19.5% and 25.1%, respectively. Deep tillage also favored shoot development. Table 6 shows that grain yield increased by 7.0-7.7% and suggests that a 30 cm tillage depth was appropriate.

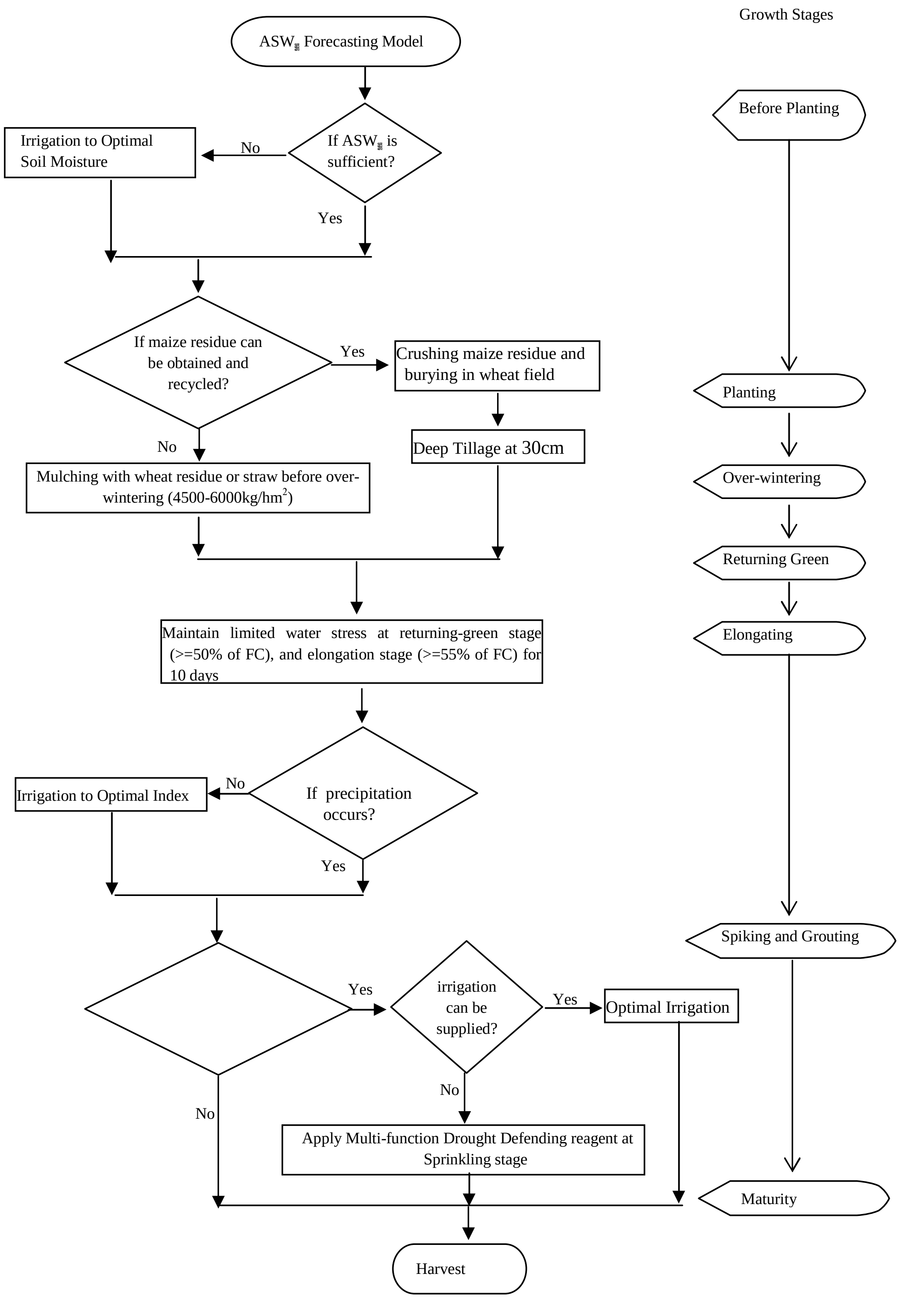

Figure 7. Operation flow chart of the integrated drought prevention and control technique system

Table 8. Experimental conditions and results of demonstrations of integrated drought prevention and control techniques during 1998~1999.

Sites	Treatment	Applied techniques	Crop yield and water use efficiency	Weather and climate condition
Shilipu in suburb of Zheng-zhou	1 (0.67 ha)	1) Sufficient ASW (?80%), 2) deep tillage at 30cm, 3)maize residue burying and wheat residue mulching (5000kg/ha), 4) limited irrigation twice (Dec. in 1998, and May in1999).	Earing rate of 42% (increased by 4%); grain yield of 6236.8 kg/ha (increased by 11.6%); water use of 430.7mm (decreased by 19%); WUE of 1.448kg/m^3, (increased by 33.6%)	The average temperature was 2.3?C higher than the ordinary year. A xerothermic wind appeared on May 27th. The total precipitation during the growth season was 113 mm (decreased by 60%). A severe drought year.
	2 (0.33 ha)	1) Sufficient ASW (?80%), 2) deep tillage at 30cm, 3) maize residue burying, 4) applying drought preventing reagent at jointing and grain filling stage, 5) limited irrigation 3 times (Dec. in 1998, March and May in 1999)	Earing rate of 48% (increased by 10%), grain yield of 6351.8 kg/ha (increased by 13.6%), water use of 511.0mm (decreased by 1%), WUE of 1.269kg/m^3 (increased by 17.1%).	
	3 (0.33 ha)	1)Sufficient ASW (?80%), 2) deep tillage at 30cm, 3)maize residue burying, 4) applying drought preventing reagent at jointing stage, 5)limited irrigation 3 times (same as II)	Earing rate of 42% (increased by 4%); grain yield of 6156.0 kg/ha (increased by 10.1%); water use of 513.3mm (equal to CK), WUE of 1.199kg/m^3, (increased by 10.6%)	
	Control (0.67 ha)	1) Sufficient ASW (?80%), 2) deep tillage at 30cm, 3)maize residue burying, 4)limited irrigation 3 times (same as II)	Earing rate of 38%, grain yield of 5590 kg/ha, water use of 515mm,WUE of 1.084kg/m^3.	
Jiezhuang, Yuan-zhuang, and farm field in suburb of Taian	Jiezhuang (2 ha)	1)Sufficient ASW (?80%), 2)deep tillage at 30cm, 3)fertilizing according to goal yield formula, 4) limited irrigation twice (May 18th and May 6th in 1999).	Earing rate of 32.3% (increased by 7%); grain yield of 7866 kg/ha, (increased by 12.5%); water use of 405.8mm (decreased by 2%); WUE of 1.29kg/m^3 (increased by 15%)	The average temperature during the wheat growth season was 0.86?C higher than the common year. It rained 135.8 mm (75.8% of the common year) during the whole season, and 48.5mm from planting to grain filling stage (42.7% of the common year). A severe drought year.
	Control (1.3 ha)	1) Sufficient ASW (?80%), 2)deep tillage at 30cm, 3)traditional fertilizing, 4) limited water stress, irrigation 3 times (Feb.20th, March. 16th, and April. 24th in 1999).	Earing rate of 29.9%, grain yield of 6923 kg/ha, water use of 414.6mm, WUE of 1.12kg/m^3.	
	Yuan-zhuang (0.7 ha)	1) Sufficient ASW (?80%), 2)deep tillage at 30cm, 3)fertilizing according to goal yield formula, 4)limited water stress, irrigation twice (April. 2nd, and May 4th in 1999)	Earing rate of 30.3%(increased by 3%); grain yield of 6736.5kg/ha (increased by 17%); water use of 379.7mm(decreased by 7%); WUE of 1.18kg/m^3 (increased by 24%).	
	Control (1.3 ha)	1) Sufficient ASW (?80%), 2)deep tillage at 30cm, 3)traditional fertilizing, irrigation 4 times (Nov.30th in 1998, March 1st, April 2nd, and May 4th in 1999)	Earing rate of 23.4%, grain yield of 5724.0kg/ha water use of 402.1mm, WUE of 0.95g/m^3,	
	Farm field (1 ha)	1) Sufficient ASW (?80%), 2)deep tillage at 30cm, 3)fertilizing according to goal yield formula, 4)limited water stress, irrigation twice (April. 6th, and May 3rd in 1999)	Earing rate of 36.2%(increased by 24%); grain yield of 7531.5kg/ha (increased by 15%); water use of 409.6mm(decreased by 8%); WUE of 1.23kg/m^3 (increased by 23%).	
	Control (0.7 ha)	1) Sufficient ASW (?80%), 2)deep tillage at 30cm, 3)traditional fertilizing, 4) traditional irrigation3 times (March 3rd, April 6th, and May 3rd in 1999)	Earing rate of 29.2%, grain yield of 6568.5kg/ha; water use of 439.7mm, WUE of 1.0kg/m^3,	
Gucheng	1 (1.4 ha)	1) Sufficient ASW (?80%), 2) deep tillage at 30cm, 3)maize residue burying, 4)limited water stress, limited irrigation.	Grain yield of 6856.5kg/ha (increased by 36%); water use of 469.3mm (decreased by 14%); WUE of 1.30kg/m^3 (increased by 60%).	The temperature was slightly higher. The rainfall during the growth season was 70.6 mm (less than one half of 150 mm in common year). It rained only 0.1 mm from Oct. 1998 to April. 1999. An extreme drought year.
	2 (0.6 ha)	1) Sufficient ASW (?80%), 2)deep tillage at 30cm, 3)maize residue mulching (4500~6000 kg/ha), 4)limited water stress, limited irrigation	Grain yield of 6051.0kg/ha (increased by 19.7%); water use of 454.6mm(decreased by 18%); WUE of 1.18kg/m^3 (increased by 46%).	
	Control (0.6ha)	1) Sufficient ASW (?80%), 2) traditional fertilizing, 3)traditional irrigation.	Grain yield of 5056.5kg/ha, water use of 533.6mm, WUE of 0.81kg/m^3.	

Table 6. Effects of deep tillage on growth and winter wheat yield (%)

Treatment	Root length	Root dry matter	Shoot height	Tillers	Leaf area	Total biomass	Harvest index	Grain yield
(tillage at 45cm depth –CK)/CK	3.0	19.5	6.0	15.6	6.0	6.4	4.9	7.0
(tillage at 30cm depth-CK)/CK	9.4	25.1	1.0	24.3	13.5	11.3	13.1	7.7

3.3.5Multi-functional drought preventingreagents

Two types of multi-functional drought preventing reagents were developed to inhibit transpiration and improve crop yield. The two years applying experiments in wheat field indicated that the multi-functional drought preventing reagents could improve the photosynthetic rate by 28%, decrease transpiration rate by 9%, increase stomatal resistance by 51%, and improve grain-filling by 44%. The water use could decrease by 28.1mm if applied it at heading stage, or 10.2 mm at grain filling stage. Table 7 shows that yield increase could amount to 10.1%, and the input/output could reach to 1:4.3.

Table 7. Effects of multi-functional drought preventing reagents) on wheat growth

Drought prevention reagents	Photosynthesis	Stomatal resistance	Transpiration	Rate of grain filling	Spike number	Water use efficiency	Yield
No.1	+18%**	+51%**	-9%	+22%	+18.2%	+2.8%**	+3.3%
No.2	+28%*	+24%**	-2%	+44%	+7.0%	+10.1%**	+1.6%

4 Concluding demonstration of integrated drought prevention and control technique system

The operation flow chart of the integrated drought prevention and control technique system is shown in Figure 7. Limited irrigation procedures are also operated according to this. Demonstration experiments on integrated drought prevention and control technique system were carried out in winter wheat fields in Gucheng, Taian and Zhengzhou for the conditions described in Table 8. It is shown that under severe drought conditions, higher yield could be obtained in wheat fields that used the integrated drought prevention and control technique system. Yield increased by 10.1~36%, total water use during the growth season decreased by 1~19%, and water use efficiency improved by 10.6~60% (Xu, 2002).

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Panicle “neck” diameter: A new drought-resistance trait of rice

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Abstract
Thirty cultivars or combinations (*indica*, *japonica* and hybrid rice) were evaluated to screen rice drought resistance traits from thirty-nine major morphological and agronomic traits of wetland and dryland varieties. Single variable stepwise regression, path analysis, multiple partial correlations and gray correlative analysis of data processing systems (DPS), and genetic analyses were conducted. Rice panicle neck diameter was firstly screened as a drought resistance trait of *indica*, *japonica* and hybrid rice, being influenced chiefly by additive genetic variance and capable of being fixed and improved by selection. It had only general narrow heritability. Its interactive narrow heritability was zero，showing that its inheritability wasn’t influenced by the environment and so it would be effective in selection under different environments. Both general and interactive heterosis of rice panicle neck diameter had very significant differences, which were positive. Its genotype-environmental interaction could not change the direction of the dominant gene effect. Therefore regardless of the different rice types or cultivars, rice panicle neck diameter was the most dependable selected trait for rice drought resistance screening, identification and breeding.

Key words: Rice; panicle neck diameter; drought resistance; drought resistance screening and identification; drought resistance inheritance and breeding.

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1 Introduction

While water resources shortages in China are becoming serious (Brown *et al.*, 1998), the extent of paddy rice grown in dry land is continually increasing. Since, to a large degree, drought tolerance and yield restrict it, so there are challenges to those growing paddy rice in dry land conditions. People began to use hybrid rice for water saving cultivation systems since it has higher yield and stronger drought resistance than conventional paddy rice (Zhao *et al.*, 1987). This was popularized, so the hybridization between paddy and upland rice has become one approach to breeding paddy rice cultivars for dry land conditions. This approach can improve the low productivity of upland rice and also strengthen drought resistance of paddy rice, so both characteristics might be included in the best hybrid combinations (Luo *et al.*, 2001; Dingkuhn, 1999; Zhang *et al.*, 1991).

Crop breeding needs some simple, dependable methods and traits to identify drought resistance of cultivars or materials and the heredity of drought resistance traits. This must be studied and applied to breeding selection through hybridization. Only those cultivars with both high yield and strong drought resistance will be bred to develop water saving and dry land cultivation of paddy rice. So research into selection and heredities of rice drought resistance traits are very important.

Table 1. Experimental cultivars (or combinations)

Number	Cultivar	Type	Number	Cultivar	Type	Number	combination	Type
1	Chaori	*japonica*	11	754	*indica*	21	UR 87641	*indica*
2	Japanjing	*japonica*	12	4015	*indica*	22	Pei’ai 64s/1068	Hybrid
3	Changlijing	*japonica*	13	Nanfeng	*indica*	23	You I465	Hybrid
4	Chao’erzhan	*japonica*	14	Upland Rice 961	*indica*	24	165s/752	Hybrid
5	Upland Rice 9	*japonica*	15	Wangdao 1	*indica*	25	Liangyoupeite	Hybrid
6	Upland Rice 44	*japonica*	16	Dehan 1	*indica*	26	Anxiang s/63	Hybrid
7	Upland Rice 277	*japonica*	17	Xinguizaozhan	*indica*	27	Peiliangyou 88	Hybrid
8	UR 95 Shucun 502	*japonica*	18	Brazilian UR	*indica*	28	Shanyou 10	Hybrid
9	UR95 Shucun 104	*japonica*	19	Xiangsimiao 2	*indica*	29	Xieyou 64	Hybrid
10	UR95 Shucun 9	*indica*	20	Ganwanxian 19	*indica*	30	Shanyou 63	Hybrid

Note：UR: Upland Rice

Table 2. Parental cultivars and hybrid combinations

Cultivar	9248 (weak)	Caofengzao (strong)	Zhongyouzao 81 (medium)
Brazilian upland rice (strong)	+		
Upland rice 87641 (weak)	+	+	+
Upland Rice No.277 (medium)	+	+	+
Upland Rice 95 Shucun NO.502 (strong)		+	

Note: The words in brackets represent differences of drought resistance.

Table 3. Analytical results of data and selected traits in *indica* rice

Traits type	Treatment	Stepwise regression	Direct path coefficient	Multiple variable regression	Grey correlative analysis	Selected traits
A	YD	A_1, A_4	A_1 (0.9185)	A_1 (r =0.8197**)	$A_1>A_3>A_6>A_2>A_5>A_4$	A_1
	DRC	A_1, A_2	A_1 (0.8636)	A_1 (r=0.8060**)	$A_1>A_5>A_3>A_2>A_6>A_4$	
B	YD	B_2, B_5	B_2 (1.1587)	B_2 (r=0.8338**)	$B_2>B_5>B_6>B_7>B_3>B_1>B_4>B_8$	B_2
	DRC	B_2	B_2 (0.7984)	B_2 (r=0.7984**)	$B_2>B_4>B_1>B_6>B_7>B_5>B_3>B_8$	
C	YD	C_2	C_2 (0.7595)	C_2 (r=0.7595**)	$C_3>C_2>C_4>C_1$	C_2
	DRC	C_2, C_4	C_2 (0.6244)	C_2 (r=0.7186**)		
D	YD					
	DRC	D_1	D_1		$D_3>D_1>D_2>D_5>D_4>D_8> D_6> D_9> D_7$	
E	YD				$E_3>E_1>E_2$	
	DRC				$E_2>E_1>E_3$	
F	YD				$F_1>F_2>F_3$	F_2
	DRC	F_2	F_2 (0.7203)	F_2 (r=0.7203**)	$F_2>F_1>F_3$	
G	YD				$G_3>G_1>G_2$	
	DRC				$G_1>G_2>G_3$	
H	YD				$H_3>H_2>H_1$	
	DRC	H_3	H_3 (0.5250)		$H_3>H_1>H_2$	

Notes：1. A: panicle morphological traits; B: plant morphological traits; C: panicle fructificational traits; D: functional leaves traits; E: growth stages traits; F: grain morphological traits; G: rice milling quality traits; H: rice appearance quality trait; YD: yield in dryland; DRC: drought resistance coefficient; A_1: panicle neck diameter; A_2: panicle length; A_3: primary branches per panicle; A_4: secondary branches per panicle; A_5: total branches per panicle; A_6: grains setting density; B_1: plant height; B_2: effective panicles per plant; B3: total internodes of main stem; B_4: reciprocal 1st internode length; B_5: reciprocal 2nd internode length; B_6: reciprocal 3rd internode length; B_7: reciprocal 4th internode length; B_8: reciprocal 5th internode length; C_1: total grains per panicle; C_2: filled grains per panicle; C_3: seed setting rate; C_4: 1000-grains weight; D_1: flag leaf length; D_2: flag leaf width; D_3: flag leaf area; D_4: reciprocal 2nd leaf length; D_5: reciprocal 2nd leaf width; D_6: reciprocal 2nd leaf area; D_7: reciprocal 3rd leaf length; D_8: reciprocal 3rd leaf width; D_9: reciprocal 3rd leaf area; E_1: total days to maturation; E_2: days from sowing to initial heading; E_3: days from initial heading to maturation; F_1: grain length; F_2: grain width; F_3: grain length/width; G_1: brown rice rate; G_2: milked rice rate; G_3: H_1 : head rice rate; rice length; H_2: rice width; H_3: and rice length/width; 2.The basic data of this table in reference of Cheng Fengmei et al., 2000a。

Table 4. Analytical results of data and selected traits on *japonica* rice

Traits type	Treatment	Stepwise regression	Direct path coefficient	Multiple variable regression	Grey correlative ananlysis	selected traits
A	YD	A_5	A_5 (0.6248)	A_5 (r=0.6248**)	$A_5>A_4>A_3>A_2>A_6>A_1$	A_1
	DRC	A_1	A_1 (0.7823)	A_1 (r=0.7823**)	$A_2>A_1>A_5>A_4>A_3>A_6$	
B	YD	B_1	B_1 (0.8742)	B_1 (r=0.7590**)	$B_4>B_1>B_6>B_3>B_5>B_2>B_7>B_8$	B_2
	DRC	B_2	B_2 (1.0345)	B_1 (r=0.8334**), B_2 (r=0.8447**)	$B_2>B_5>B_4>B_1>B_6>B_3>B_7>B_8$	
C	YD	C_2	C_2 (0.9219)	C_2 (r=0.9219**) C_3 (r=0.8164**)	$C_2> C_1>C_3>C_4$	C_2, C_3
	DRC	C_2, C_3	C_2 (0.3985), C_3 (0.4621)	C_2 (r=0.8317**) C_3 (r=0.9020**)	$C_2> C_3> C_1 >C_4$	
D	YD	D_2, D_5	D_2 (2.5545), D_5 (-3.4881)		$D_6>D_3>D_2>D_9>D_5>D_8>D_1>D_4>D_7$	D_1
	DRC	D_1	D_1 (0.6951)	D_1 (r=0.6591**)	$D_1>D_6 >D_3>D_4>D_2>D_5>D_8>D_7>D_9$	
E	YD	E_2	E_2 (-0.6091)	E_2 (r=-0.6091**)	$E_2>E_1>E_3$	
	DRC	E_2	E_2 (-0.4379)		$E_2>E_1>E_3$	
F	YD	F_1	F_1 (0.6560)		$F_3>F_1>F_2$	
	DRC	F_1	F_1 (0.4662)		$F_3>F_2>F_1$	
G	YD	G_1	G_1 (0.4469)		$G_2>G_3>G_1$	
	DRC	G_3	G_3 (0.5545)	G_3	$G_3>G_1> G_2$	
H	YD	H_1	H_1 (0.6041)	H_1 (r=0.6041**)	$H_3>H_1>H_2$	
	DRC				$H_3>H_2>H_1$	

Notes：1. See Table 3.; 2.The basic data of this table in reference of Cheng Fengmei et al., 2000b

2 Materials and methods

2.1 Selection of rice drought resistance traits

2.1.1 Experimental materials and design

Table 1 identifies the thirty rice cultivar/ combinations that were evaluated. Rice was grown in both wet and dry land conditions with the first seedlings being transplanted in 1997. Experimental plots were randomized with 4 replications, only one cultivar being grown per plot and having 5 lines per plot with 10 seedlings per line. Plot area was 2 m^2, one seedling per hill was planted. Rice grown in wetland conditions was the same as conventional paddy rice cultivation. Watering by sprinklers was used to encourage revival of transplanted rice grown in dry land conditions. From then on it was dependent on natural rainfall and received similar management to other dry land crops.

Table 5. Analytical results of data and selected traits in hybrid rice

Traits type	Treatment	Stepwise regression	Direct path -coefficient	Multiple variable regression	Grey correlative analysis	Selected Traits
A	YD	A_1	A_1 (1.1391)	A_1 (r=0.7822**)	$A_5>A_6>A_4>A_3>A_1>A_2$	A_1
	DRC	A_1	A_1 (0.7951)	A_1 (r=0.7951**)	$A_1>A_2>A_3>A_6>A_5>A_4$	
B	YD	B_2	B_2 (0.6467)	B_2 (r=0.6467*)	$B_1>B_5>B_2>B_6>B_7>B_3>B_4>B_8$	
	DRC	B_4	B_4 (0.6860*)	B_4 (r=0.6860*)	$B_4>B_1>B_5>B_2>B_7>B_6>B_3>B_8$	
C	YD	C_3	C_3 (0.9516**)	C_2 (r=0.7996**), C_3 (r=0.9516**)	$C_3>C_2>C_1>C_4$	C_3, C_2
	DRC	C_1, C_2, C_3	C_2 (0.5561), C_3 (0.7290)	C_2 (r=0.8330**) C_3 (r=0.8367**)	$C_3>C_2>C_4>C_1$	
D	YD				$D_7>D_4>D_5>D_6>D_2>D_8>D_3>D_9>D_1$	
	DRC	D_2, D_8	D_2 (0.4750), D_8 (0.7789)	D_8 (r=0.7069*)	$D_9>D_6>D_3>D_1>D_4>D_2>D_8>D_5>D_7$	
E	YD				$E_3>E_1>E_2$	
	DRC				$E_1>E_2>E_3$	
F	YD	F_3	F_3 (-0.7027*)	F_3 (r=-0.7027*)	$F_2>F_1>F_3$	
	DRC	F_2	F_2 (0.5911)		$F_2>F_1>F_3$	
G	YD				$G_1>G_2>G_3$	
	DRC				$G_1>G_2>G_3$	
H	YD	H_3	H_3 (-0.6978*)	H_3 (r=-0.6978*)	$H_2>H_1>H_3$	
	DRC				$H_2>H_1>H_3$	

Notes：1. See Table 3.
2.The basic data of this table in reference of Cheng Fengmei et al., 2001a。

Table 6. Genetic analysis of rice panicle neck diameter

Genetic variance	Panicle neck diameter	Heritability	Panicle neck diameter	Gene effect	Panicle neck diameter
Additive variance (VA)	9.13**	General narrow heritability (h_G^2%)	28.39**	Dominant effect value (Δ)	0.92**
Dominant variance (VD)	8.64	Interactive narrow heritability (h_{GE}^2%)	0.00	Dominance×environment effect value ($Δ_{DE}$)	0.68**
Addition×environment variance (VAE)	0.00	Narrow heritability (h_N^2%)	28.39**		
Dominance×environment variance (VDE)	14.39**				

Notes：The basic data of this table in reference of Cheng Fengmei et al., 2001b。

2.1.2 Measurements

Thirty-nine traits (eight types) and yield per plant (Y) were measured for breeding selection using ten plants in the center of each plot (Cao, 1997*)*. The first type was panicle morphological traits: panicle neck diameter, panicle length, primary branches per panicle, secondary branches per panicle, total branches per panicle, and grain setting density. The second type was plant morphological traits: plant height, effective panicles per plant, total internodes of main stem, reciprocal 1st, 2nd, 3rd, 4th and 5th inter-node lengths. The third type was panicle fructificational traits: total grains per panicle, filled grains per panicle, seed setting rate, and 1000-grain weight. The 4th type was functional leaf traits: flag leaf length, width and area, together with reciprocal 2nd and 3rd leaf length, width and area. The 5th type was growth stage traits: total days to maturation, days from sowing to initial heading, and days from initial heading to maturation. The 6th type was grain morphological traits: grain length, grain width, and grain length/width. The 7th type was rice milling quality traits: brown rice rate, milked rice rate, and head rice rate. The 8th type was rice appearance quality trait: rice length, rice width, and rice length/width. A formula was used to determine leaf area (Y) with

$$Y = 0.72 X + 1.20$$

where X is the product of leaf length and width *(*Kawashima *et al*, 1982).

2.1.3 Selections of rice drought resistance traits

A coefficient of drought resistance was defined as yield in dryland divided by yield in wetland. All traits were analyzed by examining links with coefficients of drought resistance and yield per plant in dry land, using single variable stepwise regression. Data was further examined using path analysis, multiple partial correlation and gray correlative analysis of data processing systems (DPS), that was developed by Zhejiang University (Tang *et al*, 1998). During screening, links with coefficient of drought resistance were considered to be the most important effects. Yield per plant in dry land was considered of secondary importance. Trait analysis was based on single variable stepwise regression, with further consideration by path analysis, multiple partial correlation and gray correlative analysis.

2.2 Genetic analysis of rice panicle neck diameter

2.2.1 Cultivars and experimental design

There were 3 cultivars of paddy rice (♀), 4 cultivars of upland rice (♂) with different drought resistance, and 8 hybrid combinations from the incomplete diallel cross in 1998 (Table 2). Parent cultivars and hybrid combinations were sown in a greenhouse on March 24, 1999 then transplanted in dry land conditions on April 30, 1999. Experimental plots were randomized with 4 replications. One cultivar was grown per plot, with 2 lines per plot having 50 seedlings per line. Each plot area was 4 m^2 with one seedling per hill being planted. Experimental design in 2000 was the same as that of 1999. Watering by sprinklers was used to encourage revival of transplanted rice grown in dry land conditions. From then on it was dependent on natural rainfall and received similar management to other dry land crops.

2.2.2 Measurement and genetic analysis of rice panicle neck diameter

During harvest, panicle neck diameters were measured for ten rice plants, in the center of each plot. Genetic analysis of neck diameters was based on software for the incomplete diallel cross and mixed linear model, according to the additive, dominant and genetic model with genotype-environment interaction. This was proposed by Zhejiang University (Zhu, 1997). The minimum norm quadratic unbiased estimation method (MINQUE) was used to estimate genetic variance components. The adjusted unbiased prediction method (AUP) was used to predict genetic effects and genotype-environmental interaction effects. (Weir, 1990; Zhu, 1997)

3 Results

3.1 Selection of rice drought resistance traits

A very significant positive correlation with the drought resistance coefficient and yield per plant of *indica* rice was found for panicle neck diameter, effective panicles per plant, filled grains per panicle and grains width. For *japonica* rice, the key traits were filled grains per panicle, effective panicles per plant, panicle neck diameter, seed setting rate and flag leaf length. For hybrid rice, panicle neck diameter, seed setting rate and filled grains per panicle had very significant positive correlation to drought resistance coefficient and yield per plant (Tables 3,4 and 5). Comparing the direct path coefficient and multivariate regression correlation coefficient, results showed that panicle neck diameter was not only the common drought resistance trait in *indica*, *japonica* and hybrid rice, but also its effect was the most important. So rice panicle neck diameter could be taken as a dependable trait for rice drought resistance screening, identification and breeding.

3.2 Genetic analysis of rice panicle neck diameter

Table 6 shows that the additive genetic variance of rice panicle neck diameter is very significant while its dominant genetic variance is not, which showed that its variation was chiefly dominated by an additive gene effect. Its genetic variance with dominance-environmental interaction was very significant, which showed that under different environments its heterosis could express greater differences. But there was no interaction between the additive and environmental gene effects, which showed that the additive gene effect was not influenced by the environment and the selected effect would be similar under different environments (Zhu, 1997). Its general narrow heritability was very significant while its interactive narrow heritability was zero, which showed that selection for it under different environments would be effective and consistent.

Additive gene effects sometimes can be improved and fixed by selection while dominant gene effects can't. However, the dominant gene effect is an important factor that produces heterosis and can be utilized by heterosis (Zhu, 1997). Both the general and interactive heterosis were very significant, and the direction of the dominance-environmental interaction was the same as that of the dominant effect. This showed that the dominant gene expressed different levels under different environments. However, the direction of the dominant gene effect did not change and was positive, so its heterosis was positive (Table 6).

4 Discussion

4.1 Selected traits and breeding application to rice drought resistance

Crop drought resistance is a complex, comprehensive behavior expressed by many traits. Crop growth ability and yield under drought stress are generally two dependent traits in identifying drought resistance. Under drought stress, various physiological and biochemical crop processes are greatly influenced and these influences will be expressed by crop morpha and yield, so yield under drought stress can express drought resistance. This viewpoint has practical importance and is supported by many specialists (Ahmadi, 1983; Jing. *et al*, 1999; Liu. *et al*, 1994; Martiniello, 1985; Yanbao, 1990; Zhou, 1996; Zhang *et al*, 1991). So yield under drought stress is a coordinated, comprehensive trait of an organism and an overall reflection of drought. However, yield can't be the sole selection criteria for various reason such low genetic potential. For yield improvement, a cultivar must usually be selected indirectly by some morphological and agronomic traits under drought stress, to breed one with both high yield and strong drought resistance. In the past, much research has shown that some selected traits of different crops were different, even if the same crop under different conditions was also different (De Datta *et al., 1988;* Fukai *et al.,* 1995; Grill *et al.,* 1998*;* Li *et al., 1993*; Li, 1993*;* Tang *et al.* 1987*; Turner,* 1979 and 1997).

Drought resistance traits of *indica, japonica* and hybrid rice have been examined systematically to show that rice panicle neck diameter was the common drought resistance trait. So this could be taken as the dependent trait of rice for drought resistance screening, identification and breeding. A similar result was obtained for spring wheat (Tang, *et al.,* 1987). Effective panicles per plant was the common drought resistance trait in *indica* and *japonica* rice, which is consistent with previous research (Li *et al,* 1993; Li, 1993; Yanbao, 1990), but it wasn't suitable for hybrid rice because of its strong stooling. Seed setting rate was the common drought resistance trait in *japonica* and hybrid rice, again being consistent with other research. Zhao (1987); Zhan (1991) and Chen *et al.* (1993) have shown that a cultivar with a higher seed setting rate has stronger drought resistance. If drought stress occurs, rice in the reproductive growth stage will be especially sensitive to drought and respond by decreasing seed setting rate. Others have considered that reduced total spikelet number was the major reason of reducing yield rather than decreasing seed setting rate (Yan*, et al.,* 1995). All research indicates that, for high yield and strong drought resistance, rice should have a wide diameter of rice panicle neck, many grains and panicles.

4.2 Heredity of rice panicle neck diameter

Only rice drought resistance has an extensive hereditary variation and can be improved through selection. Water resource shortage in China will be alleviated if breeding cultivars, with both high yield resistance and strong drought tolerance, are applied to water saving and dry land cultivation. According to the additive, dominant and genetic model with genotype-environment interaction (Zhu, 1997), results showed that improvement of rice drought resistance had great potential and could serve breeding practice well. Genetic expression of rice panicle neck diameter wasn't influenced by environment, so under different environments, selection on this basis should be effective and consistent. For this trait, both its general and interactive heterosis were very significant and positive. So rice panicle neck diameter is the most dependable selection trait for rice drought resistance and can be extensively applied to rice drought resistance screening, identification and breeding.

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Wheat dehydrin-like gene cloning and its bioinformatics analysis

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Abstract

Measurements on wheat seedlings were made to determine how membrane damage caused by water stress might be reduced. A 483 base pairs (bp) fragment was amplified by reverse transcription PCR and cloned into the expression vector pPET 32a (+). The gene was expressed in the host strain BL21. Western blotting, using a barley dehydrin multiclonal antibody, showed that the A35 kD protein was expressed. Bioinformatics analysis indicated that the protein was homologous with plant dehydrin WZY1-1. It also showed that the protein is rich in Gly (25.6%) and some other hydrophilic amino acids. The protein belongs to basic protein (pI 8.2), containing the dehydrin segments Y, K and S. Topology analysis showed that the protein contains four hydrophilic domains. The first and second transmembrane domains are 20-40 and 104-124 amino acid regions, with hydrophilic values of 1.006 and 0.949, respectively. Secondary structure prediction indicated that this protein mainly consists of a random coil and a few a-helix and has a hydrophilic nature along with heat stability. These features could help to reduce membrane damage caused by water stress, having levels of activity that are regulated through phosphorylation. Phosphorylation prediction suggested that the possible phosphorylation sites were Ser-58, -60 and –66 or Thr-7, -24 and –132 or Tyr-13, -101 and –121, mainly located in the S segment, so the S segment might play an important role in the protein.

Key words: Membrane damage, bioinformatics, protein, phosphorylation.

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1 Introduction

Dehydrin genes are in the group 2 LEA gene family in plants. The structure of the dehydrin gene is amphipathic α-helix domain(K segment) (Close T J. 1996), which is very much conserved in plants. The expression of these genes are related with the stress resistance of plants(Garay-Arroyo A,2000), that is, they can be induced by some stress conditions, such as ABA, desiccation, salting, freezing and so on(Ramanjulu S,2002; Campalans A,1999; Yamaguchi-shinozaki K,2002). Although the dehydrin gene generally exists in dehydrated cells of plants, the biochemical function of it is still unknown.

From the amino acid sequence encoded by these genes(Garnier J,1978), it was concluded that the hydrophilicity of dehydrin may be determined by amphipathic α -helix. The structure and composition of dehydrin was consistent with the properties of “YSK hand”(Close T J, 1996), and the K segment combined harmoniously with other structures (S segment in phosphorylation Serine-rich sequence(Vilardell J,1990) and conserved Y segment in N-terminal). Ceccardi TL, et al.(1994) isolated a maize *Dhn1* protein, from soluble proteins using dehydrin affinity chromatography, with 1-3 tandem repeated Y segment in its N-terminal. The sequence [(V/T)DEYGNP] of the Y segment is similar to some sequences in sites where molecular chaperones and nucleic acid are combined(Martin J,1993). There are some presumed nuclear targeting signal sequences around the conserved regions in dehydrin(Godoy J,1994; Monroy AF,1993), S segment, in which regular protein activity through phosphorylation appears before or after the K segment(Vilardell J,1990;Plana M, 1991). Under stress, many hydrophilic proteins are synthesized, among them dehydrin is the more common composition, which contains 1-10% of the properties of soluble proteins(Close T J. 1996); for instance, there is 1-2% dehydrin in soluble proteins in the mature embryo and seedling under drought conditions(Ceccardi TL, 1994; Close TJ, 1989).

The physical properties of dehydrin imply that it can act as a stabilising agent of nucleic acids or can exist as a macromolecule in the cytoplasm. The interaction between dehydrin and membranes cannot explain the relationship between dehydrin and other substances such as chromosome and nucleic acid; but the current research showed that dehydrin which contains in the cytoplasm has an inner membrane sheath . This kind of structure is consistent with the stable function of membranes(Sales K, 2000).

The activity of dehydrin is similar to the function of protein COR15 induced by cold in Arabidopsis, is that it decreases splitting produced by freezing when lamellar to hexagonal (Second phase) transiting between neighbouring membranes(Artus N N,1996; Webb MS,1996). This indicated that interactions may exist between dehydrin and the hydrophilic surfaces of macro-molecules. The cDNA of Wsc 120 encodes a protein of 390 amino acids in wheat, which shows heat stability and high hydrophilicity. It contains no glycine, phenylalanine and tryptophan, and a composition bias for glycine (26.7%), threonine (16.7%) and histidine (10.8%). In this paper, a Wzy1-1 gene from tender buds in wheat under water stress was cloned and analyzed using the bioinformatics method. The sequence homology of Wzy1-1 to other plants was tested so that its topology could be predicted and, so that some useful information for the Wzy1-1 gene and its effect on the drought resistance of plants could be provided.

2 Material and methods

2.1 Reagents and enzymes

Flash UNIQ-10 column centrifugation total RNA extraction Kit (SK361), T-Vector PCR Product Coning Kit, DNA Gel Extraction Kit, $OligoT_{18}$(G/C/A) (ShangHai Sangon Co Ltd, China); MV Reverse Transcriptase, RNA enzyme inhibiter RNAsin, Taq DNA Polymerase (Promega); T_4 DNA ligase, *Eco*RI, *Hind*III, (TakaRa).

2.2 Material culture and water stress treatment

Seeds of Zhengyin wheat (*Triticum aestivum* L.) were treated with 5% NaClO for about 5min, then soaked with water in a petri-dish for 6 hours. Next they wereallowed to germinate for 3 days (about 1.5 cm length) at 22℃ (60% relative humidity); 0.5 MPa and 0.8 MPa PEG6000 solution was added to two petri-dishes, respectively. After 30 hours, the tender buds of treatment and control were frozen in liquid nitrogen (-70℃) immediately.

2.3 Primer

The primer was designed according to sequence homology as follows: W34887 (sense), 5′ATG GAG TTC CAA GGG CAG CAC G 3′, W34888 (anti-sense), 5′CC GTA GGC TCC ACC AGT CCC AG 3′, W41035 (sense), 5′CAA GAT GGA GCA CGG CCA GG 3′, W42495 (anti-sense) 5′GC TCA GTG CTG TCC GGG CAG 3′, synthesized by Shanghai Sangon Co Ltd, China.

2.4 Total RNA extraction of tender buds in wheat and RT-PCR

The extraction and purification of RNA was carried out according to the RNA extraction kit. The primer for reverse transcription was $OligoT_{18}$ (G/C/A); Using 50 µl PCR reaction system, the amplification program was: 95°C denaturation 1 min in advance, 94°C 30s, 58°C 1min. 72°C 1min, recycle 35 times, 72°C extension 10 min.

2.5 Purification, cloning and sequence of PCR product

The amplified fraction was purified using DNA Gel Extraction Kit, cloned using T-Vector PCR Product Cloning Kit and sequenced by TaKaRa Biotechnology Co Ltd.

2.6 Bioinformatics analysis

The BLAST system was used to determine sequence homology, which analysed basic properties and structure characteristics using VectorNTI software package. The secondary structure of the protein was predicted using PHD software, and its membrane-spanning properties, topology and phosphorylation sites predicted using TopPred 2 software.

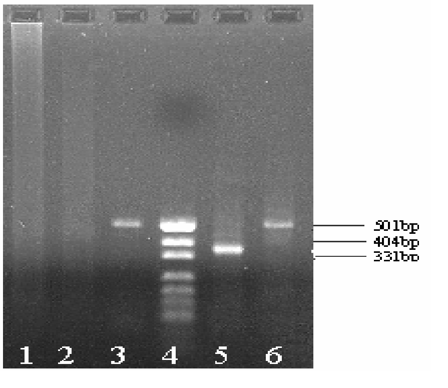

Figure 1 Agarose gels electrophoresis of amplified products of wheat mRNA under stress by RT-PCR
The primers in lane 1, 2, 3 and 6 were W41035+W42496. And the primers in lane 5 were W34887+W34887:
1: H2O; 2: Reverse transcription product of total RNA in tender buds under normal conditions; 3,5: Reverse transcription product of total RNA in tender bud under dehydration stress (-0.8MPa); 6: The same product as 3 and 5, but under –0.5 MPa stress; 4: pUC19 DNA/*Msp*I(*Hpa*II) marker

3 Results and discussion

3.1 Expression, cloning and sequence of dehydrin gene in wheat under water stress

The primers for cloning were designed according to the conserved sequence of dehydrin in wheat. The primers from 5’-terminal were W34887 and W34888, and 3’-terminal W41035

5'>CAAGATGGAGCACGGCCAGGCGACCATCCGCGTCGACGAGTACGGTAACCCGGTTGCCGGACATGGCGTAGGCACCG
GCATGGGCGCGCACGGAGGCAGCGGCACCGGCGCTGCCACTGGTGGGCATTTCCAGCCCACGAGGGAGGAGCACAAGGC
CGGCGGGATCCTGCAGCGCTCCGGCAGCTCGAGCTCCAGCTCGTCTGAGGATGATGGCATGGGCGGGAGGAGGAAGAAG
GGCATCAAGGATAAGATCAAGGAGAAGCTCCCTGGTGGCCACGGTGACCAGCAGCACGCCGATGGCACCTACGGACAGC
AGGGTACTGGCATGGCCGGCACCGGGGCACATGGCTCCGCGGCCACAGGCGGTACCTACGGGCAGCCAGGACACACCGG
AATGACCGGTACTGGGACGCATGTCACCGATGGCGCCGGCGAAAAGAAGGGCATCATGGACAAGATCAAGGAAAAGCTG
CCCGGACAGCACTGAGCA<**3'**

N>MEHGQATIRVDEYGNPVAGHGVGTGMGAHGGSGTGAATGGHFQPTREEHKAGGILQRSGSSSSSSSE
DDGMGGRRKKGIKDKIKEKLPGGHGDQQHADGTYGQQGTGMAGTGAHGSAATGGTYGQPGHTGMTG
TGTHVTDGAGEKKGIMDKIKEKLPGQH<C

Figure 2 The cDNA of dehydrin-like gene (WZY1-1) of seedling under water stress in water and amino acids sequence encoded by it. Underline sequence are Lys-rich and Ser-rich regions.

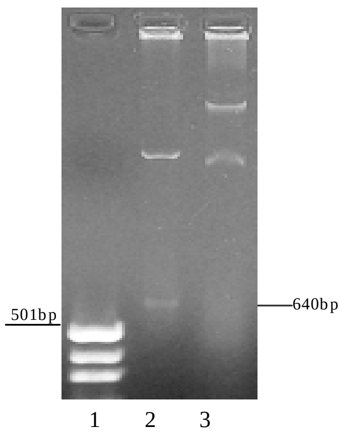

Figure 3 Gel electrophoresis of pET32a(+)-wzy1-1 recombinant plasmid digested by two enzymes

1. Marker (**λ**-*Eco*T 14 I digest);
2. The product of plasmid digested by *Eco*RI-*Hind*III

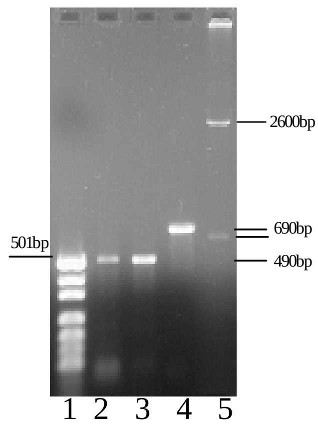

Figure 4 Gel electrophoresis of pET32a(+)-wzy1-1 recombinant plasmid by PCR.

1. Marker (DL 2000)
2. Product of plasmid digested by *Eco*RI-*Hind*III
3. Product by PCR, Plasmid as template and w41035-w42495 as primer
4. Plasmid

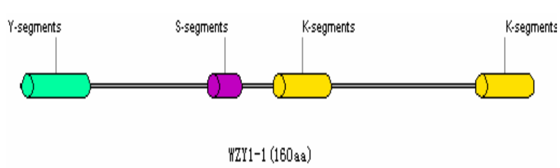

Figure 5 "YSK2" model of Wzy1-1

and W42495. The results of PCR amplification showed that 500 bp and 350 bp fractions were obtained from tender buds in wheat under water stress, using two primers of dehydrin. The same sized fraction was produced under different water stress (-0.8MPa, -0.5 MPa) using the same primer, but it did not appear for tender buds in wheat under normal conditions, indicating that there was water stress induced expression of some specific genes in wheat. Because specific primers were designed according to the cDNA of dehydrin, the fraction was closely related with drought resistance, and it may represent a dehydrin-like gene in tender buds of wheat.

The PCR products were purified corresponding to the third lane in Figure 1 using DNA Gel Extraction Kit, then cloned to the pUCM-T vector so that the length of this gene was 483 bp (Wzy1-1, login No. AF453444 in GeneBank).

3.2 Homology comparison of protein encoded by Wzy1-1 cDNA

cDNA fractions of dehydrin-like fractions in different development periods and parts of wheat were chosen from the EST bank, such as

BE499002 P12253), BE604078 (S11847) , BF428605 (P12948) , BF478341 (P12950) and BF292988 (S19130), then compared and analyzed sequences between them and Wzy1-1 clone. Results showed that there is a high sequence homology between the isolated fraction and EST fractions of other similar dehydrins.

In SwissProt data bank, some dehydrins with known functions, (such as RAB-17 in maize, DHN1 in pea, DHN3 in barley, DHN4 in barley, RAB 15 induced by root ABA in wheat, RAB21 and RAB 16C in rice) were chosen. These were then compared with the sequence of protein encoded by Wzy1-1 and analyzed using Vector NT1 software. We can conclude from the results that the isolated fractions typically, have Y, K and S segments, which is the basic property of dehydrin. The structure of the protein encoded by Wzy1-1 gene was given (Figure 5) according to the gene prediction of dehydrin structure model previously.

3.3 The bioinformatics analysis of protein encoded by Wzy1-1 cDNA

3.3.1 The composition and pI prediction of amino acids of Wzy1-1

Using the bioinformatics analysis software NTI and PHD, the composition molecular mass, pI of amino acids encoded by Wzy1-1 gene of the dehydrin-like protein in wheat were deduced, (see Table 1.)

From Table 1, we can conclude that the Wzy1-1 protein is one basic protein, because it is rich in Gly and some hydrophilic amino acids, such as Thr, Lys and Ser, but has less hydrophobic amino acids.

3.3.2. The secondary structure prediction of Wzy1-1 protein

Using the secondary structure of protein prediction software PHD provided by the bioinformatics center at Columbia University, we inferred the structure of the dehydrin-like protein encoded by Wzy1-1 in wheat. Results implied that this structure was mainly made up of random coil and few amphipathic α-helix, with extension state, high hydrophilicity and heat stability. Some authors thought that the action between dehydrin and the cell membrane may reduce membrane damage induced by stress; others thought that dehydrin could help protein fold correctly as a kind of molecular chaperone. Martin J et al(1993) research found that the Y segment of dehydrin in wheat is similar to nucleic acid combined sites of molecular chaperones in plants or bacteria. Godoy J (1994) and Monroy AF(1993) also inferred that there is nucleotide targeting signal sequence among conserve regions of dehydrin polypeptide.

```
             ....,....1....,....2....,....3....,....4....,....5....,....6
     AA  |MEHGQATNRVDEYGNPVAGHGVGTGMGAHGGSGTGAATGGHFQPTREEHKAGGILQRSGS|
     PHD |                                  EEEEE  |
     Rel |999997653333688876677765453557466666778767887535467725887349|
 detail:
     prH-|000000000123110001111000111111211101101110001100000000000000
     prE-|000001123221000011111112212120001111110011000132211137888630
     prL-|989998765555788877777776675668677777778778888766677752011369
 subset: SUB |LLLLLLLL....LLLLLLLLLLLL.L.LLL.LLLLLLLLLLLLLLL.L.LLL.EEEE..L|

      ....,....7....,....8....,....9....,....10...,....11...,....1
     AA  |SSSSSSEDDGMGGRRKKGIKDKIKEKLPGGHGDQQHADGTYGQQGTGMAGTGAHGSAATG|
     PHD |              HHHHHH                            |
     Rel |886578656889856553211344227999996766657877656668764557765577|
 detail:
     prH-|000000122000121222344556530000002111121111122111113221122111
     prE-|011210000000011111123221121000000000000000000000000000000000
     prL-|887778777888867665431122347999987777777878767778776777776777
 subset: SUB |LLLLLLLLLLLLLLLLL.........LLLLLLLLLLLLLLLLLLLLLLLLL.LLLLLLLLL|

       2...,....13...,....14...,....15...,....16
     AA  |GTYGQPGHTGMTGTGTHVTDGAGEKKGIMDKIKEKLPGQH|
     PHD |                  HHHHHHHH    |
     Rel |6556566435666334586798553212236776278999
 detail:
     prH-|1111211111111221101101223324557787510000
     prE-|0121000222111112200000000133321000000000
     prL-|7667777556777555687888765431111112478999
subset: SUB |LLLLLLL..LLLL...LLLLLLLL......HHHH.LLLLL|
```

SecStr	H	E	L
% Predicted	8.8	3.1	88.1

Figure 6 Predicted secondary structure of dehydrin Wzy1-1 cloned in wheat

H: Helix , E: Fold, L: loop AA: Amino acid PHD: Predicted model, Rel: Credible index (0-9), PrH: Possibility of helix, PrE: Possibility of fold, PrL: Possibility of loop, SuB: Sub-type, “.”: The secondary structure in these regions are not predictable.

删除的内容: o

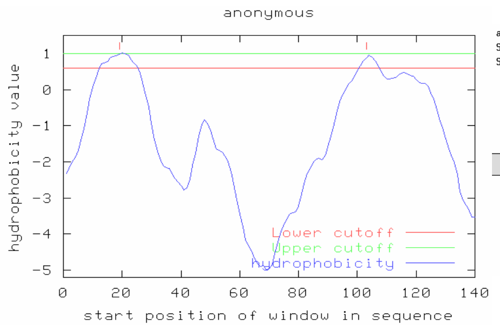

Figure 7 The hydrophilicity and membrane-spanning regions in protein

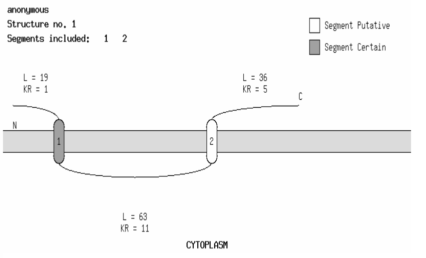

Figure 8 The topology in protein N: N-terminal, C: C-terminal, L: the number of amino acid in different structure. 1,2 represent membrane-spanning region; in front of 1 and behind 2 is CYT loop; between them is EXT loop

```
160 DEHYDRIN
MEHGQATNRVDEYGNPVAGHGVGTGMGAHGGSGTGAATGGHFQPTREEHKAGGILQRSGSSSSSSSEDDGMGGRRKKGIK    80
DKIKEKLPGGHGDQQHADGTYGQQGTGMAGTGAHGSAATGGTYGQPGHTGMTGTGTHVTDGAGEKKGIMDKIKEKLPGQH   160
......T.....Y..........T.................................S.SSSSSSS..............    80
....................Y.....................Y........T............................   160

Phosphorylation sites predicted:     Ser: 8    Thr: 3    Tyr: 3
```

Fig. 9 Predicted phosphorylation site of Wzy1-1

3.3.3. Membrane-spanning analysis of Wzy1-1

Using the protein of membrane-spanning prediction software TopPred 2 provided by the bioinformatics center in Columbia University, the results were obtained as in Figure7.

3.3.4 Analysis of hydrophilic regions and membrane-spanning regions in the protein

From Figure 7, we can conclude that there are four hydrophilic regions in Wzy1-1, among them two regions are particularly apparent: one lies in the 20th amino acid or so, the other lies in the 105th amino acid or so. Through using the software analysis, we found that two membrane-spanning regions may exist in Wzy1-1 dehydrin in wheat: the first from 20th to 40th amino acid in N-terminal (hydrophilic value 1.006); the second from 104th to 124th amino acid in N-terminal, (hydrophilic value 0.949). The existence of this kind of membrane-spanning region can explain why the action between dehydrin and the membrane can stabilize membrane structure and protect the cell under cold, drought or other stress conditions.

3.3.5 The analysis of topology

From Figure 8, we can infer that the protein sequence encoded by Wzy1-1 gene, from 1st to 19th amino acid in N-terminal, is a coil; then a membrane-spanning region; from 41st to 103rd amino acid, is a random coil. From 104th to 124th amino acid, another membrane-spanning region, the remaining part is a coil. This kind of structure determines the high stability of this protein, which is why it can dissolve in water even under high temperatures.

3.4 The prediction of phosphorylation sites in Wzy1-1

The results showed that the phosphorylation sites may be 58,60-66 sites for Ser; for Thr 7,24,132 site and for Tyr is 13,101 and 123 sites. We can find that phosphorylation sites are mainly found in the S segment, which demonstrates that the S segment plays a important role in dehydrin and Ser phosphorylation can regulate the role of dehydrin in cell.

From above, it was concluded that the dehydrin gene (Wzy1-1), cloned in our experiments under water stress in wheat, exhibited a high sequence homology to different dehydrin genes in different plants, but the gene sequence obtained from different dehydrins showed few differences. The protein encoded by this gene had the typical properties of dehydrin protein, for instance, 25% Gly, a basic protein with pI 8.2, a Ser-rich motif (SSSSSS), and two Lys-rich regions (KKGIKDKIKEKLPG). All these showed that this protein is a kind of SK2 dehydrin(Close, TJ, 1997). The topology analysis of the protein sequence encoded by Wzy1-1 gene showed that except for the two membrane-spanning regions, other parts are all made up of random coil structures. The phosphorylation sites (Ser, Thr, Tyr) were focused on the inner and outer sides of membrane, which can react with liposome membranes under stress. All this can provide useful information for the research of the secondary structure formation of dehydrin(Sales K,2000; Zhang L,2000), and of protein folding. Furthermore, because dehydrin is made up of only 1-2% of soluble protein, it can act as a molecular chaperone(Chaudhary S,1996**;**Bray E A. 1993; Ingram J,1996; Kermode AR. 1997).

Acknowledgements

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Crop water sensitivity changes and optimum water supply schedule in the semi-arid Loess Plateau of China

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Abstract

This study was conducted to determine crop water sensitivity during growth stages, and puts forward an optimum water supply schedule for crops in the Loess Plateau region. Effects of water use on productivity during growth of winter wheat [*Triticum aestivum L*] and spring corn [*Zea mays*] were investigated at Changwu Agricultural Experiment Station of the Chinese Academy of Sciences. Water sensitivity of wheat was calculated using the Jensen model. Results indicated that the Jensen model's water sensitivity index (λ) reaches it's highest value during the seedling-vegetative phase, it's second highest value during booting to heading, and third highest during heading to milk phase. So the relative importance of irrigation corresponds with these results. Optimum irrigation for winter wheat should be maintained before winter and during booting to heading stage. For corn, λ reaches it's highest value during booting to heading and it's second highest value during heading to milk phase, indicating the relative importance of irrigation applications.

Key words: Crop water sensitivity; productivity; water supply strategy; winter wheat; and spring corn.

1 Introduction

About 52% of cropland suffers from drought stress in China. Critical problems include how to use the limited water resources and decide which irrigation has the highest water use efficiency (WUE) (Blank, 1975, Obreza and Rhoads, 1988; Sadler, Bauer and Millen, 2000). This is especially so in the semi-arid region of the Loess in China (Shan, 1996; Kang and Dang, 1987). Crop water sensitivity during different growth stages is the basis of limited-water irrigation and limited-water resource optimization. The water sensitivity of winter wheat and spring corn during different growth stages is not well known for the semi-arid Loess Plateau in China. The multiplicative model of yield response to irrigation is more sensitive and more practical than the additive model in China (Kang and Dang, 1987). Hence, the Jensen's multiplicative model was used in this study. The model was employed to obtain a crop yield and water consumption relationship. Taking the relative evapotranspiration of each growth stage (i) as the independent variable, the effects of evapotranspiration in each growth stage (i) on crop yield can be expressed as:

$$\frac{Y_a}{Y_m} = \prod_{i=1}^{n} \left(\frac{ET_a}{ET_m}\right)_i^{\lambda_i} \qquad (1)$$

where Ya is actual crop yield, Ym is maximum crop yield if sufficient water is provided, ETa is actual evapotranspiration, ETm is maximum evapotranspiration, i=1,2,3…n is the ordinal number of growth stage, and λi is the crop yield sensitivity index at each growth stage.

For the Jensen model, large values of λi indicate large reductions in crop yield (Jensen, 1986). This study was conducted to determine crop water sensitivity index values during the growing season, and to put forward the optimum water supply schedule for crops on the Loess Plateau region.

2 Materials and methods

2.1 Experiment site

During 1995-1997, field experiments were conducted in rain-sheltered field plots, at the Changwu Agricultural Experiment Station of the Chinese Academy of Sciences in the southern semi-arid Loess Plateau (longitude 107°40'30"E, latitude 35°12'0"N, elevation 1200m). Mean temperature is 9.1℃ with a mean annual precipitation of 584mm. The climate is semi-humid but significant soil moisture deficits are frequent because there is a large variation in annual rainfall from 370 to 700mm. Rainfall is mainly from July to September. This non-uniform rainfall, combined with high variability from year to year, causes frequent droughts and lower crop yields. Agricultural production mainly depends on rainfall; it is a typical dry-land farming area. The parent material of the local Heilu soil is a deep moderately loamy Malan loessial soil. This is a good dry-land soil due to its porosity and large water holding capacity.

2.2 Treatments

Three soil water levels were established by differential watering of plots growing winter wheat (variety Changwu-134) and spring corn (variety Danyu-13), during different growth stages. The levels were low (D) with a relative water content of 45-55%, medium (Z) with relative water content of 60-70% and high (G) with relative water content at 75-85%. Growth of winter wheat was divided into five stages. The first seedling stage was from early October to early March; the second vegetative stage extends from early March to early April with a third jointing stage covering early April to early May. The fourth heading stage begins from early May until early June with a fifth stage to cover the milk phase. Spring corn was divided into a jointing phase from mid-June to mid-July a second stage before heading from mid-July to early August and a third flowering stage from early to late August. The fourth milk phase covered late August to late September. There were 15 winter wheat and corn treatments, with three replications. Chemical fertilizers were applied to the soil surface before ploughing, at rates of 138 kg N/ha and 112.5 kg P2O5 /ha. Time domain reflectometry (TDR) was used to measure soil water content at about 15-day intervals. Plots were watered regularly according to desired soil water content. Crop evapotranspiration (water consumption) was calculated according to irrigation quantities and soil water content measured at each growth stage. At maturity, $6m^2$ of wheat and corn was harvested in each plot, to determine crop yield. Evapotranspiration under sufficient water (GGGGG) is taken as maximum evapotranspiration (ETm), and crop yield in treatment (GGGG) is considered as maximum yield (Ym). Results were compared based on least squares differences (L.S.D). The Jensen model was used to calculate crop water sensitivity for different growth stages.

3 Results

3.1 Water sensitivity index in different growth stages

Using the Jensen model, water sensitivity indexes of winter wheat and spring corn were found as table 1. According to Jensen's multiplicative model, higher values of λ i indicate higher sensitivity of crop to water deficits and larger reductions of crop yield. Table 1 shows that the stage from seedling to vegetative (stage 1) was the most sensitive to water deficit, next sensitive stage was the jointing (stage 3) for winter wheat. Stage 2 (before heading) and stage 3 (flowering to milking) were the crucial stage to water deficit for spring corn.

3.2 Yield and water use efficiency of crops under limited water supply

Table 2 shows that Z and G water treatment during earlier stages, and D treatment during later stage were beneficial to getting higher yield and higher WUE for winter wheat.

There was positive relationship between grain yield and irrigation volume (r=0.8215**, n = 15), and also a positive relationship between grain yield and irrigation volume during seedling stage (r=0.7374**, n = 15) of winter wheat. Irrigation during the seedling stage was important to promote early vigor, to live through winter safely and gain high yield. This conclusion was not the same as results obtained by (Shan, 1996). His results showed that there were two critical water sensitive stages for winter wheat, the first one was pollen-forming stage, and the second was the beginning of milk stage to milk mature stage. There may have been two reasons for this. The first is that the experimental treatments were different. This experiment began to conduct water before winter when the seedling was complete, and soil water treatment was divided into five stages during the growth period. However, the Shan's study began water treatment when the seedling was complete and strong enough, and the period and degree of water treatment was different. The second reason is that this study was conducted in highland and gully regions in the semi-arid Loess Plateau, which belongs to the typical dry farmland, and drought was the main obstacle of crop production. It was especially importance for winter wheat to have early vigor, growth strongly, live through winter safely and get high yield (Liang and Richard, 1999). Table 3 indicated that corn yield was lowest under four stages water stress, and lower under three stages than two stages water stress. This means that the more serious water stress was, or the more water stress stages were, the lower the grain yield of corn was. The effect of water stress on yield was more important after jointing and from heading to milk stage than from the milk to mature stage.

Table 1 Water sensitivity index ($?_i$) of winter wheat and spring corn in different stages

$?_i$	Stage1	Stage2	Stage3	Stage4	Stage5
Winter wheat	0.253	0.024	0.170	0.070	0.014
Spring corn	0.0936	0.2097	0.1989	0.0261	

Table 2 Effects of irrigation on yield (kg/ha) and water use efficiency (WUE) of winter wheat during 1996-1997[a]

Treatment	Yield* (kg/ha)	irrigation (mm)	WU (mm)	WUE (kg/ha. mm)
D-D-D-D-D	2025 a	97	213	9.5
D-D-D-G-Z	3180 b	187	300	10.6
D-G-Z-D-D	3375 bc	167	278	12.1
D-Z-D-D-Z	3405 bc	269	385	8.8
Z-D-D-Z-G	3570 c	241	359	9.9
G-D-Z-G-Z	3705 cd	183	291	12.7
Z-Z-Z-Z-Z	3870 cd	241	338	11.5
Z-G-D-D-G	4020 d	281	387	10.4
Z-G-Z-D-D	4080 d	216	323	12.6
G-G-D-Z-D	4230 de	268	389	10.9
D-Z-G-Z-G	4245 de	302	403	10.5
G-G-G-G-G	4500 e	408	519	8.7
Z-Z-G-G-D	4500 e	302	420	10.7
G-Z-G-D-Z	4575 e	257	383	11.9
G-Z-G-G-D	4920 f	306	390	12.6

[a] Each value is the mean of three measurements from separate plots.

Values within a column followed by the same letter do not differ significantly ($p<0.05$) according to a protected L.S.D test.

*$L.S.D_{0.05}$=305, $L.S.D_{0.01}$=420

WU, water used; WUE, water use efficiency; D, low soil moisture with soil relative water content at 45%-55%; Z, middle soil moisture with soil relative water content at 60%-70%; G, high soil moisture with soil relative water content at 75%-85%

Table 3 Effects of irrigation volume on yield (kg/ha) and water use efficiency (WUE) of corn in 1995-1996

Treat.	Yield* (kg/ha)	irrigation (mm)	WU (mm)	WUE (kg/ha. mm)
Z-D-D-D	5216 b	186	286	18.2
Z-D-D-Z	5643 b	174	256	22.4
D-Z-Z-Z	6219 c	254	342	18.2
Z-D-Z-Z	6228 c	270	360	17.3
Z-Z-D-Z	6572 cd	335	416	15.8
Z-Z-Z-D	6905 d	220	322	21.4
Z-Z-Z-G	7497 e	259	357	21.0
Z-G-Z-Z	7497 e	277	370	20.3
G-Z-Z-Z	7641 e	383	473	16.2
Z-Z-Z-Z	7991 ef	277	370	21.6
Z-Z-G-Z	8244 f	391	515	16.1
Z-G-G-G	8945 g	492	564	15.9
G-G-G-G	9371 g	554	661	14.2
Z-G-G-Z	10062 h	447	526	19.1

[a] Each value is the mean of three measurements from separate plots.

Values within a column followed by the same letter do not differ significantly ($p<0.05$) according to a protected L.S.D test.

*$L.S.D_{0.05}$=539， $L.S.D_{0.01}$=658

WU, water used; WUE, water use efficiency; D, low soil moisture with soil relative water content at 45%-55%; Z, middle soil moisture with soil relative water content at 60%-70%; G, high soil moisture with soil relative water content at 75%-85%

The significant positive relationship was found between grain yield and irrigation volume (r=0.8831**, n=15) in spring corn.

4 Discussion

The results showed that there was an obvious relationship between the irrigation volume and yield, and there was also some difference in the importance of irrigation volume in different growth stages for wheat yield. The irrigation during seedling stage before March was the most important followed by irrigation during jointing to heading stage. The reason was that seedling stage was the crucial of root elongation and development. Through analyzing sensitivity of photosynthetic to soil water deficit in different growth stages (Liang and Kang, 1999), it was discovered that the sensitivity of photosynthetic ratio to soil water deficit was the highest during jointing to heading stage. If the water stress occurred after the jointing or heading stage, the yield would be affected greatly. So when supplementary irrigation is arranged, the seedling stage and the jointing to heading stages should be considered first. If soil water content during seedling stage meets the requirements to form strong seedling, jointing to heading stage should be given precedence to irrigation over all others.

There were great differences in the water sensitivity index of spring corn among growth stages. If the water stress occurred after the jointing or heading stages, the yield would be affected greatly. Hence, if irrigation is arranged, heading stages should be given priority, followed by the flowering stage.

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Niche indices related to water fertiliser interactions affecting spring wheat yields in semi-arid farmlands

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Abstract

Typical seasonal soil water conditions, fertilizer application and use of plastic film were all found to influence niche indices for dry-land farming. A niche index can measure of suitability of crops to particular environmental conditions. A mathematical model was developed to represent water-fertilizer interactions. Under abundant, moderate, natural and arid water supply, mean spring wheat yields were 2770, 1890, 2070 and 1175 kg ha^{-1}, respectively. Values of niche were 0.657, 0.531, 0.569 and 0.454, respectively. The maximum niche index was 0.813, gained under abundant water and fertilizer conditions, with a maximum grain yield of 4030 kg ha^{-1}. Results provide support for regulating fertilizer use in relation to soil water resources of semi-arid farmland.

Key words: Spring wheat; water; niche-fitness; yield; water-saving of semi-arid regions.

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1 Introduction

On the semi-arid Loess Plateau of China, precipitation and irrigation water are limited during the growth period of spring wheat. Application of fertilizer and limited quantities of irrigation water is important for crop growth and formation of grain yield (Li, et al, 2001a, 2001b; Li and Lin, 1997, 1998a). In the past, the main management strategy in dry-land agriculture has been to enhance water uptake from the soil profile by applying fertilizer. Although fertilization is important for maintaining productivity in dry-land agriculture, the role of fertilizer application seems to be limited because of the shortage of usable water. The key to increasing crop yield lies, to a large extent, in increasing usable water (Li, et al, 2001a).

For many years, the government has addressed the water shortage problem in dry-land areas by investing in “water-saving” agricultural projects. These projects should develop new technology for the collection and storage of water that can be used to irrigate crops in the following season. An important problem is how to use the collected water in a way that maximizes water use efficiency and grain yield. Over the last decades, a number of studies have been conducted on regulation of water and fertilizers in arid and semi-arid regions to increase crop yield (Aase, et al., 2000; Blum, et al, 1991, 1993; Clarke, et al., 1990; De Juan, et al., 1999; Egghball, et al., 1991; Feng-Min Li, et al., 2001a, 2001b; Fernaudez, et al, 1996; Li, 1998; Hussain, et al., 1995; Katerji, et al., 1998; Li et al., 1997, 1998a, 1998b; Mackay, et al., 1986; Persand, et al., 1999; Recio, et al., 1999; Stephens, et al., 1999). The objective of our paper is to present an alternative approach to study of crop management systems in semi-arid areas. Specifically, niche theory (Li and Lin, 1997) is presented with a mathematical model for evaluating niche-fittness of crops grown under different management strategies.

2 Niche-fitness model of spring wheat

2.1 Modeling of niche-fitness of spring wheat

All kinds of ecological factors related to the growth of crops are regarded as resource factors. An apparent supply-demand relationship exists between these resource factors and crop growth. The niche theory (Grinnel, 1924; Hutchinson, 1957; Levins, 1968; MacArther, et al., 1967; May, 1974; McNaughton and Wolf, 1970; Odling-Smee, et al., 1996) reveals this supply-demand relationship in the aspect of using a multi-dimensional resource spectrum. Our objective is to introduce niche theory into the research of crop growth systems. By taking spring wheat, a main crop in the semi-arid areas of China as the object, we extend Hutchinson’s (1957) niche concept of an n-dimensional super-volume. The degree of niche-fitness refers to the closeness between the actual resource state of the crop and the optimum niche (Li and Lin, 1997), from which a mathematical model is established.

Consider spring wheat as the study object and take the following ecological factors (which are closely related to the growth period of spring wheat): sunlight, temperature, soil water content and soil nutrition, into consideration. The quantitative indexes of these factors can be marked as x_1, x_2, ··· , x_n. The observed values of each group under experimental conditions can be noted as $X_t= (x_{t1}, x_{t2}, \cdots, x_{tn})$. X_t stands for an actual resource state of the crop under a certain ecological condition. It is a point in the n-dimensional resource space. Biologically, a crop will show certain adaptation to variables of each ecological factor, so the optimum value of factor *i* can be marked as x_{ai} $(i=1, 2, \cdots, n)$. x_{ai} can be obtained from experimental observation. $X_a = (x_{a1}, x_{a2}, \cdots, x_{an})$ is composed of the total of x_{ai}. X_a is the optimum niche of the crop. If n-dimensional niche region of the crop is noted as E^n, then we have $X_t?E^n$, $X_a?E^n$. The formula for the crop's niche-fitness is

$$F = ?(X_a, X_t),\ X_t?E^n, X_a?E^n \qquad (1)$$

In this formula, the niche-fitness value F ? [0,1], ? is the measurement of the distance between two vectors: $X_a = (x_{a1}, x_{a2}, \cdots, x_{an})$ and $X_t= (x_{t1}, x_{t2}, \cdots, x_{tn})$. The niche-fitness value means the fitness degree of the crop in actual state. The larger the value of F, the higher the fitness degree is. Normally, when the actual resource state may change on a large scale, the F value needs a wide distribution on the subset [0, 1]. However, the often used closeness formula (Feinsinger, 1981) needs modification. In the following section, we will give a new model of F value on the [0, 1].

In order to establish a new model, suppose there are *m* kinds of crop experiments. The related observation results are as follows:

No.	Indexes			
	x_1	x_2	…	x_n
1	x_{11}	x_{12}	…	x_{1n}
2	x_{21}	x_{22}	…	x_{2n}
…	…	…	…	…
i	x_{i1}	x_{i2}	…	x_{in}
…	…	…	…	…
m	x_{m1}	x_{m2}	…	x_{mn}
m+1	x_{a1}	x_{a2}	…	x_{an}

where $a=m+1$; line $i(x_{i1}, x_{i2}, \cdots, x_{in})$ in the table stands for observation values under experiment *i*, which is an actual resource state in E^n. The optimum niche obtained from experimental data can be noted as $X_a = (x_{a1}, x_{a2}, \cdots, x_{an})$. The data are standardized according to the following formulas:

$$x'_{ij} ? x_{ij} \Big/ \frac{1}{n} \overset{m?1}{\underset{i?1}{?}} x_{ij}\ ,\ i=1,2,\cdots,m;\ j=1,2,\cdots,n. \qquad (2)$$

$$x'_{aj} ? x_{aj} \Big/ \frac{1}{n} \overset{m?1}{\underset{i?1}{?}} x_{ij}\ ,j=1,2,\cdots,n. \qquad (3)$$

The absolute difference is repeatedly calculated between x'_{ij} and x'_{aj},

$$?_{ij}\ ?|x'_{ij} ? x'_{aj}|\quad i=1,2,\cdots,m;\ j=1,2,\cdots,n. \qquad (4)$$

$$?_{\min}\ ?\ \min\{?_{ij}\}\ ?\ \min\{|x'_{ij} ? x'_{aj}|\} \qquad (5)$$

$$?_{\max}\ ?\ \max\{?_{ij}\}\ ?\ \max\{|x'_{ij} ? x'_{aj}|\} \qquad (6)$$

The corresponding model of niche-fitness is established:

$$F_i\ ?\ \frac{1}{n}\overset{n}{\underset{j?1}{?}} \frac{\min\{|x'_{ij} ? x'_{aj}|\}\ ?\ ?\max\{|x'_{ij} ? x'_{aj}|\}}{|x'_{ij} ? x'_{aj}|\ ?\ ?\max\{|x'_{ij} ? x'_{aj}|\}}$$

$$,\ i=1,2,\cdots,m. \qquad (7)$$

In Equation (7), F_i stands for the crop's niche-fitness value under the experiment *i*. F_i ? [0, 1], ? is the parameter of the model, ? ? [0, 1]. In order to have a reasonable distribution of F_i , suppose $?_{ij}\ ?\ \overline{?_{ij}}$, then $F_i =0.5$, i.e.

$$\overline{?_{ij}}\ ?\ \frac{1}{mn}\overset{m}{\underset{i?1}{?}}\overset{n}{\underset{j?1}{?}} ?_{ij}\ ,\ \frac{?_{\min}\ ?\ ??_{\max}}{\overline{?_{ij}}\ ?\ ??_{\max}}\ ?\ 0.5 \qquad (8)$$

? can be estimated from this formula.

2.2 Sample calculation and analysis

The experiment is done with timed observation at fixed positions. The main variables are as follows:

x_1= the medial temperature in soil of 0-30 cm;

x_2= the medial sub aerial temperature of 0-50 cm;

x_3= the rate of water content in the soil layer of 0-30 cm;

x_4= the rate of water content in the soil layer of 30-60 cm;

x_5= the amount of quick-acting nitrogen manure in the soil;

x_6= the amount of quick-acting phosphate manure in the soil.

The observation results of each index are shown in Table 1. By standardizing all data in Table 1 according to Equation (2) and (3) and using Equations (4), (5), (6) and (8), we can obtain $d_{\min}$= 0.0393, $d_{\max}$= 0.4946, and a= 0.2862. The specific calculation formula is

$$F_i\ ?\ \frac{1}{6}\overset{6}{\underset{j?1}{?}} \frac{0.1809}{|x'_{ij} ? x'_{aj}|\ ?0.1416}\quad (i=1,2,\cdots,15) \qquad (9)$$

The niche-fitness values are shown in Table 2 according to Equation (9) and standardized values.

In order to explain the point, Feinsinger's (1981) percentage similarity formulas are tested and verified as follows:

$$PS_i\ ?\ 1\ ?\ 0.5\overset{n}{\underset{=1}{?}}|p_i\ ?\ q_i|?\overset{n}{\underset{=1}{?_j}}\min_j\{p_i, q_i\}$$

$$,\ (i=1,2,\cdots,m;\ n=6), \qquad (10)$$

here, $P_{ij} ? x'_{ij} / \overset{6}{\underset{j?1}{?}} x'_{ij},\quad q_{ij} ? x'_{aj} / \overset{6}{\underset{j?1}{?}} x'_{aj}.$ (11)

.

The calculation results are shown in Table 2.

Table 1. Observed values of ecological factors in the experiments[a]

No.	Water	Fertility	Index of ecological factors					
			X_1 (°C)	X_2 (°C)	X_3 (%)	X_4 (%)	X_5 (mg・kg^{-1})	X_6 (mg・kg^{-1})
1	Full water	Zero	18.9	18.9	14.1	13.2	51.7	15.8
2		Low	19.3	19.4	14.1	13.5	79.2	19.9
3		High	19.9	19.8	16.2	15.3	89.2	22.6
4	Moderate water	Zero	19.3	19.1	11.6	9.8	52.8	15.5
5		Low	19.1	19.2	12.0	10.8	63.6	16.7
6		High	19.3	19.3	13.5	11.4	78.8	19.7
7	Arid	Zero	18.7	18.4	9.3	7.6	53.4	14.4
8		Low	18.9	18.7	8.7	8.4	66.8	16.1
9		High	18.3	17.7	8.9	7.7	79.9	18.7
10	Natural rain	No P.F.[b] covering	19.2	18.7	12.1	10.4	58.3	15.5
11		P.F. covering (30days)	20.5	19.6	14.7	12.9	58.8	16.8
12		P.F. covering (60days)	21.0	21.0	14.4	12.9	59.5	17.2
13		The most suitable values	22.0	22.1	18.2	16.8	96.4	24.6

[a]The data are mean values of three samples. [b]P.F. is plastic film.

Table 2. Niche-fitness values and grain yield of spring wheat

Number	F_i	*PS*	Grain yield (kg ha^{-1})
1	0.522	0.934	1740
2	0.637	0.984	2540
3	0.813	0.995	4030
4	0.479	0.911	1480
5	0.506	0.934	1710
6	0.607	0.972	2470
7	0.423	0.887	960
8	0.455	0.903	1210
9	0.483	0.895	1360
10	0.485	0.927	1490
11	0.576	0.939	2560
12	0.645	0.934	2170

Table 3. Values of leaf area index[a] (LAI) of spring wheat

Fertility	Water			
	Full water	Moderate water	Arid	Natural rainfall[b]
Zero	3.35a	3.53a	3.70a	3.91a
Low	4.89b	4.08b	4.64b	6.70c
High	7.75c	5.88c	5.22c	5.68b
Mean	5.33b	4.50b	4.52bc	5.43b

[a]Means followed by different letters within rows were significantly different at p=0.05.
[b]The controlled condition of water: full water, 510 mm; moderate water, 400 mm; arid, 260 mm; natural precipitation, 416.7 mm.[c] P.F. is plastic film.

2.3 Statistical analysis of relationship between yield and niche-fitness of spring wheat

According to the results observed from experiment on the regulation of water and fertilizer in Table 3 and the corresponding values of niche-fitness in Table 2, we adopted the linear regression $y=a+bx$ and obtained the following formula:

$$y= -2148.8+7466.4\,\hat{x}\,, (R^2=0.97, F=159.4), \quad (12)$$

where y represents the yield of spring wheat and $\hat{x}$ is the value of fitness F_i.

In addition, we can obtain the regression relationship between the yield and the value of fitness PS_i as follows:

$$y= -18604.9+22026.1\,\hat{x}\,, (R^2=0.81, F=42.7)\,, \quad (13)$$

where y represents the yield of spring wheat and $\hat{x}$ is the value of fitness PS_i.

The two formulas above depict the linear relationship between the yield of spring wheat and its fitness; both passed the significance test ($p=0.05$). In Table 2, we see that the varied ranges of niche-fitness F_i and PS_i are 0.423= F_i =0.813 and 0.887= PS_i =0.995 respectively. Obviously, the varied range of F_i is more extensive than that of PS_i, hence F_i better reflects the varied differences of fitness under different water and fertilizer conditions and the influence of fitness on the yield of spring wheat.

3 Materials and methods

An experiment was carried out on horizontally terraced fields in central Gansu Province, China. The elevation is 2010m. The soil is loess with a field water holding capacity of about 22%. The fields were divided into 4×4m plots. An improved, drought resistant spring wheat, No. 24, was sown (210kg·ha^{-1}) on the 20th of March each year and harvested at the end of July.

The experimental treatments included four different levels of water supply: arid, natural precipitation, moderate water, and full water. We used mobile rain sheds to keep out precipitation during the crop growth period. Artificial watering simulated the natural precipitation. The water levels were controlled between 500-520mm at the full water level, 400-420mm at the moderate water level, 240-260mm at the arid level. No rain sheds were used for the natural precipitation treatment. Experiments were conducted by making use of natural precipitation (382mm) plus 0d, 30d, or 60d of plastic film covering.

The experiment also included three levels of fertilization: zero (check), low, high. At planting, 186 and 372 kg·ha^{-1} of $(NH_4)_2HPO_4$ were applied to the low and high fertilizer treatments respectively. In total there were twelve treatment combinations. Each treatment was replicated twice for a total of twenty-four plots. The treatments were randomly assigned to the plots.

At each phenological period, we measured leaf area, root volume, plant height, density, and number of leaves. We also sampled the soil from 0-30cm and 30-60cm. For each soil sample, we measured water content (by using oven drying method), organic matter (by using the potassium dichromate method), effective phosphorus (by using sodium hydrogen carbonate), and nitrogen (by using the diffusion absorption method). The soils in this area have adequate K, so we did not measure this. At harvest, the number of heads, the average amount of a head, the weight of 1000 grains, and the yields of seeds were measured.

4 Results and discussion

4.1 Dynamics of the leaf area index in water-fertilizer regulation experiment

The values of leaf area index of spring wheat under different experimental conditions of water and fertilizer are shown in Table 3. During the growth period of spring wheat, the leaf area index increased from trifoliate to jointing to florescence and decreased from florescence to milk stage. The leaf area index has the most significant response during florescence. The average values of the leaf area index with full water during the florescence were 2.23, 2.94 and 3.78 in the zero, low, and high fertilizer treatments respectively. With moderate water, the values were 1.58, 2.19 and 2.94 while under arid conditions, they were 1.27, 1.42 and 1.56. Under natural precipitation conditions, the values for leaf area index during florescence were 2.64, 2.96 and 2.84 with 0d, 30d and 60d of plastic film coverage respectively. From the above analysis, we can see that the leaf areas index of spring wheat will increase with plastic coverage and in the end will lead to an increase of grain yield.

4.2 Relationship between niche-fitness and yield of spring wheat

The calculations for niche-fitness show that the F_i values with full water were 0.522, 0.637 and 0.813 under zero, low and high fertilizer conditions. Compared to the zero fertilizer treatment, the F_i value increased by 21.9% and 55.6% in the low and high fertilizer treatments respectively. For the moderate water treatment, the F_i values were 0.479, 0.506 and 0.607 in the zero, low and high fertilizer treatments. Compared to the zero fertilizer treatment, the F_i value increased by 5.6% and 26.6% under low and high fertilizer respectively. Under arid conditions, the F_i values were 0.423, 0.455 and 0.483, an increase of 7.6%, and 14.0% in the low and high fertilizer treatments respectively. These results indicate that the F_i value will increase as fertilizer increases under conditions of full and moderate water. Crop niche-fitness represents the degree that habitat conditions fit the growth of crop. The PS_i value calculated in this paper implies that a distinct percentage comparability relationship lies between the growth of crop and temperature, water and soil nutrition.

Moreover, the niche-fitness of crop was in accordance with the yields. The larger the F_i and PS_i value, the higher the yield was. According to statistical analysis, there was a significant linear relationship between the F_i and PS_i values and yield, which can be depicted in formula (12) and (13).

4.3 Effect of plastic film covering

In semi-arid areas, the application of plastic film covering can remarkably increase soil temperature and water-holding capacity. In addition, plastic film can accelerate the early development of crops. The values for niche-fitness F_i in treatments No. 11 and No. 12 (under experimental conditions of 30 and 60d plastic film covering respectively) increased from 0.485 to 0.576 and 0.645. That is an 18.8% and 33.0% increase compared with the control field No. 10. Spring wheat yields in samples No. 11 and No. 12 increased from 1490 $kg \cdot ha^{-1}$ to 2560 $kg \cdot ha^{-1}$ and 2170 $kg \cdot ha^{-1}$, a 71.2% and 45.1% increase compared to the control field. These results indicate that plastic film covering after sowing results in an increase in niche-fitness and crop yield.

4.4 Improved yield and water use efficiency of spring wheat

The mean grain yield of spring wheat under the full water, moderate water, natural precipitation, and arid treatments were 2770, 1890, 2070 and 1180 $kg \cdot ha^{-1}$ respectively. Compared to the arid treatment, the mean grain yield increased by 136%, 61% and 76% respectively. The fitness mean values were 0.657, 0.531, 0.569 and 0.454 respectively (Table 2).

Water use efficiency (WUE) was calculated by dividing grain yields by water use. The mean water use efficiencies under full water, moderate water, arid, and natural precipitation conditions were 5.33, 4.60, 4.52 and 5.43 $kg \cdot mm^{-1} \cdot ha^{-1}$

Table 4. Water use efficiency of spring wheat[a] ($kg \cdot mm^{-1} \cdot ha^{-1}$)

No.	Water[b]	Fertility	The leaf areas index ($cm^2 \cdot cm^{-2}$)			
			Trifoliate stage	Jointing stage	Florescence	Milk stage
1	Full water	Zero	0.18?0.02a	1.85?0.17a	2.23?0.21a	0.71?0.05a
2		Low	0.24?0.02a	2.01?0.18a	2.94?0.24ab	0.97?0.08ab
3		High	0.29?0.03b	2.29?0.24b	3.78?0.32c	1.12?0.11b
4	Moderate water	Zero	0.17?0.02a	1.33?0.14c	1.58?0.14d	0.52?0.04c
5		Low	0.23?0.02a	1.69?0.16ac	2.19?0.22a	0.71?0.06ab
6		High	0.26?0.03ab	2.06?0.20ab	2.94?0.31b	0.86?0.09b
7	Arid	Zero	0.15?0.01c	1.12?0.11c	1.27?0.12d	0.35?0.03c
8		Low	0.16?0.01ac	1.21?0.13c	1.42?0.15d	0.44?0.04c
9		High	0.21?0.02a	1.31?0.14c	1.56?0.16d	0.47?0.05c
10	Natural precipitation	No P.F.[c] covering	0.19?0.02ac	1.34?0.15c	2.64?0.24ab	0.59?0.04ac
11		P.F. covering (30days)	0.21?0.02a	1.91?0.18a	2.96?0.24ab	0.86?0.08ab
12		P.F. covering (60days)	0.23?0.03ab	2.04?0.21ab	2.84?0.29b	0.81?0.09b

[a]Means followed by different letters within rows were significantly different at p=0.05.
[b]Water use efficiency under natural precipitation without fertilizer application but with 0d, 30d and 60d plastic film covering.

respectively (Table 4). With different fertilizer application under full and moderate water conditions, water use efficiencies were significantly different. The differences were also significant with and without plastic film covering under natural precipitation conditions. The maximum value of WUE was 7.75 kg・mm^{-1}・ha^{-1} in the full water and high fertilizer treatment. The maximum grain yield (4030 kg・ha^{-1}) was also in that treatment.

The theory and model of niche-fitness of crops is a new development of the classical niche theory. The analysis offers a clear theoretical framework and corresponding quantitative method on how to improve the values of a crop's niche-fitness and grain yield in semi-arid fields through the regulation of water and fertilizer. Crop yield is tightly related to the value of niche-fitness, which means the yields will be larger with higher niche-fitness. Therefore, we can enhance niche-fitness and grain yield through rational fertilizer and plastic film covering when water supplies. The model has great significance for the study of improving agricultural production in semi-arid regions. For example, we can attain the aim of improving the crop's niche-fitness and yields ultimately by forecasting each year's precipitation and ensuring rational application of fertilizer. The results offer a better understanding of water-fertilizer management for water-saving agriculture. This research on the relationship between niche-fitness and grain yields will have an important effect on agricultural water management in semi-arid areas.

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Effects of chemical treatments or coverings on growth and yield of maize grown in broad ridges

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Abstract
Seven forms of cultivations were compared for maize *(Zea mays)* planted from April to Oct 2002 in Yan'an region. These were broad ridge culture (BR), broad ridge covered with plastic film (PFR), emulsion asphalt (EAR), polyacrylamide (PR) and Aquasorb (AR) respectively, intercropped with soybean (Glycine max) (IR), and with no treatment (CK). The aim was to examine measures to enhance resistance to drought and to increase yield of maize in an area that belongs to the semi-arid Loess Plateau region of China. Results indicated that at the seedling stage the PFR, PR and AR treatments required 23.8%, 12.1%, and 13.7% less water respectively than the control. The intercrop also used 7.2% less water than the control. At the same time, the BR and treated ridges could noticeably raise temperatures at 5 cm depth. The soil temperatures in the BR, PFR, EAR, PR, AR treatments were raised by 2℃, 5℃, 4.5℃, 1℃ and 2℃ respectively. Broad ridges covered with chemical materials could observably boost maize growth and biomass accumulation. The yield results showed that broad ridges covered with plastic film and emulsion asphalt were the best ways to enhance maize yield in Yan'an region. Maize yields had been increased relative to the control by 72% and 77.7% respectively.

Keywords: Maize (*Zea mays*); broad ridge culture; mulch; growth; yield.

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1 Introduction

Yan'an, in north Shaanxi province, is located at the center of the Loess Plateau in NW China, where soil erosion and fertility loss have arisen throughout intensive human activity. Sustainable agricultural production is closely related to both the eco-environmental situation and economic development. In resolving this problem, broad ridge culture on contour lines is found to be well suited to sloping land of arid and semi-arid regions (Zhang, 1998; Xuan, 1999). This farming system can markedly reduce erosion, decline in fertility and conserve soil water through reducing runoff, raising soil surface temperatures and increasing crop yields. So this cultivation method was promoted widely in arid and semi-arid regions, such as in Yan'an. There, annual rainfall often is the only available water source, since there is no groundwater for irrigating crops. So water has become the major limiting factor because rainfall varies widely both spatially and over time.

Rainfed cropping is predominant in Yan'an region, where annual average rainfall ranges from 480 to 650mm but with an uneven distribution. From November to April in second year, the climate is often dry and chilly, so cropping in this season is difficult to germinate and growth. However, from May to October, rainfall is mostly stormy with significant runoff loss, and the accompanying high evaporation rates often create crop water stress. Maize is a favored crop, being suited to the Yan'an area, as it's growing period fits very well with the rainy season. Maize is an important crop providing the main food for people and forage for animals. It yields much more than many other field crops such as wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), or bean (*Phasseolus vulgaris* L.). So, the annual average acreage planted to maize in Yan'an region is about 120,000 hm^2, accounting for 18% of all land planted to foodstuffs. However, maize yield accounts for 26.4% of total foodstuffs yield.

From experience, several technical innovations could offer possibilities for improving productivity of cropping systems such as using plastic film and crop straw to cover the soil surface, inter-cropping legumes, grazing, or using soil improvement substances or water retention substances. Mulching with plastic film was identified as a favorite planting method in arid and semi-arid regions after many years of field experiments (Shi, 1989; Shi 1998). This saves significant amounts of soil water by limiting evaporation, raises soil temperatures, advances crop growth stages and then significantly increases grain yield. There a long history of traditional Chinese agriculture, intercropping practice is already a well-integrated and complex system. In particular, intercropping grain crops with legumes can improve soil structure, with positive interactions between multiple crops and enhanced total yields. In recent years, several chemical materials were tried as ways of improving production in arid and semi-arid region, such as aquasorb, polyacrylamide, and asphalt emulsion. These all prevent water loss to ensure efficient crop emergence, enhance crop drought tolerance and ensure harvest, even in dry years. These cultivation practices were often adopted separately, with few attempts to combine them. Therefore, this experiment was set up to test whether such chemical treatments might be gainfully combined with broad ridge cultivation of maize (*Zea mays* L.). The focus was the extent of retained soil moisture and associated crop yields in Yan'an region.

2 Materials and methods

2.1. Location, climate and soil

The experiment was conducted during April to October 2002, at Feimahe village, which has an agricultural research and demonstration area linked to the Chinese Academy of Science. It is near Liulin Town, in Baota district of Yan'an city, (Latitude $36^0$55'N, longitude $109^0$37'E, altitude 1150m. No irrigation was applied during the maize growing period. Mean annual rainfall is 550mm (Table 1), with about 470mm falling between April and October, which accounts for 85% of the annual total. Timing and amounts of rainfall are highly variable and frost usually commences in late-October.

Table 1. Mean annual rainfall and monthly distribution at the experimental site

Rainfall (mm)	Jan	Feb	March	Apr	May	Jun	Jul	August	Sep	Oct	Nov	Dec	Total
Average	3.9	5.7	16.0	32.6	46.5	57.7	121.4	123.1	86.3	41.1	19.7	3.3	557.3
2002	--	--	--	27	44.8	191.4	75.2	56	61.4	50.7	--	--	506.5

The field soil is representative of Huangmian soil, being widely distributed on the Loess Plateau. The previous crop was maize. Before sowing, five soil samples were obtained from the plots at 50cm depth. Soil conditions had been identified as follows: organic matter content of 0.83%, total nitrogen of 0.05%, available phosphorus of 5.8ppm, exchangeable potassium of 160ppm, bulk density of 1.31g/cm^3 and a field capacity value of 22.9% water content.

2.2 Treatment and material

Seven forms of maize cultivation were compared, being broad ridge cultivation (BR), broad ridge covered with plastic film (PFR), emulsion asphalt (EAR), polyacrylamaide (PR), and aquasorb (AR), respectively, intercropping with soybean (Glycine max)(IR), and with no treatment (CK). The broad ridge was built as a ridge 0.5m wide, furrow width 0.3m, and height from ridge top to furrow bottom of approximately 25~30cm. Plots were 4m wide × 8.5 m long, with three replications. The target plant population was 35,000 plants per hm^2 in each treatment.

The Institute of Agricultural Science of Yan'an supplied the maize variety, Shendan No.10, and soybean variety, Jindou No.20, were supplied. Maize was planted on the ridge, while soybean intercropped with maize was planted in the furrow bottom, at a density of 70,000 plants per ha. Around the square experiment field, other varieties of maize were planted to reduce the marginal use and protect invasion from animals.

Plastic film, of 0.005mm thickness, was only applied to the ridge. Shaanxi Kerui Co. Ltd supplied asphalt emulsion, a byproduct of the petroleum industry. It is a kind of multi-functional liquid applied at about 450~500 kg per hm^2. After sowing, asphalt emulsion was evenly mixed with water in the proportion 1:10, and then the mixture was sprayed on ridges. Aquasorb (made by the Northwest Industrial University, China), was a sort saline of polypropylene sodium which could retain soil water well, when used at the rate of 30~45kg per hm^2. Aquasorb was mingled with dry soil in the ratio 1:20, and then the mixture was scattered on the ridge after sowing. Elsewhere polyacrylamide has been used with irrigation, but in this instance polyacrylamide was used in the same way as the Aquasorb.

When sowing, 750 kg per hm^2 calcium super phosphate was applied and applications of 225kg urea per hm^2 were given at 40 days and 70 days after sowing.

2.3 Measurements

Maize height, stem base diameter, leaf area and biomass were measured every 20~25days after emergence. Final grain yield was measured using a quadrat measuring 4 m×5 m. Maize grain and straw were oven dried at 70^{o}C, and yield was expressed at 13% moisture content.

Soil thermometers were arranged at 5, 10, 15, 20 and 25cm depths, respectively. Soil temperature variation from 8:00 am to 6:00 pm was recorded at the seedling stage and jointing stage, respectively.

Neutron access tubes to 140 cm depth, with detachable tops to permit machinery passage, were located in the center of each plot for soil moisture determination and data was recorded every 20~30days. The CNC100 probe is made in China. Installation of access tubes was completed after the field had been prepared. Readings were taken in the center of each 20cm layer. The neutron probe was calibrated at the site and results were generally shown as total soil water (SW) in mm for the top 100cm. Readings below 100cm were variable and were judged not to reflect water extraction by crops.

Water use efficiency (WUE) was determined from kernel weight per ha and total water consumed, being the sum of precipitation and the difference of soil water pre-sowing minus that after maize harvest.

Data were analyzed separately for maize using Excel software. Significance of both differences or correlations at the $P<0.05$ and 0.01 levels were noted as * and **, respectively.

3. Results and discussion

3.1 Soil temperature and moisture

Generally temperature in April was variable, with the lowest temperature falling below 0^{o}C, and the difference between day and night temperatures frequently exceeding 20^{o}C. So it was necessary to use film-mulched crops or postpone sowing stage to avoid crops suffering frost damage. Farmer often start to sow in early-May when the temperature becomes steady and its feasible for crops to grow. But then some precipitation and soil water is consumed to no advantage due to evaporation and time for crop growth is shortened.

Effects of increased temperature arising from different mulches strongly indicated that the plastic film and asphalt emulsion were the two best materials to enhance soil temperature from the seedling to jointing stage (Table 3). These mulch treatments enhanced soil temperature by 4~5^{o}C at 5cm depth and 2~3^{o}C at 10~15cm depth, which benefits maize emergence and seedling growth. The AR, PR and BR treatments also enhanced mean temperatures by 2~3^{o}C at 5~10cm, which helped maize to emerge early compared to the control. Maize under PFR and EAR reached jointing 4~5days early, and booted 7~10days in advance of the control due to soil temperature being raised. The time of seed filling was lengthened by 10~15 days, by comparison with the CK. Crops did not senesce ahead of controls, as reported by Shi (1998). Aquasorb and polyacrylamide were regarded as soil structure improvers, especially for 10~25 cm depths, thereby enhancing conserved water in recent years (Li, 2002; Jie, 2000; Huang, 2002; Feng, 2001; Xia, 2002). Observation results indicated that maize under AR and PR also booted 3~5days ahead of the control, and the seed filling stage lengthened by 5~8 days. The effect of BR was as similar to that of AR and PR. Notably, intercropping brought forward the jointing and booting stages though soil temperatures remained unaffected.

Table 2 Total soil water content in 1-m soil layer during maize seedling stage

Treatment	IR	AR	PFR	PR	EAR	BR	CK
SW (mm)	153.5	162.8	177.3	161.4	138.75	140.4	143.25
MT (%)	7.16	13.66*	23.76**	12.71	-3.14	-1.94	0

SW: soil water MT: more than CK

Evaporation was usually intense during the corn seedling stage as the leaf area index was very small. However, this condition would improve if applications of mulch with plastic film, polyacrylamide and Aquasorb were adopted (Table 3). Vapor loss to the air was obstructed due to mulching with plastic film, while rainfall effectively accumulated in furrows and then infiltrated. Aquasorb and polyacrylamide could absorb non-ionic water some hundreds times their own weight because of their special chemical structure. They could form a reticular structure on soil surface when coming into contact with water in soil (Huang, 2002, Li, 2002), this structure functions much the same way as a plastic film. So soil water contents under PFR, AR and PR were clearly greater than the control. Soil water content was different from that under the IR treatment, exceeding that of the control and BR treatment. Furthermore the soil water distribution changed, with deep soil water being stimulated to move upward. This may be the reason for high water loss from the BR treatment. Asphalt emulsion was a brown viscous liquid, which could form a membrane when coming into contact with water, similar to the Aquasorb and polyacrylamide. But the continuity and toughness of the asphalt membranes were not as significant that of the Aquasorb and polyacrylamide. Even rainfall could do damage to the emulsion membrane. Under the EAR treatment, increased temperature and soil surface area were judged to be reasons for water use being comparable to the control.

Table 3 Mean temperatures at various soil depths

Depth	IR	AR	PFR	PR	EAR	BR	Control
5cm	32.7	34.3	36.2	33.8	36.5	33.9	32.4
10cm	29.7	31.5	32.8	31.2	32.6	30.7	29.9
15cm	27.2	28.0	30.6	28	29.3	27.8	27.1
20cm	25.8	26.6	29.6	26.4	27	26.2	26.0
25cm	25.3	25.7	27.8	25.6	26.3	25.9	25.0
MT1	31.2	32.9	34.5	32.5	34.5	32.3	31.1
MT2 (%)	0.1	1.8	3.4*	1.4	3.4*	1.2	--

MT1: mean temperature in 0~10cm soil; MT2: more than Control

3.2 Maize height, leaf area and diameter of stem base

Results of maize height, leaf area and diameter of stem in different stages clearly showed that broad ridge culture combined with mulch and intercropped with soybean improved maize growth (Table 4). In particular, effects of these practices were markedly different during the jointing and booting stage, which was attributed to temperatures being raised or soil water being well conserved under the treatments. While not strong as plastic film in conserving water, the applied emulsion asphalt did fix some plant growth regulator, soil regulator and some fertilizer. Maize in EAR treatment grew very well since more nutrition had been supplied and the root environment had been improved, so growth was even better than that in the PFR treatment. Results indicated the best cultivation measures in Yan'an region were broad ridges combined with film, emulsion asphalt and intercropped with soybean.

Nutrition or water was well supplied by these three measures, especially at jointing and booting stages. The basis for yield is created during these stages. Relative to the control, the PFR, EAR and IR maize heights were greater by 31~49%, 30~47% and 16~23%, respectively. For PFR, EAR and IR, the stem diameters increased by 21~42%, 24~45% and 11~37%, respectively. Leaf areas in PFR and EAR also increased 39%~92% and 59~92% compared to the control during these stages. Similar effects appeared in AR and PR treatments but not as strongly as for PFR or EAR.

Table 4 Maize height, diameter and leaf area of each treatment at various growth stages

Time		IR	AR	PFR	PR	EAR	BR	CK
Jun 8	Height	25.7	26.3	35.0	25.0	30.7	24.0	26.3
Jun 28	(cm)	94.2	81.0	104.5	95.2	100.8	83.5	77.7
Jul 6		118.3	128.0	151.3	131.7	150.0	107.0	101.7
Jul 28		262.3	255.0	279.7	255.7	278.8	224.7	213.7
Sep 26		236.0	237.0	248.3	264.0	260.0	246.0	238
Jun 28	Diameter	2.91	2.65	3.17	3.10	3.46	2.75	2.63
Jul 6	of stem	3.47	3.76	3.99	3.30	3.66	3.08	2.96
Jul 28	(cm)	3.40	3.23	3.60	2.57	3.66	2.61	2.53
Sep 26		2.93	3.47	3.40	2.30	3.37	3.03	2.63
Jul 6	Leaf area	0.465	0.534	0.760	0.487	0.759	0.416	0.395
Jul 28	(m^2/plant)	0.899	0.964	1.002	0.873	1.148	0.694	0.721

In addition, growth status of maize in PFR, EAR and IR treatments were superior to the control and other treatments. For instance, leaf color was darker green, with wider and longer leaves, angle of stem with leaves less compare to other treatments. Air and sunlight were effectively used and more carbohydrate was produced and accumulated in maize. Amounts of roots and weights distributed within the 30cm depth of the PFR, EAR and IR treatments were considerably greater than the control.

3.3 Maize yield and WUE

The PFR, EAR and IR were appropriate measures to increase yield in Yan'an region according to results of grain yield (Table 5). The yield improvements in the PFR, EAR and IR treatments were greatly beyond expectation. Possible reasons to explain this are that precipitation during jointing in April to June, especially in May, was conserved and used. Also increased temperatures greatly accelerated maize growth, making the maize stronger and capable of accumulating more biomass. Finally, a clear, warm autumn was beneficial since maize in PFR, EAR and IR treatments was quite advanced in the seed filling stage when temperatures reduced and day length shortened in late-August. In the case of the IR treatment, perhaps rhizobia on soybean roots supplied additional N. As for the AR and PR treatments, there were moderate yield improvements, which accord with improved water retention and higher temperature.

WUE data showed a similar result to yields, being highest for PFR, EAR and IR, moderate in PR and AR. and lowest for BR and CK.

Table 5 Grain yield and WUE under difference chemical or cover treatment

	IR	AR	PFR	PR	EAR	BR	CK
Yield (kg/hm^2)	10,560	7,132	11,071	8,415	11,436	6,710	6,435
MT (%)	64.1	10.8	72.0	30.8	77.7	4. 3	
WUE	21.8	14.2	22.6	16.8	22.0	13.1	12.9
MT(%)	68.8	9..9	75.6	30.0	70.6	1..3	

WUE: water use efficiency. (kg/mm.hm^2)

4 Conclusions

Mulching with plastic film and asphalt emulsion were the best forms of cover to increase grain yield in arid and semi-arid areas. Also corn intercropped with soybean was a better plant measure here. Results of this experiment were similar to many other research reports concerning plastic film and emulsion asphalt covering. So repetition was judged unnecessary. As for Aquasorb and polyacrylamide, they showed moderate effects of improved water-retention and yield, but their effects to control erosion were not nsignificant, especially in hilly-gully region in Loess Plateau. Whereas the effect of broad ridge culture relative to the control was not as marked as results elsewhere.

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Effects of Aquasorb mixed with fertilizer on growth and WUE of potatoes in semi-arid areas of China

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Abstract

Growth and water use efficiency (WUE) of potatoes was examined for combinations of “Aquasorb”, a chemical agent for water saving, and nitrogen fertilizer. The potato *(Solanum tuberosum* L.) variety was Kexing No.1, with field plots being located in Yan’an region of the semi-arid Loess Plateau in China. There, mean annual rainfall is 430mm. Ten treatments were based on Aquasorb, with or without fertilizer, being widely incorporated across the seedbed, within furrows or being applied via holes. During the prophase vegetative growth stage, the canopy area of potato seedlings increased by 11.8%-54.8% for different chemical agent treatments, compared with the controls. Aquasorb and N fertilizer application could enhance leaf photosynthesis markedly at the flowering and potato tuber growth stages. Biomass was significantly increased by 46.7%-98.8% on applying Aquasorb mixed with N fertilizer, but only by 6.4%-28.2% on applying the chemical agent alone or by 35.5% with only N fertilizer. The marketable yield of potatoes was 26.7%-56.7% higher than the control for the chemical agent alone, 33.3% higher for just N fertilizer, and 75%-108% higher for Aquasorb mixed with N fertilizer. WUE at flowering stage increased only 33.1% to 62.0 by using Aquasorb and 76.4% by applying N fertilizer, and increased 62.3% to 85.1% with mixed application of Aquasorb and N fertilizer. At harvest stage, WUE increased from 13.4% to 47.8%, 32.7% and 54.6% to 93.8% respectively. The chemical agent was best-incorporated in furrows rather than using holes and a 0.10-0.15 m deep application was better than 0.05 m depth.

Key words: Aquasorb; growth; water use efficiency (WUE); potato *(Solanum tuberosum* L.)

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1 Introduction

Northern Shaanxi is located in the belt between arid to semi-arid region, having a mean temperature ranging from 7.7-10.6°C, accumulated day degree temperature ranged from 2724-3863℃ per year, altitude is 1200 m, annual number of frost-free days and rainfall are 140-170 days and 490 mm, respectively. The temperature difference between day and night is large (Wei, 1990). Potato is one of major crops in this region, with an annual planted area of more than 133,300 hm^2, being about 14% of total farmland area. The total yield amounts to 16,000 ton (Yan *et al*, 1999). Potatoes are very important in the development of farming economy of northern Shaanxi. Though, drought and limited inherent soil fertility are the main limiting factors restricting high yield development of potatoes. Thus, it’s necessary to search for new technologies and methods for drought resistance and yield improvement of potatoes.

Applying Aquasorb has become a means of chemical saving water in agriculture and forestry in recent years. Benefits include saving water, improving soil texture and enhancing fertilizer use efficiency. Some experiments have already verified that potato yields could be increased with this treatment (Huang, 2002,1999). At present, promotion is restricted since optimal application methods are unknown. There are also difficulties in establishing an economic level of use. Combining Aquasorb and fertilizer into a new product might encourage wider use Many experiments have shown that combined water and nitrogen fertilizer are primary factors influencing potato yield (Belanger *et al*, 2001). So this research is to establish results of mixed use of Aquasorb and nitrogen fertilizer on growth and WUE of potato in Yan’an region.

2 Materials and methods

2.1 Introduction

During May to September in 2002, field plots were located in terraced fields of the Loess Plateau in Yan'An region, Shaanxi province, North West China. The potato variety was KeXin No.1 with seed tubers being obtained from Yan'an Agricultural Research Institute. Aquasorb is a white dry granular agent produced by North-West Industry University. Before sowing, tuber seeds were treated by plant ash to protect against insects and reduce disease incidence.

Soil bulk density and water holding capacity was 1.33 g/cm^3 and 22.9%, respectively. Phosphorus was applied at 750 kg/ha as a base fertilizer before sowing. Row spacing, plant spacing and ridge height were 48cm, 38cm and 15cm, respectively. Plant density was about 45000/ha. The chemical treatments were applied at two different depths of 5cm and 10-15cm, either put along the furrows or into holes. There were ten treatments in all of Aquasorb mixed with nitrogen, (Table 1). All treatments were replicated 3 times, making 30 plots, each 3m wide and 25m long. Plots were arrayed randomly. Insecticides were applied as required, to maintain special pests below threshold levels.

2.2 Measure index and method

Potato plant height and canopy area were measured by ruler, with biomass being measured by electronic balance to a precision of 0.1 gram. Rate of leaf photosynthesis was determined using the improved half leaf method, with leaves being selected from the upper canopy. Measurements were taken from 9 a.m. to 2 p.m. Total weight of tubers was recorded for each plot.

Table 1. Experimental treatments with Aquasorb and fertilizer application methods for potatoes

No.	Aquasorb treatments at seeding growth stage	No.	Aquasorb+N Fertilizer treatment in budding growth stage
A1	5cm deep furrow application	A1F	5cm deep furrow application
A2	10-15cm deep furrow application	A2F	10-15cm deep furrow application
B1	5cm deep hole application	B1F	5cm deep hole application
B2	10-15cm deep hole application	B2F	10-15cm deep hole application
CK	Control	F	Control +N fertilizer

3 Results

3.1 Effects of Aquasorb on potato growth and photosynthesis response

Table 2 shows that all methods of applying Aquasorb encouraged good shoot configuration during the seeding period, giving rapid increase in canopy area. Chemical treatment improved plant growth at the seedling stage. Furrow application appeared preferable to point application in holes, with deeper being better than shallow application. The capacity of absorbing and making water available in the soil-root system was enhanced through this treatment, as evidenced by the speed of canopy development.

Figure 1 shows that the photosynthetic rate of potato leaves in the flowering stage was higher than that in the tuber enlarging stage and that chemical plus fertilizer treatment enhanced rates during both stages. Whilst leaf photosynthetic rates were higher for the chemical plus fertilizer treatment, the difference was not significant. Never-the-less, increased photosynthetic rates are consistent with tuber yield being positively correlated with canopy development (Yang, 1995; Day, 1998; Sinclair,1989).

3.2 Influence of Aquasorb and N fertilizer on potato biomass in flowering stage

Flowering is the key stage for transport of assimilates from shoot to tuber, when above ground plant biomass is a maximum. Table 3 showed that biomass increased slightly for small applications of Aquasorb or N fertilizer, being 6.4%-28.2% and 35.5% respectively. Using mixed Aquasorb and N fertilizer, the biomass increased by 46.7%-98.8%, with deep furrow applications yielding highest. This shows an interaction between the chemical agent and N fertilizer, in which N fertilizer use efficiency is improved and generates improved growth.

3.3 Impact of Aquasorb and N fertilizer on growth period and yield

Water shortage and fertilizer deficiency makes crop stems and leaves drier, shortening time for leaf photosynthesis and reducing yield. Figure 2 shows that potato growth periods were prolonged by 6-8, 12 and 14-15 days, respectively for the chemical agent, fertilizer and combined chemical agent and fertilizer treatments, respectively. Table 4 shows that when using Aquasorb alone or N fertilizer alone, yield was only increased by 26.7-56.7% or 33.3%, respectively. With mixed chemical and fertilizer treatments, yield increased by 75-108%, especially for the tubers larger than 10 cm.

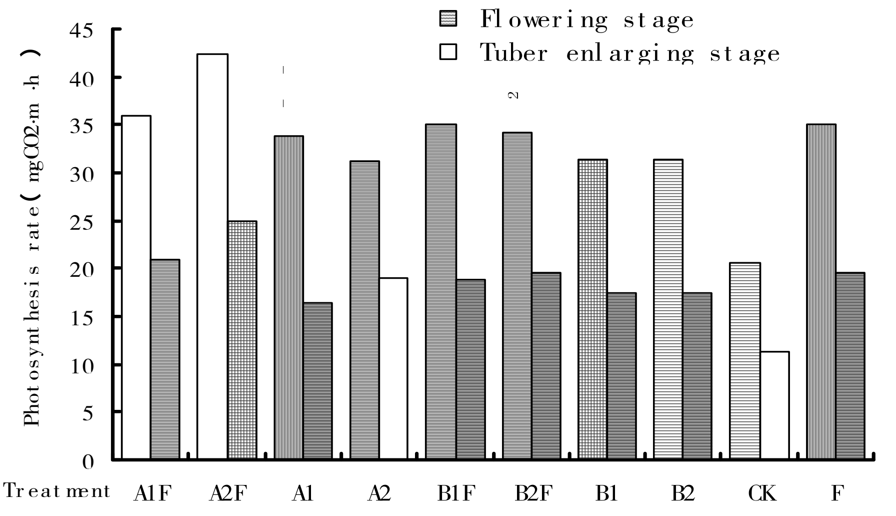

Fig. 1 the leaf photosynthesis rate in different stage

Table 2. Effects of Aquasorb on potato seedling stage

Treatment	Plant Height (cm)	Canopy		Canopy area (cm^2)	Increased percent of canopy area
		East-West (cm)	South-North (cm)		
A1	32.2	37.4	38.4	1436	31.1%
A2	26.8	39.8	42.6	1695	54.8%
B1	31.8	34.8	35.2	1225	11.8%
B2	31.1	37.6	39.6	1489	35.9%
Control	29.2	32.6	33.6	1095	-

Table 3. Biomass of potatoes at flowering stage

Treatment	A1F	A2F	A1	A2	B1F	B2F	B1	B2	CK	F
Total biomass	289.7	349.7	200.8	225.5	324.8	258	221	187.1	175.9	238.3
Increased percent (%)	64.7	98.8	14.1	28.2	84.7	46.7	25.7	6.4	-	35.5

Table 4. Yield of potatoes for different Aquasorb and N fertilizer treatments

Treatment	A1F	A2F	A1	A2	B1F	B2F	B1	B2	CK	F
Yield (kg)	20700	22500	13680	16920	19800	18900	15750	13680	10800	14400
Increased percent (%)	91.7	108.3	26.7	56.7	83.3	75.0	45.8	26.7	-	33.3
>10cm Tuber yield (kg)	7800	9600	5940	4275	6525	7050	4680	4500	2520	5670
Percent of tuber (>10cm) (%)	37.7	42.7	43.4	25.3	33.0	37.3	29.7	32.9	23.3	39.4

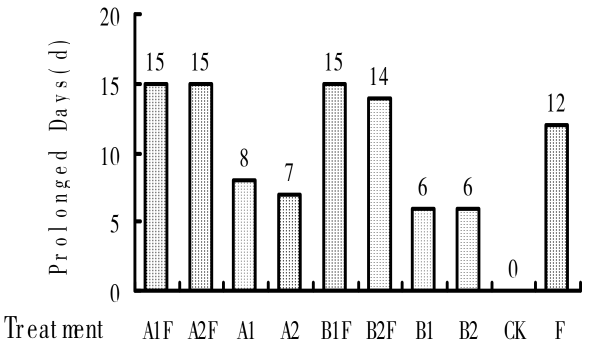

Fig.2 Prolonged days of aquaorb and N fertilizer to growth period of potato

3.4 Effects of Aquasorb and N fertilizer on potato WUE

Table 5 shows that water use efficiency (WUE) of potatoes increased dramatically when applying Aquasorb and N fertilizer. At flowering stage, WUE increasing was major related to dry matter production and soil water saving. Dry matter and water saving were increased from 26.4-31.9g and 7.7-12.3mm with using Aquasorb, respectively, WUE increased from 33.2-62%. Single using N fertilizer, no huge change in saving water, but dry matter arrived to 36.90g, and WUE increased 76.5% compared with control. Mix using Aquasorb and N fertilizer, dry matter and saving water were from 31-36.4g and 4.5- 11.2mm, respectively. WUE increased 62-85%. To harvesting stage of potato, the WUE with Aquasorb mixing N fertilizer increased significant main for dry matter accumulated largely but not for saving water increasing. Compared with control at this stage, Aquasorb can make potato WUE increase 13.4-47.8%, N fertilizer 32.7%, and mixing using Aquasorb and N fertilize, WUE increase 59.5-93.8%.

There is a strong negative correlation between cereal dry matter production and water use efficiency in well-watered crops (Ehdaie, 1991; Condion, 1987).

Table 5. Potato WUE at different growth stages

Treatment	July 18th Flowering stage					Sept 28th harvest stage				
	DM (g)	Save water(mm)	Use water (mm)	WUE	Increased percentage	DM(g)	Use water (mm)	Save water(mm)	WUE	Increased percentage
A1F	34.4	-9.8	225.5	0.1587	68.3%	149.44	358.8	-9.9	0.4165	76.4%
A2F	36.4	-9.6	225.8	0.1745	85.1%	161.40	352.7	-16.0	0.4576	93.8%
A1	31.9	-12.3	223.1	0.1527	62.0%	107.90	346.9	-21.8	0.3110	31.7%
A2	31.2	-7.7	227.6	0.1516	60.8%	125.20	358.7	-10.0	0.3490	47.8%
B1F	35.1	-4.5	230.8	0.1663	76.4%	145.05	375.5	6.8	0.3863	63.6%
B2F	31.0	-11.2	224.1	0.1530	62.3%	136.00	361.1	-7.6	0.3766	59.5%
B1	28.3	-11.1	224.2	0.1364	44.7%	115.83	354.1	-14.6	0.3271	38.5%
B2	26.4	-8.2	227.1	0.1162	23.3%	97.59	364.5	-4.2	0.2677	13.4%
Control	19.7	0.0	235.3	0.0943	-	87.07	368.7	0.0	0.2361	0.00%
F	36.9	-1.0	234.3	0.1575	67.1%	116.90	373.2	4.5	0.3132	32.7%

4 Discussion

Yield of potatoes increased when applying a chemical agent and nitrogen fertilizer as a result of increased seedling canopy, leading to increased photosynthetic rate and accumulation of plant shoot biomass. The higher shoot biomass at this stage was propitious for final tuber yield. WUE of potato was increased markedly by applying Aquasorb and N fertilizer, and interaction of Aquasorb and N fertilizer were productive. In all methods, 10-15cm deep furrow application of chemical agent and nitrogen fertiliser gave the best result.

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Effects of deficit irrigation on yield, yield components and water use efficiency of Winter Wheat

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Abstract

The influence of the extent of deficit irrigation on yield and yield components of wheat was examined for different growing stages. Pot experiments showed that medium water deficits during crop revival and small water deficits during the grain filling stage improved grain production. From jointing to anthesis, water deficits reduced grain production, but slightly improved seed weight. Medium to serious water deficit during jointing and booting significantly reduced spike numbers and seed numbers per spike. Three years of field experiments also showed that removing the irrigations during crop revival and the late grain filling stages not only improved grain production but also water use efficiency. For the three seasons, irrigation twice, at jointing and at booting to anthesis, produced the maximum grain production by comparison with other arrangements. Jointing, booting and grain filling were the best time for irrigation, when applying water three times. Reducing the normal number of 4 irrigations to either 3 or even 2 is an option for reducing irrigation water use in the region. Irrigation scheduling should improve water use efficiency and grain production of winter wheat.

Key words: Deficit irrigation; grain yield; water use efficiency; winter wheat.

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1 Introduction

Deficit irrigation, the deliberate and systematic under irrigation of crops, is a common practice in many areas of the world (English and Raja, 1996). The potential benefits of deficit irrigation derive from three factors: increased irrigation efficiency, reduced costs of irrigation and opportunity costs of water (English *et al*., 1990). In serious water shortage regions, to improve irrigation efficiency by applying deficit irrigation scheduling would be an important measure for sustainable irrigation water use. In the North China Plain, winter wheat is one of the major crops and generally grows from October of the previous year to late May or the first ten days of June in the next year. During this period, rainfall ranges from 80 mm to 150 mm, and is far below the water requirement of winter wheat, which is usually 450 to 480 mm. High production of this crop depends heavily on irrigation. While massive extraction of groundwater in the North China Plain has led to a rapid decline in the groundwater table. Irrigated agriculture relying on overexploiting groundwater is doomed as unsustainable (Yang and Zehnder, 2001). So it is very important to reduce irrigation water use by improving water use efficiency.

Crops respond in various ways to soil water deficits and their responses depend upon timing, duration and severity (Hsiao, 1990; Hsiao and Bradford, 1983). Much research has shown that the differences in sensitivity to water stress during crop growth and development were significant and could be used for partial irrigation scheduling (Nam et al., 2001; Mugabe and Nyakatawa, 2000; Ghahraman and Sepaskhah, 1997; Stegman et al., 1990; English and Nakamura, 1989). Therefore, an understanding of the effects of water stress and stress severity at different growing stages of crops is a necessary prerequisite when planning irrigation scheduling. This study evaluated effects of water stress, and extent of stress at different growing stages of winter wheat, on yield and determined effective deficit irrigation scheduling to improve water use efficiency in the piedmont of Mt. Taihang in the central part of the North China Plain.

2 Materials and Methods

2.1 Introduction

Two seasons of pot experiments and three seasons of field experiment were carried out at the Luancheng Experimental Station of Chinese Academy of Sciences. This is located in the central part of the plain at the base of Mt. Taihang (37°53´N, 114°40´E; 50 m above sea level). Pot experiments were carried out from 1996 to 1997 and 1999 to 2000 to determine effects of water stress and different stress levels on yield and yield components of winter wheat. From 1999 to 2002, field experiments were carried out to examine deficit irrigation scheduling effects on grain production and water use efficiency of winter wheat, over three seasons. The soil was loamy, with about 1.4% (w/w) organic matter content in the tillage layer. Available N, P and K were about 60, 15 and 90 mg/kg, respectively.

The cultivar used for winter wheat was “503” (*Triticum aestivum* L.) in 1996/1997 and “4185” (*Triticum aestivum* L.) in the other seasons. Winter wheat was generally sown at the beginning of October with a row spacing of 16 cm, and a density of 300 seeds m^{-2}. The seedling stage was complete at the end of November. December, January and February was the long over-wintering period. In March, winter wheat began to revive, at the end of dormancy. The jointing stage was at the beginning of April, followed by the booting stage throughout most of April and with heading and flowering stages at the end of April or the beginning of May. From then on, the grain filling stage began. Harvesting typically occurred during the first ten days of June. Chemical fertilizers of N, P and K were applied as base fertilizer. Nitrogen was applied again at the jointing stage.

Maize was manually inter-planted into winter wheat 5 to 7 days ahead of harvest, to prolong the growth period of maize. At the end of September, maize was harvested. Then land was plowed to prepare for winter wheat planting at the beginning of October. Depending on the rainfall conditions of the rainy season from July to September, in some dry years, land was irrigated to ensure that the soil moisture conditions were favorable for sowing wheat.

Average rainfall during the winter wheat season in this region is about 117 mm, and potential evapotranspiration calculated by the Penmen equation recommended by FAO is 485 mm (Allen et al.,1998). Farmers generally irrigate winter wheat 4 to 5 times each season. The irrigation totally depends on underground water in this region and the underground water table currently declines rapidly, at more than 1 m/yr.

2.2 Pot treatments

Pots contained soil from nearby fields, taken from the soil surface to a depth of 45 cm. They were 50 cm in height and 25 cm in diameter. Average soil bulk density was 1.45 g/cm^3, with a field capacity of 24% (g/g) and wilting point of about 9% (g/g). Before filling pots with soil, the soil moisture was measured and the weight of the pots recorded. After filling the pots, weight of pots and soil was recorded to calculate dry soil weight in each pot as the means to control soil moisture level. The density of winter wheat in each pot was kept at the level of the average density measured at the nearby field before treatments begun.

After over-wintering, different water stress levels were created by controlling amounts of water added. Pots were placed in the field and a rain-proof shed was moved to cover the pots whenever there was rainfall. Pots were weighted daily to keep the soil moisture at the required level. During stages when water deficit was not being controlled, soil moisture was kept at a constant level of 21% (g/g). Three levels of water deficit were applied during the revival, jointing, booting to flowering and grain-filling growth stages. A constant level of 21% (g/g) soil moisture was also maintained during the whole growth period to act as a control. Each treatment had three replicates so that 39 pots were used in total.

In the 1996-1997 season, three levels of water stress for each of the four growth stages were identified from the value of K in the following equation:

$$WA=ET*K \qquad (1)$$

where WA is daily water addition to a pot, ET is daily water consumption calculated by daily weightings, K = 0.8 represents a slight deficit treatment; K=0.6 represents a medium deficit treatment and K=0.4 is the severe deficit treatment.

In the 1999-2000 season, the three levels of water deficit at each of the four growth stages were 12%, 15% and 18% gravimetric water contents for severe, medium and light deficit treatments, respectively. These moisture levels were equivalent to 50%, 62.5%, 75% of field capacity values.

At harvesting, total aerial biomass, grain yield, spikelet numbers, kernel numbers per spikelet and thousand-kernel weight were recorded for each pot.

2.3 Field treatments

A randomized plot design was used for the field experiments. There were six treatments as listed in Table 1. The control treatment was four irrigation applications, as scheduled for the surrounding farmland. Two schedules of both two and three irrigation applications were used to compare grain production and water use efficiency of winter wheat for different deficit irrigation scheduling. A treatment without irrigation was used to compare the irrigation benefit corresponding to different treatments. Each treatment had four replicates. The area of each plot was 5?8 m^2. Between two plots, there was a 2 m width zone without irrigation to minimize the effects of two adjacent plots. Each treatment was replicated four times. Surface irrigation was applied using a low-pressure water hose with a flow meter to record water applied to each plot. Individual plots were harvested manually and then grain yields were obtained after separation by thresher. After grain was air-dried, both weights and thousand kernel weights were measured. Before harvesting, spikelet numbers per unit area were counted and 40 spikelets were taken from each plot to count the kernel numbers per spikelet.

Soil volumetric water contents were monitored weekly at intervals of 20 cm down to 2 m using a neutron meter (IH-II) with access tubes installed at the center of each plot. Surface soil moisture was measured by taking soil cores. Total water use, defined as initial soil water content minus final soil water content plus precipitation, irrigation, runoff, drainage and capillarity rise, was calculated using the following equation:

$$TWU = P + I + \Delta W - R - D + CR \qquad (2)$$

where TWU = total water use during the whole crop growth period, P = precipitation, I = irrigation, ΔW = soil water contents at sowing minus soil water contents at harvest for the 2 m root zone, R = runoff, D = drainage from the root zone and CR = capillary rise to the root zone. Runoff, drainage and capillary rise were negligible and not considered. Thus $TWU = P + I + \Delta W$ was used under our experimental conditions. Rainfall was recorded at a meteorological station near the site.

Water use efficiency (WUE), defined as crop yield divided by water use, was calculated using the following equation:

$$WUE = Y/TWU \qquad (3)$$

where Y is grain yield.

Rainfall conditions during the three winter wheat seasons are listed in Table 2. 1999/2000 was dry with rainfall less than half of the normal amount for winter wheat. The 2000/2001 and 2001/2002 seasons were normal with rainfall near the long-term average but had different seasonal distributions. More rainfall fell during the earlier growth stages in 2000/2001 and during later stages in 2001/2002.

Table 1 The timing of irrigation for different treatments during 1999 to 2002

Growing stages (DAS)	Sowing (0)	Over wintering (80)	Revival (150)	Jointing (180)	Booting (195)	Heading (205)	Flowering (215)	Grain filling (220)	Maturing (240)
Non-irrigation (T0)									
Two Irrigations(T2a)	√		√						
Two irrigations (T2b)			√			√			
Three irrigations(T3a)	√		√				√		
Three irrigations(T3b)			√		√			√	
Four irrigations (T4)	√		√		√			√	

2.4 Data analysis

All the collected data was statistically analyzed. Standard deviations for each treatment were calculated and means among treatments were compared using Least Significant Differences (LSD) at P=0.01 probability.

3 Results and discussion

3.1 Sensitivity to water stress

In the 1996/1997 season, soil deficit was influenced by low evapotranspiration rates. During the revival stage in March and early April, temperatures were relatively low and the crop was short, so daily evapotranspiration was low. Soil moisture levels for the treated pots remained at relatively high levels by comparison with other stages when water deficit was imposed. While in the 1999-2000 season, a control soil moisture level was fixed for the entire growing season. Figure 1 shows the mean grain production and its standard deviation for different treatment in two seasons for the pot experiment. Grain production was significantly reduced when severe and medium water stresses were applied from jointing to flowering stages during both seasons. The yield reduction was about 15%-20% for severe water stress and 5%-10% for medium water stress compared with the control treatment. At the jointing stage, light water stress didn't affect grain production. At the booting to heading stage, even light water stress slightly reduced grain yield. During revival, medium water stress produced even more grain than that for light stress in the 1999/2000 season. While in the 1996/1997 season, grain yields of the three treatments were not significantly different during this stage because there had been only slight differences in soil moisture. During grain filling, medium and light water stress produced the same yield as the control treatment in 1999/2000. Since evapotranspiration was strong at grain filling stage, the soil moisture levels for light, medium and severe water deficit at that stage in 1996/1997 was much lower, then medium water stress treatment also affected the grain production.

Table 2. Monthly and total seasonal rainfall (mm) for winter wheat from 1999 to 2002 and the long term average

Seasons	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
1999-2000	21.1	6.1	0.2	11.4	0.0	0.8	2.5	12.0	54.1
2000-2001	72.1	8.4	0	8.3	6.9	0.5	23.3	6.2	125.7
2001-2002	15.4	5.6	0	1.2	0	5.5	30.1	45.7	103.5
Average of 1951 to 2000	26.2	14.3	3.7	2.9	6.5	10.9	18.9	33.9	117.2

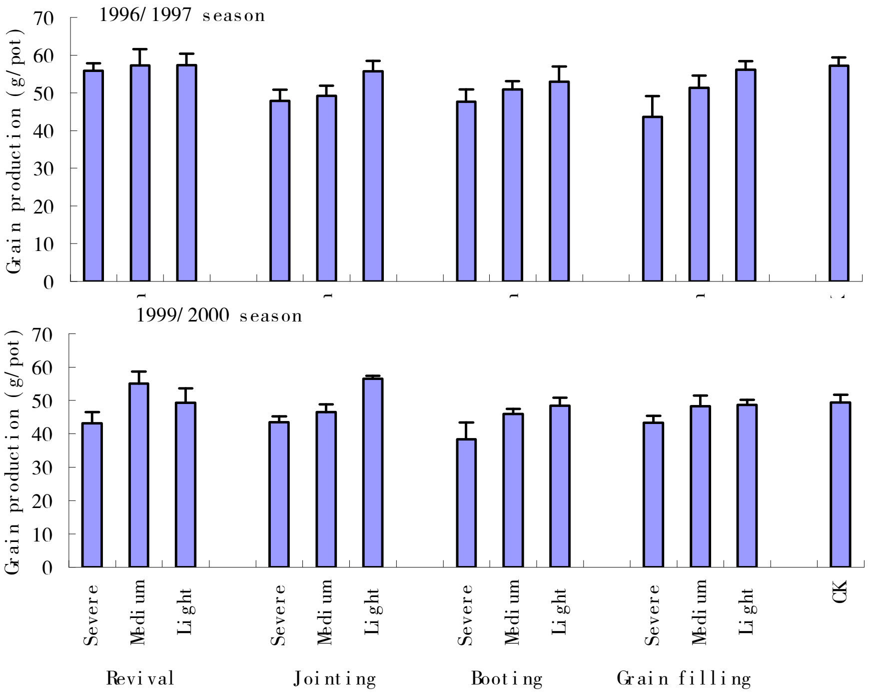

Figure 1 Grain production of winter wheat under different levels of water stress during four growth stages in 1996/1997 and 1999/2000 (pot experiments)

The above analysis showed that from booting to flowering was the most sensitive stage of winter wheat to water stress. At this stage even slight water stress could affect yield. Next was the jointing stage. During this stage severe and medium water stress both reduced grain production, but slight water stress could improve yield. During revival and grain filling stages, only severe water stress affected yield. Especially at the revival stage, medium water stress could favor grain production. Previous field results also showed that the most sensitivity stages to water stress of winter wheat was from jointing to flowering. The sensitivity to water stress index at revival and later grain filling stages were negative, indicating that moderate water stress at these two stages was favorable to grain production (Zhang *et al*., 2003; Yuan *et al*, 1992).

3.2 Water stress on yield components

Components of yield included spikelet number per unit area, kernel numbers per spikelet and thousand-kernel weight. Table 3 shows the effects on yield components of extent of stress during the four growth stages. Drought stresses during the reproductive stage could have large effects on yield and yield components (Pantuwan *et al.*, 2002). Water stress from jointing to anthesis significantly reduced spikelet numbers and kernel numbers per spikelet, but increased seed weight. The increased seed weight was not enough to compensate for loss of total kernel numbers per pot and yield reduction was unavoidable. During revival, water stress greatly increased spikelet numbers, but reduced both kernel numbers per spikelet and seed weight. The grain production of the medium water stress treatment was the highest since its total kernel numbers per pot was significantly higher than other treatments, even its thousand-grain weight was reduced in 1999/2000. A conclusion might be that the total kernel numbers per area are more important to grain production than one-thousand kernel weight. Severe water stress during grain-filling stage decreased seed weight, but slight water stress improved seed weight in 1999/2000.

Theoretically, increasing the number of kernels that comprise the sink even at the expense of kernel weight can increase grain yield (Duggan *et al.*, 2000). Figure 2 shows that there was a significant relationship between grain production and total kernel numbers per pot. No significant relationships were found between seed weight, spikelet numbers per pot or kernel numbers per spikelet and grain production per pot. Total kernel numbers per unit area greatly influenced grain yield.

Table 3 Water stress and stress degree at different growing stages of winter wheat on the effects of yield components in 1996/1997 and 1999/2000 (pot experiments)

Sea-sons	Yield compo-nents	CK*	Percentage increased or reduced (-) compared with CK											
			Revival			Jointing			Booting-flowering			Grain filling		
			L*	M*	S*	L	M	S	L	M	S	L	M	S
1996 /1997	SN*	46.7	0.7	0.6	0.0	-1.4	-6.4	-7.9	-7.1	-6.7	-8.5	-1.8	-1.2	-1.5
	KPS*	33.9	-0.7	0.0	-0.9	1.5	2.4	-1.2	-3.4	-9.5	-9.9	1.6	-1.8	-2.0
	KW*	36.1	1.3	3.4	-1.7	-5.3	0.2	0.4	2.2	3.0	2.6	-0.9	-5.6	-9.7
1999 /2000	SN	44	22	18	25	-9.0	-2.2	2.2	-9.0	-6.8	-16	0.7	-1.2	1.1
	KPS	30.5	-25	-12	-27	7.7	-16	-26	-1.2	-2.3	-18	0.1	1.7	-2.8
	KW	36.8	-8.7	-5.6	-10	6.5	9.8	4.2	2.3	3.5	7.2	0.5	-0.7	-11.5

*: CK: the controlled treatment; SN: mean spike number per pot; KPS: mean kernel number per spike; KW: thousand kernel weight (g); L: light water stress; M: Medium water stress and S: severe water stress.

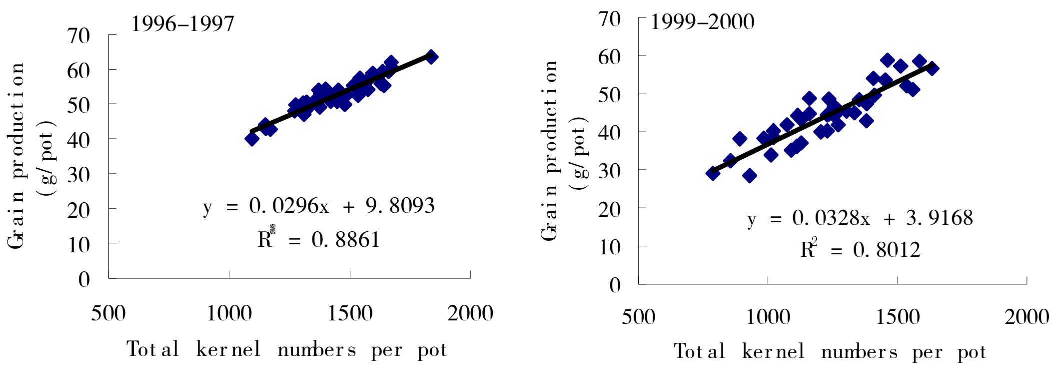

Figure 2 Relationships between total kernel numbers per pot and grain production in 1996/1997 and 1999/2000

3.3 Effects of irrigation on yield and WUE

Whilst rainfall conditions were different for the three seasons, the effects of irrigation application on yield and WUE were significant (P=0.01) and consistent. Figure 3 shows the grain production and WUE of different irrigation treatments for the three seasons. From no-irrigation to 2 irrigation applications, grain yield was improved by 20% in the dry season of 1999/2000. Since rainfall was very small during the winter wheat growing season, compared with its water requirements, water stored in the soil profile in this region played an important role in guaranteeing winter wheat production, even in very dry seasons. Winter wheat root systems generally reached 2 m deep and the 2 m soil profile could hold water more than 700 mm at field capacity (Zhang and Yuan, 1995). Before sowing winter wheat, soil moisture was usually good. So the rain-fed winter wheat could still produce an economic return even with little seasonal rainfall. Results from these three seasons showed that more than 200 mm soil water was used by the rain-fed winter wheat. For irrigated treatments, stored soil water still took up a considerable proportion of the total water consumed, ranging from a half to a quarter. Thus soil water stored before sowing winter wheat was very important for the high production of this crop.

Figure 3 also shows that for the same number of irrigation applications, there were significant differences (P=0.01) in yield and WUE because the difference in the timing of application. Yield and WUE of T2a and T3a were lower than that of T2b and T3b in all the three seasons. T2b was 4.1%, 28.9% and 5.7% higher in yield and 3.3%, 24.2% and 16.2% higher in WUE than T2a in the three seasons, respectively. T3b was 9.3%, 6.1% and 4.9% higher in yield and 15.8%, 6.3% and 13.2% higher in WUE than T3a in the three seasons, respectively. The difference in irrigation scheduling for T2a, T3a with T2b and T3b was that the former was arranged with irrigation earlier than later. Results from the pot experiment and other research showed that the reproductive period was generally the most sensitive stage to water stress. If irrigations were applied before the reproductive stage like T2a, though its spikelet numbers per area and kernel numbers per spikelet were not significantly different from T2b, its seed weight per thousand was 10%-15% lower than T2b. The situation was the same for T3a and T3b. So it was preferable to arrange the limited numbers of irrigation from jointing to earlier grain filling of winter wheat. Yuan et al. (1992) also recommended reducing the irrigations at seedling and revival stages.

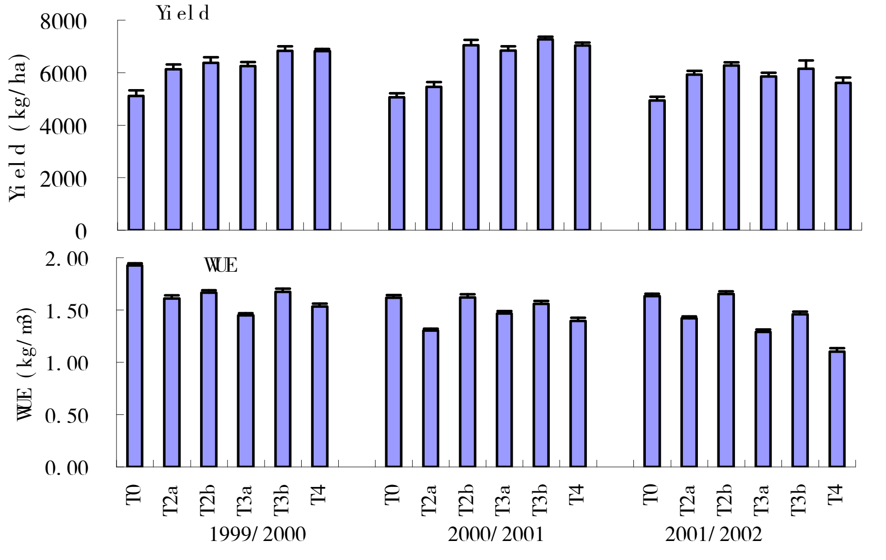

Figure 3 Yield and WUE for different treatments at the three seasons

Maximum production and WUE was not achieved with the most frequently irrigated treatment (T4) in the three seasons. In the dry season of 1999-2000, the T3b treatment produced the same amount of grain production as T4, but WUE of the former was significantly greater than the latter. In the wet seasons of 2000-2001 and 2001-2002, T2b and T3b produced the maximum level of production. Irrigation at the later grain-filling stage could also be omitted.

3.4 Modified water use efficiency

WUE calculated by equation (3) doesn't separate the irrigation benefit from that of rainfall and soil water (Howell, 2001). Bos (1980, 1985) developed expressions that can, perhaps, more consistently discriminate between the role of irrigation and other water on WUE. His expressions can be written for *ET*wue and *I*wue as:

$$ET\text{wue}=(Y\text{i}-Y\text{d})/(ET\text{i}-ET\text{d}) \quad (4)$$

$$I\text{wue}=(Y\text{i}-Y\text{d})/I\text{i} \quad (5)$$

where *Y*i is yield, *ET*i is *ET* for irrigation level *I*, *Y*d is yield and *ET*d is *ET* for an equivalent dryland or rainfed-only plot, and *I*i is the amount of irrigation applied for irrigation level i. ET is total evapotranspiration as calculated from equation (2). Based on these equations, *ET*wue and *I*wue were calculated for each treatment of the three seasons (Table 4). Results showed that in the 1999/2000 dry season, T3b had the maximum *ET*wue and *I*wue whilst, for normal conditions in 2000/2001 and 2001/2002, T2b produced the maximum *ET*wue and *I*wue. So the normal four times irrigation of winter wheat in this region could be reduced to three times in very dry seasons and to two times in other seasons. The timing of irrigation should be arranged from jointing to grain-filling period. It could be concluded that deficit irrigation of winter wheat not only improved water use efficiency and crop production, but also improved the benefit of irrigation water in the region studied. Timing of irrigation was also very important in ensuring this benefit.

4 Conclusions

Occurrence and extent of water deficit affected yield and yield components of winter wheat. During the critical period from jointing to booting, total spikelet and total kernel numbers per spikelet were determined, despite tiller formation taking

Table 4 Calculated ETwue and I wue to each treatments during the three seasons

Treatments	1999/2000		2000/2001		2001/2002	
	*ET*wue	*I*wue	*ET*wue	*I*wue	*ET*wue	*I*wue
T2a	8.8	8.5	3.8	3.4	8.7	8.3
T2b	10.7	10.6	16.4	16.5	17.5	11.1
T3a	6.8	6.3	11.6	9.9	6.2	5.1
T3b	12.0	11.2	14.5	12.2	10.3	6.7
T4	8.9	7.1	10.4	8.2	3.3	2.8

place during the over-wintering and crop revival stages. Thus limited irrigation should be arranged during this period. Results showed that deficit irrigation didn't reduce yield, especially when the irrigation scheduling was well managed. In regions of serious water shortage, deficit irrigation based on the crop characteristics should be applied and other options for enhancing WUE should be incorporated with irrigation management. These include crop management to enhance precipitation capture and reduce soil water evaporation, irrigation systems that apply water to crops efficiently; user participation in operation and maintenance and water pricing and legal incentives to reduce water use and improve water use efficiency (Wallace and Batchelor, 1997).

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Dynamic water production functions for rice in North China

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Abstract

Alternative forms of a dynamic production function were compared, which described dry matter accumulation and seed production for rice, based on data from lysimeters and ceramic pots. Response functions were obtained for the whole growing season and for three separate growth stages covering transplanting to tillering, jointing/ boot stage to heading/ florescence and milk stage to harvest, respectively Coefficients were determined for linear subsection functions of an incremental dry matter production function, based on the Morgan model. Exponential and third order polynomial functions were also fitted to the incremental growth rate functions. A dynamic rice production model was developed with coefficients being determined from data collected in 1998 in Shenyang. The model was then tested with data collected in 1999 and model sensitivity was examined. Results show that the model is well adapted to local conditions.

Key words: Rice; dynamic model; dry matter; water deficit; influence function.

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1 Introduction

1.1 Static and dynamic models

Crop water production functions can be divided into two groups, namely static and dynamic models. Static models depict macroscopic relationships between water and final crop dry matter or seed production. They don't represent the underlying mechanisms governing accumulation of dry matter. Dynamic water production models represent these processes as functions of soil water content. Dynamic models can simulate or forecast accumulated dry matter, together with crop growth status, for different levels of soil water content, as predicted by soil water movement within the soil-plant-atmosphere continuum (SPAC). Many dynamic models of water production functions for dry-land crops have been researched. Feddes (1978,1987) advanced a dynamic, mechanistic model and Morgan (1980) proposed a dynamic maize model. Currently, there is only a static rice water production function (Mao,1994) and no dynamic function has been reported. Studying rice dynamic water production functions has both theoretical significance and practical relevance, in optimizing irrigation management to realize sustainable water resources use, especially in North China.

1.2 Dynamic rice production model

Growth of rice is a continuous, though fluctuating, process. Increases in dry matter are monotonic, but accumulation rates can vary with growth stage. With sufficient water supply, Hanway (1963) considered that crop dry matter might be expressed by the following relationship for incremental dry matter accumulation:

$$C_d(t)/C_d(t-1) = ?\,(t) \qquad (1)$$

where Γ(t) is potential rate of dry matter increase, C_d(t-1) and C_d(t) are increments of increased dry matter for periods t - 1 and t, respectively. So maximum final dry matter yield can be expressed can be based on a multiplicative function:

$$YD(T) \;?\; YD_0 \mathop{?}_{t?1}^{n} \;?(t) \qquad (2)$$

where *YD* (*T*) is a maximum value of final dry matter production, YD_0 is dry matter production at time of starting calculation, n is number of time periods. Equation 2 is used to calculate dry matter production under sufficient water supply conditions. With adequate nutrients and in the absence of disease, soil water status becomes the main effect on crop growth. Since effects of water stress are cumulative, so stress in any growth period has an influence on final crop yield. Then, to represent actual incremental dry matter production, equation 1 must be modified as follows:

$$\frac{A(t)}{A(t\;?\;1)} \;?\; ?(t) \;?\; P(Am_t) \qquad (3)$$

where A(t) and A(t-1) are actual dry matter production for intervals "t" and "t-1", respectively, and P (Am_t) represents influence of water deficit. Deficit is represented by

$$Am_t \;?\; \frac{?_t \;?\; ?_{\min}}{1 \;?\; ?_{\min}} \qquad (4)$$

when $\theta_t = \theta_s$=100%=1, takes Am_t=1. where θ_t is average root zone water content at time t, expressed as a % of saturated soil water content (θ_s), $\theta_{\min}$ is the limiting soil water content, expressed as a % of θ_s, corresponding to a maximum root zone suction at which rice can remain alive. The value of P (Am_t) is 1, when soils are either saturated or ponded, corresponding to no soil water suction. It takes the value 1/Γ（t）when stress prevents growth. Using equation 3 rather than 1, then from equation 2, actual final dry matter yield is given by:

$$Y(T) ? YD_0 \overset{n}{\underset{t?1}{?}} ?(t) ? P(Am_t) \qquad (5)$$

where Y(T) is actual final dry matter production when suffers from different degree water stress for rice, YD_0 is dry matter production at time of starting calculation.

In general, seed production is expressed as follows:

$$Y_g ? YG_0 \overset{n}{\underset{t?1}{?}} ?(t) ? P(Am_t) ? MY \qquad (6)$$

where Y_g is seed production at harvest, (kg/ha). YG_0 is the potential seed production at time of starting calculation with $YG_0 = 0.6482 \times YD_0$, (kg/ha). MY being a constant, and MY = -1365.7 for rice, (kg/ha).

1.3 Morgan model

Morgan (1980) proposed that incremental dry matter accumulation was described by:

$$\Gamma(t) = t^{?} \quad \text{where} \ ? = x(Am) \qquad (7)$$

giving

$$Y(T) ? YD_0 \overset{n}{\underset{t?1}{?}} ?(t)^{x(Am_t)} \qquad (8)$$

and

$$Y_g ? YG_0 \overset{n}{\underset{t?1}{?}} ?(t)^{x(Am_t)} ? MY \qquad (9)$$

where x (Am_t) are linear functions describing dependence of growth rate on water content, for a particular growth stage.

$$x(Am_t) ? \begin{cases} a_1 Am_t ? b_1 & 0 ? Am_t ? Ams_1 \\ a_2 Am_t ? b_2 & Ams_1 ? Am_t ? Ams_2 \\ ? & ? \\ a_m Am_t ? b_m & Ams_{m-1} ? Am_t ? Ams_m ? 1 \end{cases} \qquad (10)$$

where Ams_i（i = 1，2，…，m）correspond with limiting values of soil water suction.

Since the functions P (Am_t), x (Am_t)should be monotonically increasing, so when $Am_t = 0$, $x(Am_t) = 0$; and when $Am_t = 1$, $x(Am_t) = 1$。This gives $b_1 = 0$, $a_i \times Ams_i + b_i = a_{i-1} \times Ams_{i-1} + b_{i-1}$. For the two boundary points and requirement that each section must join, a set of simultaneous equations is obtained from best fit lines to describe the measurements. These can be solved since here are more equations than unknowns.

Steps for determining a_i and b_i are based on data for periods of average suction and rooting depth of different growth stages. (1) To calculate the availability comparative soil water suction (Am_t); (2) to linearise formula (7) and (8) as follow:

$$InY(T) ? InYD_0 ? \overset{n}{\underset{1}{?}} x(Am_t) ?(t) \qquad (11)$$

For $x(Am_t)$ being linear function of subsection, they are linear equations about parameters (a_i, b_i, i=1,2,…m). Based on equation (9), the accumulative total of above items in equation (11) can be expressed as follows:

$$In(Y_g ? MY) ? InYG_0 ? \overset{n}{\underset{1}{?}} x(Am_t) ?(t) \qquad (12)$$

where T_i expresses that there are T_i（i=1，2，…，m）days in full growth period with soil water suction range of（Ams_{I-1}，Ams_i）.

$$\overset{n}{\underset{1}{?}} x(Am_t) ? ?(t) ? \overset{m}{\underset{i=1}{?}} \overset{T_i}{\underset{t=1}{?}} (a_i ? Am_t ? b_i) ? ?(t_i) \qquad (13)$$

Using least squares fits and formula (10), the parameters "a_i, b_i"(i = 1,2,…,m) and YD_0 can be determined.

1.4 Reference (9) model

Reference (9) proposed a continuous function for corn soil water response.

$$? ? e^{Am_t}(Am_t^{?} ? 1) \qquad (14)$$

Equation 14 meets the three control conditions: (1) x (Am_t) should be monotonically increasing; (2) when $Am_t = 0$, $x(Am_t) = 0$; and (3) when $Am_t = 1$, $x(Am_t) = 1$。so accumulated growth is given by:

$$W(D) ? W(0) \overset{D}{\underset{t?1}{?}} ?(t)^{1? e^{m_t}(Am_t^{\beta} ?1)} \qquad (15)$$

where D is total days of calculation, W(D) is the accumulation production of dry matter in D days from the start time, W(0) is the production of dry matter at the start time.

There are only two unknown variables W(0) and β in equation (15), which can be calculated from observed data. Taking logarithms to right and left of equation (15) gives:

$$InW(D) ? InW(0) ? \overset{D}{\underset{t=1}{?}} In?(t) ? \overset{D}{\underset{t=1}{?}} e^{m_t} In?(t) ? \overset{D}{\underset{t=1}{?}} Am_t^{\beta} ? e^{m_t} ? In?(t)$$

then expressing $Am_t^{?}$ as a series gives

$$InW(D) ? InW(0) ? \overset{D}{\underset{1}{?}} ?(t) ? \overset{D}{\underset{1}{?}} e^{Am_t} In?(t) ?$$

$$\overset{D}{\underset{1}{?}} e^{Am_t} ? In?(t) ? [1 ? (InAm_t) ? ? ? \frac{(InAm_t)^2}{2} ? ?^2 ? \frac{(InAm)^3}{3?2} ?^3 ? ?]$$

Let $InW(D) ? \overset{D}{\underset{t?1}{?}} In?(t) ? c; InW(0) ? a;$

$e^{Am_t} ? In?(t) ? F$, so then

$$C ? a ? \overset{D}{\underset{1}{?}} F ? [(InAm_t) ? ? ? \frac{(InAm_t)^2}{2} ? ?^2 ? \frac{(InAm)^3}{3?2} ?^3 ? ?] \qquad (16)$$

2 Materials and methods

Experiments were conducted at the irrigation experimental station of Shenyang Agricultural University from 1998 to 1999. There were 12 reinforced concrete lysimeters, each 2.5m×2.0m and 2.3 m depth. Effects of soil water stress on rice yield were also measured with 39 ceramic pots. Soil moisture potential levels were used as indices to control irrigation. Each growth stage had 4 levels of water supply. The control (CK) was a shallow water supply during all growth stages, which had a lower limit of 30kPa soil moisture potential only in the final tillering stage. The 3 other treatments were different levels of drought. Gentle, moderate and severe degrees of stress were defined by 30～40 kPa, 40～50 kPa and 50～60 kPa potentials, respectively. Treatments 1, 2 and 3 were those treatments that suffered different degrees of drought up until mid-term tillering. Treatments 4, 5 and 6 were those with drought prior to the booting stage. Treatments 7, 8 and 9 were the treatments with drought during the heading stage and anthesis, while treatments 10, 11 and 12 were the treatments with drought in the milk maturity stage. The 39 pots were randomly arranged with 13 irrigation treatments, using three replicates. Soil water tension was measured by U type mercury tensiometers made by Nanjing Soil Physics Institute.

3 Results

The Figure 1 shown beneath is a water response function for the whole growing period.

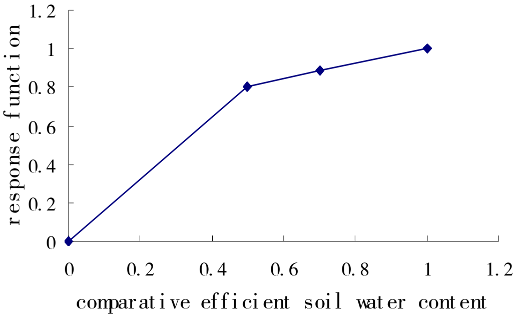

Figure 1. Response function describing effects of water stress

A mathematical model, found to fit the experimental data, is as follows:

C_d = -2E-06 t^3 + 0.0003 t^2 - 0.0085 t + 0.0482

R^2 =0.992 (17)

where C_d is relative accumulation of dry matter and t is number of days from transplanting.

Results showed that rice dry matter production was linked to obvious growth stages, similar to corn and wheat. The first phase is from transplanting to mid-term tillering, which is very sensitive to water deficit. To research effects on rice yield of water stress in different growing stages, the whole growing period was divided three phases: rice transplanting stage to tiller stage, jointing and boot stage to heading and florescence, milk stage to harvest respectively. Corresponding coefficients were calculated for the respective water response function shown in Figure 2.

Treatment regimes could be divided into three parts based on relative soil water content. Based

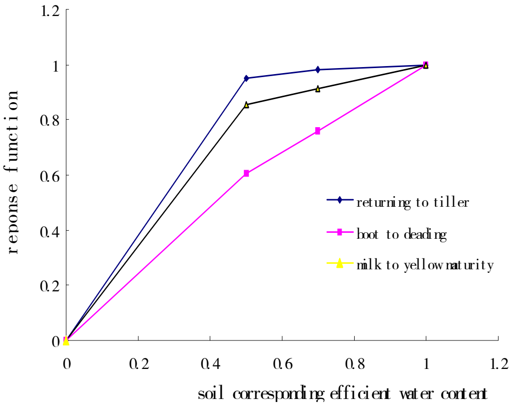

Figure 2. Water response function of three periods

on the fitted variance and double correlation coefficient both being optimal, distinct water stress sections of Figure 2 were identified as the soil water efficiency sections (0.7,1), (0.5,0.7), (0,0.5), respectively. These represent light (0-40 kPa water soil suction), moderate (40-50 kPa water soil suction), and severe (50-60 kPa water soil suction) water stress parts. Critical values of soil water content were $Ams_1 = 0.5$， $Ams_2 = 0.7$, as shown in Figure 2. Coefficients were fitted to linear relationships describing each part of the response functions shown in Figure 2. These are given in Table 1.

As seen from Figure 2, sensitivity of rice to water stress in the three periods is rather similar. Results also showed that rice dry matter accumulation is linearly related to seed production by:

$Y_g = 0.6482\ YD - 1365.7$ （18）

where Y_g and YD are seed and dry matter production, respectively, (kg/ha) at harvest.

The random selection of linear relationships put forward by Morgan, to artificially partition the response function, can be improved. While it is true that, the greater the number of relationships is, the better is water response representation, but the difficulty of determining coefficients becomes greater. When the data for 1998 is analyzed to fit the model in equation 19, using nonlinear regression, the results obtained are those in Table2. It is possible that ? is best described by a third order polynomial, given by:

$$? \ ? \ ?Am_t^3 \ ? \ bAm_t^2 \ ? \ cAm_t \ ? \ d \qquad (19)$$

Based on the earlier discussion covering selecting values of P (Am_t), the coefficients in equation (19) can be determined using $c \ ? \ 1 \ ? \ a \ ? \ b$. Using data for 1998, the fitted coefficients are as given in Table 3.The change of ? with efficient soil water suction is shown in Figure 3.

Table 1. Coefficients of incremental growth rate functions ?

Growth stage	a_1	a_2	b_2	a_3	b_3	Y_0	Correlation coefficient	material
Whole growing period	1.60	0.45	0.575	0.367	0.633	0.3	0.826	dry matter
Transplanting to the end of tiller	1.90	0.15	0.875	0.07	0.93			
Jointing and boot stage to heading and florescence	1.208	0.785	0.212	0.797	0.203	0.4	0.871	dry matter
Milk to yellow maturity	1.71	0.3	0.705	0.283	0.717			

Table 2. Coefficients of exponential ? function

Growth stage	β	$X(0)$	correlation coefficient	production data
Full growth period	0.2019	0.33	0.87	dry matter

4 Discussion

4.1 Response function models

Yield of rice was forecast using all the on the response function models described above, based on the 1999 data. The production forecasts agreed well with the actual production values and the results of tests are presented in Figure 4.

4.2 Sensitivity analysis

Results of model tests using 1999 data showed that a dynamic production model deduced from the 1998 data, could forecast crop yield for of drought effects. To examine model sensitivity and analyze the effect of different test treatments on fitted parameters, a sensitivity analysis was carried out on parameters the linear subsections, based on the 1998 experimental treatments. The results are given in Table 4.

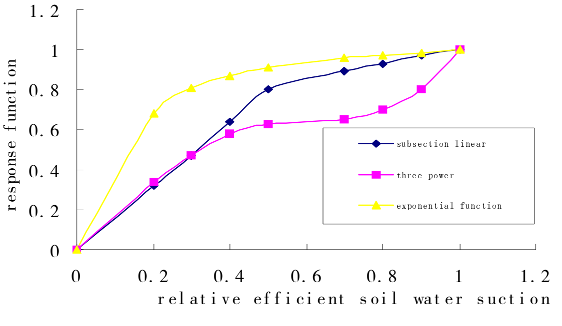

Fig.3 The change of α in different function form with relative efficient soil water

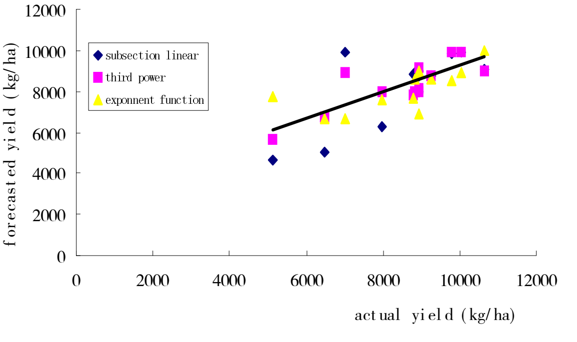

Fig.4 The results of models testing with the data measured in 1998 and

Table 3. Coefficients when ? is a third order polynomial

Growth stage	a	b	c	Y_0	correlation-coefficient	production data
Full growth period	0.947	-2.419	2.472	1.3	0.812	dry matter

Table 4. Parameter comparison of different treatments

Sequence number	a_1	a_2	b_2	a_3	b_3	production data
① taking out treatment 10,11and12	1.55	0.47	0.542	0.43	0.57	dry matter
② taking out treatment 1,2 and 3	1.46	0.54	0.46	0.54	0.46	dry matter
③ taking out treatment 4, 5 and 6	1.62	0.44	0.59	0.35	0.65	dry matter
④ taking out treatment 7, 8 and 9	1.59	0.39	0.60	0.42	0.58	dry matter
⑤ all test data	1.60	0.45	0.58	0.37	0.63	dry matter

5 Conclusions

Incremental dry matter data for 1998 was analyzed and results used to make projections for rice production in 1999. The dynamic production model could efficiently estimate rice yield under different water supply conditions. The results show that a third power polynomial function and a group of linearised subsections are consistent relatively, with the two functions being almost superposed during periods of water severe stress. But the exponential function is close quite to that of the linear subsections in the period of moderate and light water deficit. Differences of model precision are not large, arising from using the whole growing period or partial phases of the water response function. Both methods show that the sensitivity of rice growth to soil water deficit is high in the range of severe water deficit above 50 kPa. With a reduced degree of soil water deficit the reduced growth diminishes rapidly. In the range of moderate water deficit, the sensitivity of rice growth to soil water deficit is low**.**

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Physiological effect of new anti-transpirant application on maize

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Abstract

The physiological effect of a new anti-transpirant on maize was studied by field trial. It was sprayed at 10 days before heading stage (A), ear filling stage (B) and 10 days before heading stage + ear filling stage (C), using the following concentrations: 0.5, 1.0, 1.5 and 2.0 ml/l. The results indicate that new anti-transpirant raised nitrate reductase activity (NRA), free proline content, chlorophyll content and water content of leaves, thus drought stress can be mitigated. It also raised the photosynthetic rate and reduced transpiration rate, led to growth stimulation and water loss reduction. The results indicate that treatment (C) has a cumulative effect compared with treatment (A) and (C), except for NRA. Grain yields were increased by 5.4% to 29.6%, depending on the different treatments. Optimal concentration was 1.5 ml/l, and the optimal application period was 10 days before heading stage + ear filling stage (C).

Key words: Anti-transpirant; *maize*; physiological effect; drought stress.

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1 Introduction

An anti-transpirant is a material which can reduce the transpiration rate and water loss of plants by application to the leaves (Wang, 2000). They are traditionally classified as metabolic, film-forming and reflecting anti-transpirants. No bi-functional anti-transpirant shows both metabolic regulation and film-forming effects. So there is a great need for research on such an anti-transpirant.

The major component of the new anti-transpirant used in this trial is Fulvic acid (FA). It can reduce stomatal opening status and form a film on leaves after spraying, so it is a bi-functional anti-transpirant. Field trials have been very limited (Peng 1999), so it is necessary to carry out field trials to test its effect under field conditions. Water shortage is the most important factor that restrains corn yield in arid and semiarid areas in north China. The purpose of this trial is to test the regulatory effect of the new anti-transpirant on maize, so as to give the optimal concentration and application period.

2 Materials and methods

2.1 Experimental plot and plant species

The experimental plot was set up in Taiyuan, Shanxi province. The soil texture at this site is calcium carbonate brown soil and the pH is 7.6. "CAU 108" was chosen as the trial maize species. The new anti-transpirant was sprayed at 10 days before heading stage (A), ear filling stage (B) and 10 days before heading stage + ear filling stage (C), using the following concentrations: 0.5, 1.0, 1.5 and 2.0 ml/l, comparing the treatments non-application (Control), water application and FA-P (1.5ml/l). The area of each treatment is 2.6×3.0m^2 with 3 repeats.

2.2 Determination of physiological indices

Photosynthesis rate (PR), transpiration rate (TR) and stomatal conductance (SC) were measured with a portable photosynthesis system (CI-301, CID, Inc., Washington, U.S.A.) from 9.0am to 11.0am. Nitrate reductase activity (NRA) was measured by sulfanilic acid colorimetry (Shanghai Society for Plant Physiology, 1985). Free proline content (FPC) was measured by sulfosalicylic acid extraction and colorimetry (Zhu, 1983). Leaf chlorophyll content (LCC) was measured by colorimetry (Zhu, 1990). Hp-7550 spectrophotometer was used for these three indices' measurement. Wet weight and dry weight were measured to determine leaf water relative content (LWRC). Weight per hundred grains, grain number per spike and yield of every treatment was determined when harvested.

3 Results and discussion

3.1 Photosynthesis rate (PR)

Photosynthesis rate (PR) under each concentration level of new anti-transpirant increased compared with CK, though 1.0 and 1.5 ml/l concentrations had the more obvious effect. Spraying twice had a greater cumulative effect on PR increase than a single spray (Figure 1 to 3). The effect on PR of the new anti-transpirant was no longer obvious after 18 days (Figure 1). Compared with FA-P, another effective metabolic anti-transpirant, the effect of new anti-transpirant was more obvious under 1.5 ml/l, while not as obvious as FA-P under 0.5ml/l.

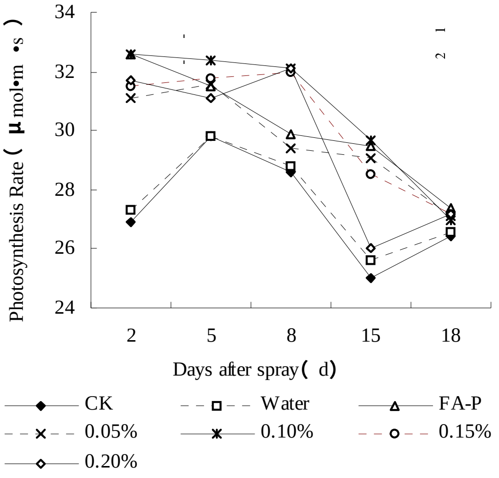

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Fig.1 Effect on photosynthesis rate of different treatments (A)

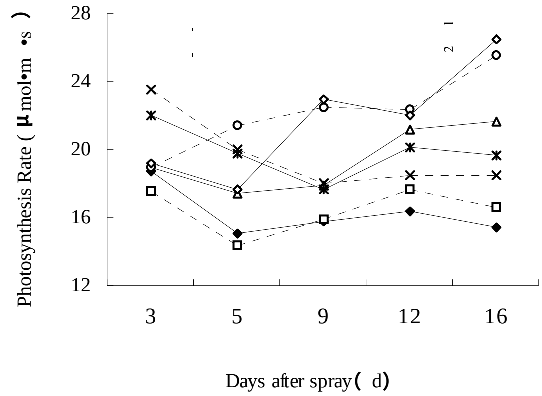

Fig.2 Effect on photosynthesis rate of different treatments (B)

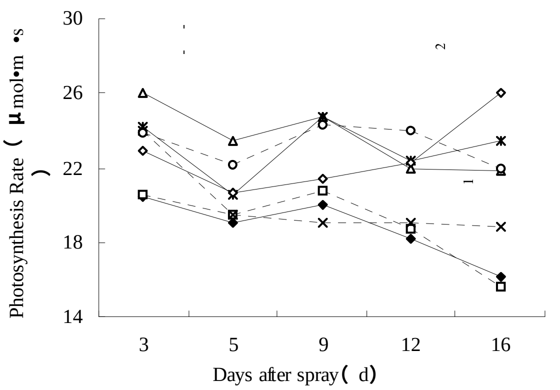

Fig.3 Effect on photosynthesis rate of different treatments (C)

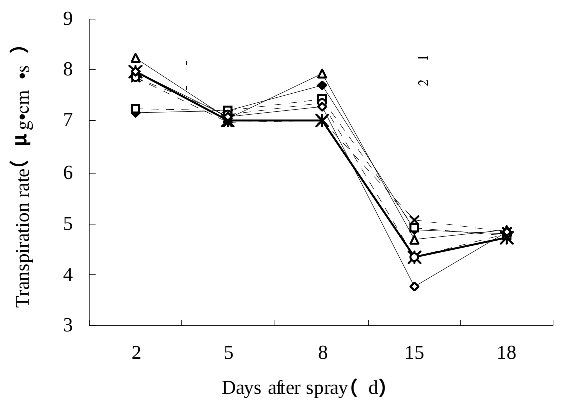

Fig.4 Effect on transpiration rate of different treatments (A)

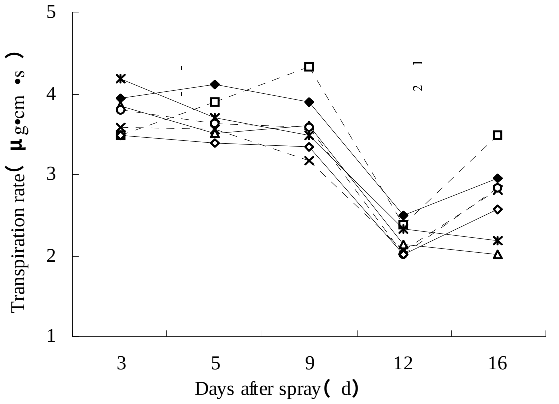

Fig.5 Effect on transpiration rate of different treatments (B)

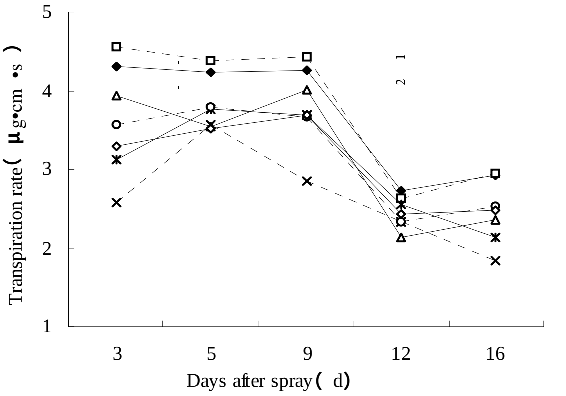

Fig.6 Effect on transpiration rate of different treatments (C)

Table 1 Rate of change in chlorophyll content of leaves under different treatments (%)

Treatment times	Water	FA-P	New anti-transpirant (ml/l)			
			0.5	1.0	1.5	2.0
10 Days before heading stage (A)	4.26	8.7	12.0	10.2	11.8	11.6
Ear filling stage (B)	-0.57	8.6	8.1	10.0	16.3	13.4
10 Days before heading stage + Ear filling stage (C)	1.90	15.6	18.3	17.6	18.1	22.6

3.2 Transpiration rate (TR)

In treatment A, the first measurement of the new anti-transpirant didn't show any anti-transpiration effect, (Figure 4). In treatment B and C, both the new anti-transpirant and FA-P had an anti-transpiration effect (Figures 5 and 6). The new anti-transpirant had a cumulative effect when sprayed twice as compared to a single spray. The anti-transpiration effect of the new anti-transpirant was not obvious after 18 days. The new anti-transpirant had more effective anti-transpiration effect than FA-P under every treatment and concentration, except the concentrations 1.0 and 1.5 ml/l at ear filling stage.

3.3 Leaf chlorophyll content

Each concentration raised leaf chlorophyll content (LCC) (Table 1), among which concentration 2.0 ml/l had the most obvious effect. There was a largest relative increase, 53.2%, of LCC of new anti-transpirant than CK under this concentration. LCC increase effect of new anti-transpirant under treatment C was better than treatment A and B. LCC increase effect of new anti-transpirant was more effective than FA-P, except concentration 0.5 ml/l.

3.4 Nitrate reductase activity (NRA)

Water stress can reduce NRA, so NRA is an important anti-stress physiological index. Each concentration increased NRA, with effects of 1.0 and 1.5 ml/l concentrations being more obvious. NRA in treatment C was less than treatment B, except for the 1.5 ml/l concentration, so there wasn't a cumulative effect of the new anti-transpirant on NRA after a second spray. The ratio of NRA increase, relative to the control, for each concentration of the new anti-transpirant in treatment A was greater than that of FA-P, while those of treatment B were smaller than FA-P. In treatment C, NRA ratios were larger than the control at 1.0 and 1.5 ml/l concentrations and smaller than for FA-P at 0.5 and 2.0 ml/l concentrations. (Table 2).

3.5 Free proline content

Free proline accumulation in plant under water stress can reduce water loss of plant. There were both increases and reductions of free proline content for different concentrations, and rates of increase were larger than the reductions on the whole. Increased rate of free proline content of new anti-transpirant in treatment C was larger than that in treatment A and B. Free proline content increase rate of new anti-transpirant under each concentration was larger than that of FA-P. (Figures 7 - 9).

3.6 Relative water content (RWC) of leaf

New anti-transpirant increased relative water content of leaf, and the increase effect of concentrations 1.0, 1.5 and 2.0 ml/l in treatment C were better than that in treatment A and B. The increase of RWC of concentrations 1.5 and 2.0 ml/l were larger than that of FA-P. (Table3).

Table 2 Nitrate reductase activity (NRA) change rate of leaf under different treatment (%)

Treatment times	Water	FA-P	New anti-transpirant (ml/l)			
			0.5	1.0	1.5	2.0
10 Days before heading stage (A)	5.7	15.6	26.8	19.0	28.4	36.5
Ear filling stage (B)	11.7	66.0	29.3	49.8	37.9	50.9
10 Days before heading stage + Ear filling stage (C)	4.3	42.0	25.1	42.8	43.1	26.2

Table 3 Relative water content (%) change rate of leaf under different treatment (%)

Treatment times	Water	FA-P	New anti-transpirant (ml/l)			
			0.5	1.0	1.5	2.0
10 Days before heading stage (A)	-0.01	0.36	0.91	1.18	1.29	1.35
Ear filling stage (B)	-0.21	1.15	0.80	0.61	1.92	1.04
10 Days before heading stage + Ear filling stage (C)	0.40	1.32	0.65	1.23	2.08	1.83

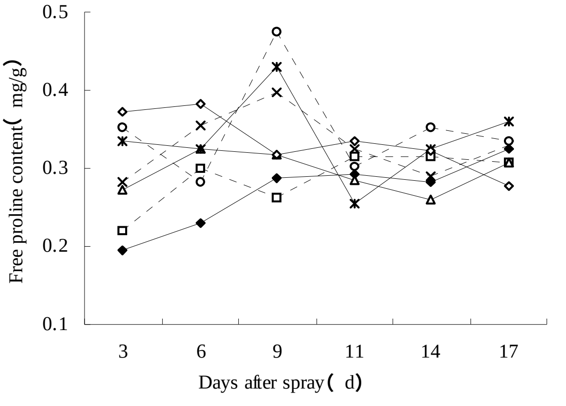

Fig. 7 Effect on free proline content of different treatments (A)

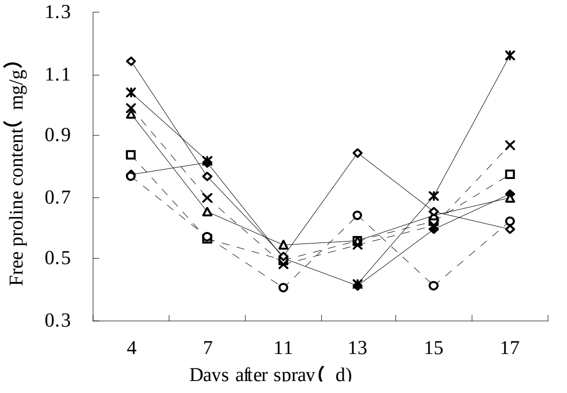

Fig. 8 Effect on free proline content of different treatments (B)

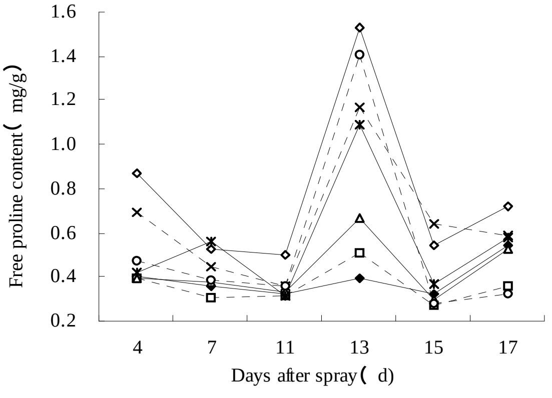

Fig. 9 Effect on free proline content of different treatments (C)

3.7 Stomatal conductance

Stomatal conductivity increased with each concentration. The concentration 1.5 ml/l had the most obviously increase rate compared with CK. The increased rate at 1.5 ml/l was larger than that of FA-P in treatments A and C. (Table 4).

3.8 Yield analysis

There was a yield reduction at a concentration of 2.0 ml/l compared with CK and three other concentrations increased yield in different rates

Table 4 Stomatal conductivity changes under different treatments (mmol $m^{-2} s^{-1}$)

Treatment times	Water	FA-P	New anti-transpirant (ml/l)			
			0.5	1.0	1.5	2.0
10 Days before heading stage (A)	-0.5	33.9	17.5	29.0	38.5	27.9
Ear filling stage (B)	6.6	36.6	21.9	27.3	35.9	23.6
10 Days before heading stage + Ear filling stage (C)	0.8	32.9	17.0	28.8	35.0	22.9

Table 5 Weight per 100 grain (g) under different treatments

Treatment times	Control	Water	FA-P	New anti-transpirant (ml/l)			
				0.5	1.0	1.5	2.0
10 Days before heading stage (A)	24.9	23.9	25.0	25.1	23.6	24.0	24.9
Ear filling stage (B)	25.6	25.1	26.2	27.8	26.1	26.9	24.7
10 Days before heading stage + Ear filling stage (C)	22.3	24.9	23.9	25.4	23.0	25.3	23.4

Table 6 Grain number per spike under different treatments

Treatment times	CK	Water	FA-P	New anti-transpirant (ml/l)			
				0.5	1.0	1.5	2.0
10 Days before heading stage (A)	558	600	585	621	696	668	509
Ear filling stage (B)	543	568	612	527	559	556	502
10 Days before heading stage + Ear filling stage (C)	592	601	615	587	609	676	560

Table 7 Yield under different treatments (kg/ha.)

Treatment times	CK	Water	FA-P	New anti-transpirant (ml/l)			
				0.5	1.0	1.5	2.0
10 Days before heading stage (A)	4811	4954	5063	5400	5682	5542	4380
Ear filling stage (B)	4802	4936	5543	5082	5060	5179	4288
10 Days before heading stage + Ear filling stage (C)	4565	5182	5097	5156	4847	5915	4530

from 5.37% to 29.58%. The increase in yield mostly resulted from grain number per spike. There was a cumulative effect of yield increase at 1.5 ml/l. But the increase was not statistically significant, at a level of α=0.05. Rates of yield increase by the new anti-transpirant in treatments A and C were larger, while in treatment B it was less than that of FA-P. (Table 5 to 7).

4 Conclusions

The new anti-transpirant reduces transpiration rate by covering stomata and diminishing stomatal opening status. Stomata are the main means of water loss and CO_2 absorption, so there should be an appropriate concentration to assure that there is no reduction in photosynthesis rate. The optimal concentration is 1.5 ml/l, and the optimal application period is 10 days before heading stage + ear filling stage (C). The effect of the new anti-transpirant on yield, at its optimal concentration, was more effective than FA-P.

The effect of the new anti-transpirant on photosynthesis rate, transpiration rate, NRA and free proline content were not clear even after 2 to 3 weeks. This time period depends on the differences in the weather, crop species, the plants themselves and so on.

The new anti-transpirant had a cumulative effect on yield increase under double application while FA-P didn't have such an effect. This conflicts with the results of FA-P on winter wheat (Gan, 1995), and perhaps results from the difference in crop species and soil water and fertility conditions.

The major component of the new anti-transpirant is fulvic acid (FA) which has the advantage over other anti-transpirants of being abundant, cheap and non-harmful, so FA anti-transpirant represents the new research direction for anti-transpirants. Research work in the future should emphasise optimal concentration for different crop species and the effects under field conditions.

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Effects of brackish water use and dynamic soil salt content balance in very-early maturing cotton planting area

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Abstract

The soil salt content could be balanced over the years in brackish water areas, where annual precipitation is less than 110mm and the absolute frost-free season is 120 days. Many years of field experiments have shown that before sowing cotton, fields must first be soaked with river water having a salt level less than 1g/l. Yield of un-ginned cotton could be more than 300 kg/mu, or 400 kg/mu if low arch shelves were used. This is based on irrigating cotton twice, with brackish water of up to 5g/l salt content. Irrigating once with brackish water reduces yield and root-layer salt accumulates. Irrigating 3 times, generates an improvement for one year but there are subsequent losses due to long term salt accumulation. Four irrigations create severe problems. So, applying brackish water to irrigate cotton is an appropriate water saving measure. It is an effective way for farmers in underdeveloped brackish water regions to improve their well-being.

Key words: Super-early maturing cotton; application of brackish water; soil salt content balance.

1 Introduction

Being different from that with fresh water, irrigation with saline water should not only consider a crop's water demand, but also control concentration of soil salt. That is, the accumulation of salt should not exceed soil's salinity tolerance. The key to saline water irrigation management is ensuring that precipitation or irrigation can leach increased salt from saline irrigation water. A stable salt content should be reached over the years. When irrigating with saline water, salt content in the cultivated layer should be controlled so as not to exceed the crop's tolerance; soil solution concentrations also should be controlled to not exceed a crop's physiological limits These are usually salt contents of 10-12g/l. In brackish water areas, with salt contents higher than 5g/l, cotton fields must be soaked with river water before sowing. Experiments were conducted with different irrigation times and amounts to seek a good irrigation technique that can maintain a long-term soil salt balance and meanwhile realize high yields. Such techniques can guide farmers in backward arid areas in using brackish water to irrigate cotton and encourage cotton planting so that these people might become better off.

2 Materials and methods

Experiments were conducted at an experimental station near a lake area, in Mingqing County. The soil texture is light sandy loam and has moderate water permeability. Before storage irrigation, soil salt contents for a 0-100cm depth were 0.31%~0.49%, 0.4%~0.7%, 0.2% and 0.1%~0.7%, respectively, in the years 1995, 1996, 1997 and 1998. The bulk density, specific gravity, porosity and maximum field capacity values were 1.55g/cm^3, 2.64, 41.3% and 20.8%, respectively. Local ground water was used to irrigate a cotton field, which had salt contents of 4.97, 5.47 and 6.70 g/l, respectively, in the years 1996, 1997 and 1998. Taking no irrigation as the comparison, four patterns of irrigation were examined, with practices being replicated 3 times in 1996, and twice in 1997 and 1998. The experimental plan is shown in Table 1.

3 Results

3.1 Saline water irrigation and cotton yield

Table 2 shows that cotton yields were raised with increasing irrigation applications. Yield was lowest with no irrigation, the average being 34.2~52.5 kg ginned cotton per mu. For irrigation once, average yield was 46.7~65.5 kg, or 32.3% higher than that in comparison with no irrigation. Irrigation twice generated 64.7~105.1 kg/mu, that is a 91% increase. Average yields were 73.1~113.6 kg/mu with irrigation 3 times. When combined with shed mulching, which was set up in 1996 and 1997, average yield was 175.7 kg and 147.9 kg, or 313% higher, based on three irrigations for the whole season.

3.2 Effects of salt content of soil and water quality on cotton yield

Table 3 shows that salt content for the 0-100cm depth was lowest in 1997, with an average value for the 4 treatments of 0.22%, being 15.9% lower than in 1995 or 35% lower than in 1996.

Ginned cotton yield was also highest in 1997, which was 13.8% higher than that in 1995 and 53.7% higher than in 1996. In 1997, soil salt content of all treatments was lower than 0.3%, while ginned cotton yield surpassed 100 kg/mu with irrigation twice and it surpassed 113 kg/mu with irrigation 3 times. So, under specific conditions, relatively high yields could still be reached when highly mineralized water was applied, as long as irrigation was conducted in a proper way.

When the irrigation application amount was 50 m^3/mu, by comparison with brackish water, Table 4 shows that cotton yield decreased significantly after irrigation with saline water. But when the irrigation amounts were 80 m^3/mu and 130 m^3/mu, the yield almost no different. Relatively high yield and improved quality of cotton were attained when sheds and mulch films were also used.

3.3 Salt content change in cotton growth period

Generally speaking, from Table 5 it can be seen that soil will accumulate salt when is irrigated with saline water. But after rainfall leaching or using a large quota of river water, it can be desalted to reach a balanced salt content and there is no long-term salt accumulation. Experiments showed that the 0-100 cm soil depth was desalted during sowing to cotton harvest in 1995, while soil of all cotton fields had accumulated salt when irrigated with brackish water in 1997. The phenomenon was connected with the different hydrological years and variation of ground water level.

Table 1. Experimental plan for mulched cotton in brackish water area

Treatments	Irrigation amount (m^3/mu)	Irrigation once		Irrigation twice		Irrigation 3 times	
		Growth period	Irrigation amount	Growth period	Irrigation amount	Growth period	Irrigation amount
No irrigation							
Irrigation once	50			Start of flowering	50		
Irrigation twice	80~100	Budding	30~50	Start of flowering	50		
Irrigation 3 times	130	Budding	30~50	Start of flowering	50	Middle of boll	50
Low arch shed	80~100	Budding	30~50	Start of flowering	50	Increase irrigation times in drought year	

Table 2. Results of brackish water irrigating cotton from 1995 to 1997

Year	Treatments	Irrigation (m^3/mu)	Ginned cotton yield (kg/mu)	Range yield increase (%)
1995	No irrigation	0	52.5	
	Irrigation once	50	64.3	22.3
	Irrigation twice	80~100	84.8	61.4
	Irrigation 3 times	130~150	90.0	71.4
1996	No irrigation	0	34.2	
	Irrigation once	50	46.7	36.5
	Irrigation twice	80~100	64.7	89.18
	Irrigation 3 times	130~150	70.1	105.0
	Low arch shed	130~150	175.7	413.6
1997	No irrigation	0	47.7	
	Irrigation once	50	65.5	38.0
	Irrigation twice	80~100	105.1	121.6
	Irrigation 3 times	130~150	113.6	139.6
	Low arch shed	130~150	147.9	211.8

Table 3. Soil salt contents and cotton yield for brackish water irrigation from 1995 to 1997

Irrigation times	1995		1996		1997	
	Salt content in 0-100cm after harvest (%)	Cotton yield (kg/mu)	Salt content in 0-100cm after harvest (%)	Cotton yield (kg/mu)	Salt content in 0-100cm after harvest (%)	Cotton yield (kg/mu)
0	0.222	52.5	0.276	34.2	0.177	47.4
1	0.302	64.3	0.496	46.7	0.257	65.5
2	0.290	84.8	0.499	64.7	0.269	105.1
3	0.256	90.0	0.557	70.1	0.191	113.6
Average	0.267	72.9	0.457	53.9	0.224	82.9

Table 4. Influence of different water quality on cotton yield and quality

Process	Water quality	Irrigation (m^3/mu)	Plant height (cm)	Boll number of each plant	Single boll weight (g)	Number of twigs per plant	Ginning outturn (%)	Length of velveteen (mm)	Yield of ginned cotton (kg/mu)
Mulched cotton	Brackish water	50	49.5	7.2	3.83	6.8	37.4	34.4	115.9
		80	57.9	7.4	3.82	6.6	36.6	34.4	119.4
		130	61.2	7.0	3.72	6.0	37.2	33.0	113.8
	Saline water	50	36.3	4.7	4.29	4.2	38.1	47.3	65.5
		80	44.6	6.7	4.14	5.3	36.7	47.8	105.1
		130	44.4	7.3	3.87	6.0	35.6	47.6	113.6
Shed and mulched cotton	Brackish water	130	56.4	8.8	4.77	6.8	41.1	36.6	194.0
	Saline water	130	62.3	8.5	4.73	7.1	36.2	48.7	147.9

Table 5. Change of soil salt content during cotton's growth period

Year	Treatment	Before sowing		After harvest		Whole growth period
		Salt content (%)	Total salts (kg/mu)	Salt content (%)	Total salts (kg/mu)	Salt changes (kg/mu)
1995	No irrigation	0.284	2837	0.202	2013	-824
	Irrigation once	0.565	5640	0.352	3515	-2125
	Irrigation twice	0.432	4317	0.256	2558	-1758
	Irrigation 3 times	0.485	4842	0.322	3210	1632
1997	No irrigation	0.216	2158	0.177	1770	-387
	Irrigation once	0.216	2158	0.256	2561	+403
	Irrigation twice	0.141	1403	0.269	2688	+1285
	Irrigation 3 times	0.141	1403	0.191	1910	+507

Charts of soil salt content changes are given in Figures 1-3 for 0-20, 0-60 and 0-100 cm depths. These are based on the different treatments and irrigation amounts from 1995 to 1998. The results showed that:

(1)Soil salt content was basically in balanceor dropped slightly. Soil salt content of the surface 20cm layer was 0.19~0.28 before storage irrigation in 1995 and 0.18~0.28 in 1998. Salt content of the shallow and intermediate layer (0-60cm) was 0.30~0.37 in 1995 and 0.20~0.25 in 1998. A fall of 30% is apparent for the 0-100 cm depth by 1998. So, under the right circumstances, salt accumulation can be avoided when irrigating cotton with brackish water less than 3 times.

(2)Salt accumulated when irrigating cotton 3 times with brackish water in the growing period. The extent of salt accumulation at the 20-60cm depth was most severe for either one or three irrigation applications and the extent was similar for the 0-20 and 60-100 cm layers. Compared with the period before storage irrigation, the harvest increased 0.04~0.08 in maximum; in layer depth of 0-60cm, the content increased 0.06~0.15 in maximum; and in depth 0-100cm it increased about 0.075 in maximum. Surface soil was desalted by a single irrigation with a resultant salt content of 0.25%. Though salt accumulated at 20-100 cm depth, being about 0.10% higher in 0-60 cm layer or 0.06% higher for the 0-100 cm depth. This shows that irrigating cotton 3 times with brackish water is not recommended during its growth period. Also it's not conducive to leach soil salt by irrigating only once.

(3)Soil remained in a desalted condition after irrigating twice during cotton's growing period. So cotton irrigated twice with brackish water during its growth period was conducive to soil improvement and at the same time yielded high benefits.

4 Discussion

When brackish water is used to irrigate cotton, the following comprehensive measures are crucial to realizing the target of high efficiency and quality: ①guaranteeing sufficient soil moisture content before sowing. Irrigate cotton fields with surface water using 100 m^3/mu, this not only leaches soil salt but also guarantees sufficient water in early cotton growth; ②mulching. Cover the field with mulch film of 1.45 m width, using 7 rows of plants per film and about 25-30 cm row spacing to reduce evaporation and raise soil temperature. This helps produce high yield and quality; ③controlling stalk and plant density.

Mainly apply artificial and chemical measures to control stalk height below 70cm, while bud numbers should be 7-9 per plant and plant density about 13,000 per mu; ④controlling irrigation times. Based on water demand in the cotton growth period, cotton is irrigated 1-3 times with brackish water in the key periods of budding, flower initiation and the middle boll period of boll. This prevents unproductive cotton growth, guarantees all plants being mature before the frost season and encourages a long cotton velvet.

5 Conclusions

(1)In brackish water areas with only 120 days in a frost-free season, applying appropriate measures makes cotton yields of 300 kg/mu of un-ginned cotton, or higher, possible when irrigating 1-3 times with 50-130m^3/mu. The yield for cotton planted in low arch shelves can reach 400kg/mu, or higher, compared with 120~180kg/mu for dry farming.

(2)With a single soaking of fresh water, cotton fields irrigated with brackish water remained desalted compared with no irrigation and cotton yield was relatively high. Yield was highest in drought years for cotton that was irrigated 3 times, but salt accumulated. So, soil salt content could reach a balance over time when irrigation was carried out scientifically according to rainfall conditions.

Effects of combined plastic mulching and bunch seeding on soil-water use and spring wheat yield in arid regions of northwest China

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Abstract

Experiments to examine water use and yield improvement of plastic-mulched and bunch-seeded (PMBS) wheat were conducted at Zhangye, Gansu Province of northwest China between 1989 and 1992. Results showed that PMBS could efficiently reduce soil evaporation by 55% as compared with non-mulching. For the pre-seedling and seedling stages, despite the reduction of soil evaporation there was greater decline in soil water consumption than for non-mulched treatments. Maximum leaf area index (LAI) of spring wheat in a plastic-mulched field was about 1.5 times higher than the non-mulched one. So greater water consumption occurred and soil water content became less than that in non-mulched field for spring wheat, after the tillering stage. In addition, PMBS could improve yield, but the scale of the yield improvement declined with increasing irrigation amounts. Under conditions of limited irrigation, PMBS generated larger yield improvements, with the maximum increase being more than 100% that of yields with no mulching. In contrast, with adequate irrigation, the extent of yield improvement was little, water use efficiency (WUE) was no higher or even lower than that of non-mulched plots.

Key words: Spring wheat, plastic mulching, water consumption, water use efficiency, yield

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1 Introduction

Water shortage is a serious problem in China, since water resource per capita is only one fourth of the world average. Precipitation in the arid region of northwest China is low with 40~200 mm in Gansu's Hexi corridor, which is a main agricultural production area. In addition, evaporative demand is very high and amounts to 1500~3000 mm. So rainfall can not meet water demands for crop production and irrigation is required for agricultural production in this region. But the total water resources of arid regions of northwest China are scarce, accounting for 4.67% of national resources. Total water resource per 10 000 km^2 is 532 million m^3, which is far lower than the average level for China of 2 862 million m^3 per 10 000 km^2. However, the land area amounts to one fourth of all China (Liu and Ma, 1998), so access to drinking water can be restricted in a few regions.

In the arid region of northwest China, 90% of water resource is used for agriculture. Spring wheat is the major crop. Its water requirements are quite large, requiring amounts that can exceed 600 mm. Due to the fact that flood irrigation is a major form of irrigation for wheat, evaporation is very significant after irrigation. So, how to reduce evaporation and improve WUE are important problems that should be solved to save water in agriculture.

There are many methods to reduce evaporation and improve WUE, so two especially important methods are introduced. Drip irrigation is widely used for major crops and the water saving effect is very significant. WUE can be improved through reducing evaporation and crop water consumption. However, the use of drip irrigation for wheat production is limited due to high cost. Another method is mulching, which can check evaporation, preserve soil water and improve WUE. In comparison with other mulching materials, plastic film can not only reduce evaporation but also improve soil temperature as well as yield. In addition its cost is low, its operation is simple and so the plastic mulching technique is widely applied.

Before 1987, the plastic mulching technique was mainly used for widely spaced crops rather than densely seeded crops in China. With the invention of techniques for combined plastic mulching and bunch seeding of densely-seeded crops, use of plastic mulching for wheat production became widely extended. In 1991, field application of the technique was no more than 10 ha. By 1996 the area had become 40 thousand ha, increasing to 200 thousand ha throughout China by 1997 (Zhang and Guo, 2000). Many studies have indicated that the combination of plastic mulching and bunch seeding of wheat will reduce evaporation and increase soil water storage (Zhang and Yang, 2001).

It also reduces irrigation quota and improves WUE (Li and Xie, 1993). The technique should play an important role in arid and developing regions. But in practice, some problems with the plastic mulching technique have been discovered, for instance low yield and WUE. So further investigation of yield improvement by plastic-mulched and bunch-seeded wheat was required in arid irrigated regions. This paper compares and analyzes water use characteristics of plastic-mulched wheat with conventional cultivation, based on experimental results from between 1989 to 1992.

2 Materials and methods

2.1 Site description

The experiments were carried out at the Zhangye Station of water-saving agriculture, Gansu Academy of Agricultural Science (38°56´N, 100°26´E, 1570 m a.s.l elevation) from 1989 to 1992. The groundwater level was about 100 m deep and the soil type was a sandy silt loam with a bulk density of 1.4 g/cm^3 in the 0~200cm soil layer and a volumetric field capacity value of 31.7%. Mean annual temperature is 7℃ with an annual sunshine duration of 3 085 h. Mean annual rainfall is 129 mm with an evaporative demand of 1 076 mm, measured by E601 evaporation pan.

2.2 Experimental design

Two experiments are described. One experiment was a split-plot design with irrigation frequency as the main treatment and irrigation amount as the subplot treatment. The main plots received either two or three irrigations. The five levels of application to sub-plots were 480, 375, 270, 165 and 60 mm. All plots were randomized with three replications. In addition, non-mulched plots were designed as controls. Two irrigations were applied at the five-leaf and heading stages, respectively, while three irrigations were applied at the three-leaf, spike formation and filling stages, respectively. Another experiment was conducted to control soil water content at different levels of 85%, 70%, 60%, 50% and 40% of field capacity in the main root zone. These were the deficit irrigation treatments for comparison with a non-irrigated control. So the five soil water levels were considered as 5 treatments. Irrigation was applied whenever soil water content dropped below the deficit level.

2.3 Evaporation measurement

Evaporation was determined from June 21, 1990, using small lysimeters made by ourselves. The instrument was composed of an inner and outer tube. The inner was 10 cm diameter and 20 cm high, while the outer tube was of the same height but with a larger diameter to be able fit around the inner tube. An undisturbed soil sample was obtained by pushing the inner tube into a field row at 8 am in the morning. On plastic-mulched plots the inner tube was covered with plastic film having the same size of sowing hole in it, then the hole was covered with soil. Next, the inner tube and soil core soil was packed with gauze and weighed on an electronic balance with a sensitivity of 0.01g. Then it was put into the outer tube and both tubes were put into the hole from where the undisturbed soil had been taken. At 8 am the next day, the inner tube was again weighed and the undisturbed soil was changed. Two small lysimeters were put in the cultivation plots, then determinations were carried out continuously for 10 days.

2.4 Sowing technique

Firstly, fields were leveled and plastic film was spread out across the soil surface. Then holes were drilled 10 cm apart with a 20-cm spacing between rows. Spring wheat was seeded with 10 grains per hole, at the same time as manure and chemical fertilizer were being applied.

2.5 Determination of soil water content and evapotranspiration

Prior to sowing, two access tubes were installed to a depth of 1.5 m in each plot. At sowing, volumetric soil water contents were measured to a depth of 1.3 m in each plot, using a neutron water meter (Hydro probe model 503,CPN Company, Martinez, CA). These were repeated at intervals of 10—11days. Readings were taken at 0.3 m and 0.4 m depth, then at 0.2 m intervals from 0.6 m to 1.4 m. Surface soil water contents were determined gravimetrically using two sites per plot at 0.2 m soil depth. Accumulated water use or evapotranspiration (ET) was calculated by the water balance equation:

$$ET = (P+I) - D - \Delta S$$

where P is precipitation, I is irrigation, D is downward drainage out of the root zone, and ΔS is change in soil water storage of the soil profile considered. On the experimental site, no surface runoff occurred since rainfall intensity is usually low. The maximum amount of irrigation water was determined only to fill the deficit in the root zone in the full irrigation treatments. Also, soil moisture measurements were taken down to 130cm, which was well below the effective root zone (120cm). So deep percolation was ignored.

Water use efficiency was calculated from:

$$WUE = Gy/ET$$

where WUE is water use efficiency for grain yield; Gy, is grain yield (kg・ha^{-1}), and ET is total cumulative evapotranspiration (mm) over the growing season.

2.6 Leaf area and dry matter measured

Leaf area index (LAI) was measured every 10 days, beginning at tillering, using the LI-3000 area meter (LI-COR, Lincoln, NE). Twenty wheat plants were destructively sampled in each plot for every measurement. After the leaf area measurement, samples were dried for 48 hours at 70℃ in an oven to measure dry matter.

3 Results

3.1 Soil moisture dynamics

Soil water variation in the plastic-mulched and non-mulched plots without irrigation (1989) are presented in Figure 1. Rainfall in the spring wheat growing season was 51.9 mm and maximum daily rainfall (June 22) was only 7.9 mm. So soil water contents declined continuously, but rates of loss were different. Soil water contents, of the plastic-mulched plots, were higher than those of the non-mulched plots before seedling and at seedling stage. However, after mid-April, with both leaf area and water consumption increasing, so soil water content in the plastic-mulched plots became lower than that of the non-mulched plots. In the later growing stages of wheat, the difference between water contents of the plastic-mulched treatments and the controls increased. By the ripening stage, soil water content in the plastic-mulched plot was 4% lower than that of the non-mulched plot. So wheat could use more soil water from the plastic-mulched plots than from the non-mulched ones.

In addition to the soil water dynamics of plastic-mulched and non-mulched plots, Figure 2 gives data for plots receiving 165 mm irrigation in 1990. In all treatments, soil water content in the 0~60-cm soil depth had a fluctuating decline due to irrigation and crop water consumption. Two irrigations had been applied at the four-leaf stage. The plastic-mulched plot received water on April 23rd while the non-mulched plot was irrigated on May 2nd, then both received water in the blooming stage on June 8th. Soil water content in the plastic-mulched plot was higher than that of the non-mulched plot with two peaks being caused by irrigations. Then soil water contents declined linearly, with soil water loss in the plastic-mulched plot being more significant than that of the non-mulched plot. So soil water content of plastic-mulched plots were always lower than those of non-mulched plots in the middle and later stages of wheat growth. Soil water contents at 60~120 cm fluctuated less than those in the 0~60 cm layer. There were small fluctuations in the former before and during the seeding stage, with the two irrigations causing a small peak, after the elongation stage on May 15. Differences of soil water content between the plastic-mulched and the non-mulched plots gradually increased as the growing season extended. By the ripening stage soil water content in the plastic-mulched plot was 4.2% less than that of the non-mulched plots. So results demonstrated that plastic-mulched wheat could use more soil water from deeper layers.

3.2 Comparing plastic-mulched and non- mulched plot water use

Table 1 describes water use of spring wheat for different growth stages and for the whole season with different irrigation applications and soil moisture contents. Total water use was always more than that of the non-mulched plots for the plastic-mulched plots with either full or deficit irrigation treatments. As irrigation quantities increased, total water use in the plastic-mulched and non-mulched plots increased. Looking at water consumption in different stages, evapotranspiration of wheat in plastic-mulched plots was greater than that of the non-mulched plots before the tillering stage. After tillering, evapotranspiration in the plastic-mulched plots increased swiftly, which resulted in evapotranspiration and total water use being higher than that of non-mulched plots. Table 2 shows that a plastic-mulched plot could reduce evaporation by about 55% in comparison with a non-mulched plot. Cutting such evaporation loss can improve WUE.

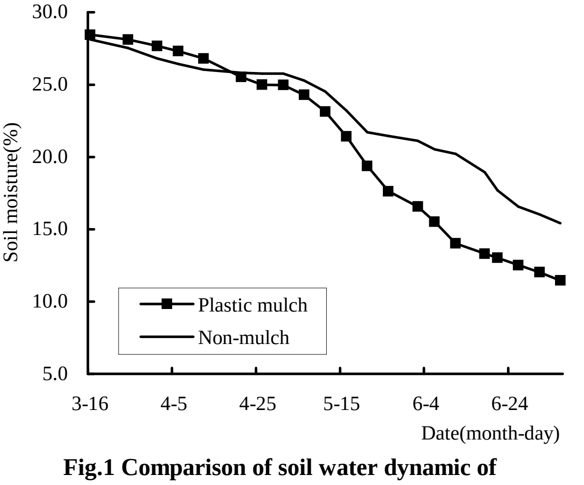

Fig.1 Comparison of soil water dynamic of plastic-mulched plot with that of non-mulched plot under non-irrigation condition

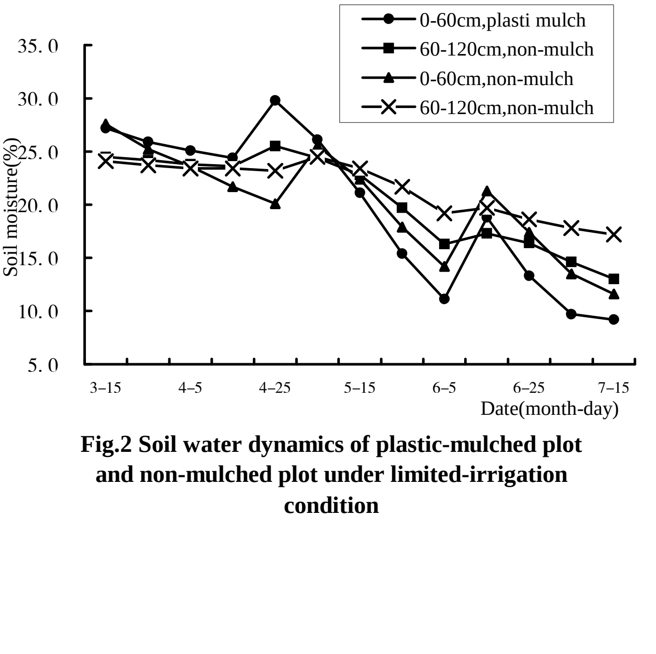

Fig.2 Soil water dynamics of plastic-mulched plot and non-mulched plot under limited-irrigation condition

Table 1. Comparison of evapotranspiration between plastic-and non-mulched plots (mm)

Treatments	Way of cultivation	Planting-seedling	Seedling-tiller	Tiller-Elongation	Elongation-heading	Heading-ripening	Planting-ripening
Irrigation application (mm)							
0	Plastic-mulch	14.2	30.6	82.7	87.0	86.6	301
0	Non-mulch	32.9	30.1	37.1	47.4	72.2	220
60	Plastic-mulch	23.0	17.3	85.7	84.4	108.0	318
60	Non-mulch	37.6	34.7	53.9	66.9	80.9	274
165	Plastic-mulch	21.2	17.3	110.9	102.4	153.5	405
165	Non-mulch	42.4	36.3	70.7	68.6	133.0	351
270	Plastic-mulch	23.6	14.3	120.6	122.5	219.5	501
270	Non-mulch	37.9	39.0	93.9	71.8	175.1	418
375	Plastic-mulch	22.5	16.5	163.5	134.6	278.7	616
375	Non-mulch	41.3	39.6	117.2	73.0	239.0	510
The deficit irrigation treatments (% of the field capacity)							
40	Plastic-mulch	16.3	30.3	91.1	118	312	567
40	Non-mulch	34.8	35.3	43.8	78	241	434
50	Plastic-mulch	18.5	30.1	90.3	186	370	695
50	Non-mulch	32.1	34.8	39	104	301	510
60	Plastic-mulch	18.2	28.2	82.1	179	383	691
60	Non-mulch	37.3	30.8	61.1	137	374	640
70	Plastic-mulch	16.2	28.2	79.5	197	411	731
70	Non-mulch	36.3	31.1	93.3	148	341	649
85	Plastic-mulch	15.6	39.8	125.7	209	388	778
85	Non-mulch	31.8	57.5	121.2	168	358	736

3.3 LAI and dry matter mass

There were also significant differences between the various irrigation and deficit irrigation treatments. LAI increased with increase in irrigation quantities and soil water content. In comparison with the non-mulched plots, LAI of plastic-mulched plots grew rapidly after seedling, with maximum LAI of all such treatments being about 1.5 more than that of non-mulched plots. In later stages, LAI of plastic-mulched plots significantly declined to become close to or less than that of the non-mulched plots, suggesting premature senescence.

The trend of wheat dry matter accumulation was described by $y = c/(1+ae^{-bx})$ (Figure 3), with dry matter accumulation of plastic-mulched and non-mulched plots increasing with soil water content. But for the same soil water conditions, dry matter accumulation in the plastic-mulched plot was higher than that in the non-mulched plot. The lower soil water was the greater the difference, so results showed that plastic-mulched wheat was better adapted to arid environments.

3.4 Comparing plastic-mulched and non-mulched plot yields

Plastic-mulched spring wheat could improve yield (Table 3) and the range of yield improvement was related to irrigation application or soil water content. Small irrigation applications or lower soil water content resulted in a large margin of yield improvement. For irrigation at 40% of field capacity or no-irrigation, yield of plastic-mulched plots increased by 100% comparing with non-mulched plots. When irrigation exceeded 480 mm, or minimum soil water content exceeded 70%

Table 2. Comparison of evaporation (mm) between plastic-mulched plot and non-mulched plot

Date (month/day)	Plastic-mulched polt	Non-mulched plot	Date (month/day)	Plastic-mulched plot	Non-mulched plot
6/20	0.42	1.26	6/26	0.27	0.84
6/21	0.80	1.45	6/27	0.42	1.26
6/22	0.41	0.85	6/28	0.28	0.86
6/23	0.21	0.35	6/29	0.23	0.44
6/24	0.11	0.20	6/30	0.43	0.86
6/25	0.83	1.45	mean	0.40	0.89

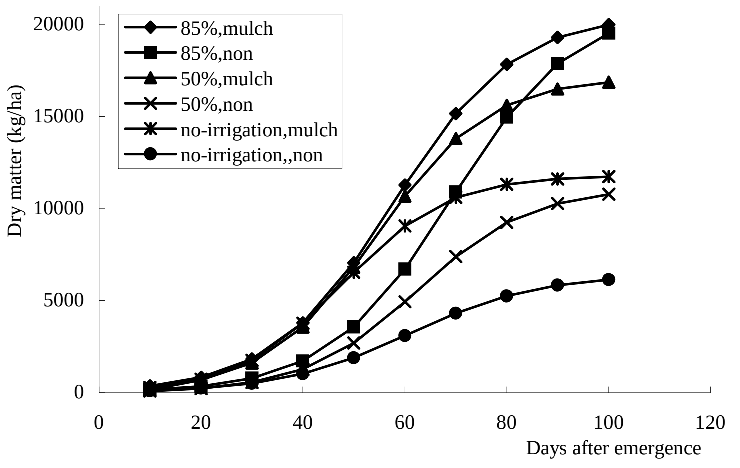

Fig.3 Dry matter accumulation of wheat under diferent soil water content-controled of the field capacity

Table 3. Yield of wheat, water use and WUE under different treatments

Treatments	Yield (kg/ha)			Evapotranspiration (mm)			WUE (kg/m^3)		
	Plastic	Non-	increase%	Plastic	Non-	increase %	Plastic	Non-	increase %
Irrigation quota (mm)									
60	3860	2315	66.8	318	274	16..6	1.22	0.845	43.3
165	4974	3654	36.1	405	351	15.5	1.23	1.04	18
270	5589	4263	31.1	501	418	19.8	1.12	1.02	9.4
375	5813	5213	11.5	616	510	20.7	0.94	1.02	-7.7
0	4293	2133	101.3	301	220	37.0	1.43	0.97	46.8
Deficit irrigation treatments (% of field capacity)									
40	5964	2837	110	567	434	30.8	1.05	0.65	60.7
50	6687	4754	40.7	695	510	36.1	0.963	0.931	3.4
60	7082	6102	16.0	691	640	7.9	1.03	0.953	7.6
70	6741	6481	4.0	731	649	12.5	0.921	0.998	-7.7
85	6663	6318	5.5	778	736	5.7	0.856	0.858	-0.2

of field capacity, the range of yield improvement for plastic-mulched plot was only 9.9%. Figure 4 shows that the more water was consumed, the less the yield of spring wheat improved, compared with non-mulching. When water use reached 740 mm, yield improvements became negligible. So PMBS is better adapted to limited irrigation condition.

Li and Xie (1993) and Fan et al. (1997) showed that grain number per head of spring wheat could be improved due to plastic mulching. For limited irrigation conditions, it could improve number of heads, had little effect on 1000 grain weight. With improvement of grain numbers per head and number of heads so there is a resulting higher yield.

3.5 Comparing plastic-mulched and non-mulched plots WUE values

Table 3 shows that with increasing irrigation and soil water content, WUE of the plastic-mulched plot reduced. WUE for plots having no irrigation or irrigation with only 60 mm were higher than 1.28 kg/m^3, while WUE of 480 mm applications or with irrigation at 80% of field capacity were lower than 0.9 kg/m^3. For irrigation with less than 270 mm or at soil water contents lower than 60% of field capacity, WUE of the plastic-mulched plots was significantly higher than that of non-mulched plots. Though for irrigation with more than 375 mm or at soil water contents higher than 70% of field capacity, WUE of plastic-mulched plots were closer to those of non-mulched plots. Again results show that the technique of plastic-mulched wheat is adapted to circumstances of limited-irrigation.

4 Discussion

Many experiments have indicated that the PMBS technique for spring wheat has beneficial effects on plastic mulching population structure (Tang et al., 1999), growth rhythm (Li et al., 1999; Tang et al., 1999; Zhang et al., 1999), physiologic biochemical characteristics (Xu et al., 2001) and root distribution (Ma, 1999). Water use of wheat changed (Li and Xie, 1993), with yield and WUE also increasing so plastic-mulching was considered a breakthrough of cultivation technique (Zhang and Guo, 2000). This technique achieved success in spring wheat in arid irrigated regions of China, then rapidly extended to spring and winter wheat in arid field. Now, plastic-mulched wheat has become an important cultivation technique, but results in this study indicated that water use of wheat under plastic-mulching conditions are greater than for non-mulched conditions. Plastic-mulching could reduce evaporation, but due to leaf area increased, transpiration is enhanced and total evapotranspiration enhanced accordingly. So, PMBS could improve yield and WUE under limited-irrigation condition. This technique only slightly improves yield, used more water and reduced WUE under adequate irrigation conditions. So the results suggest that PMBS is only adapted to limited-irrigation wheat fields in arid or semi-arid regions.

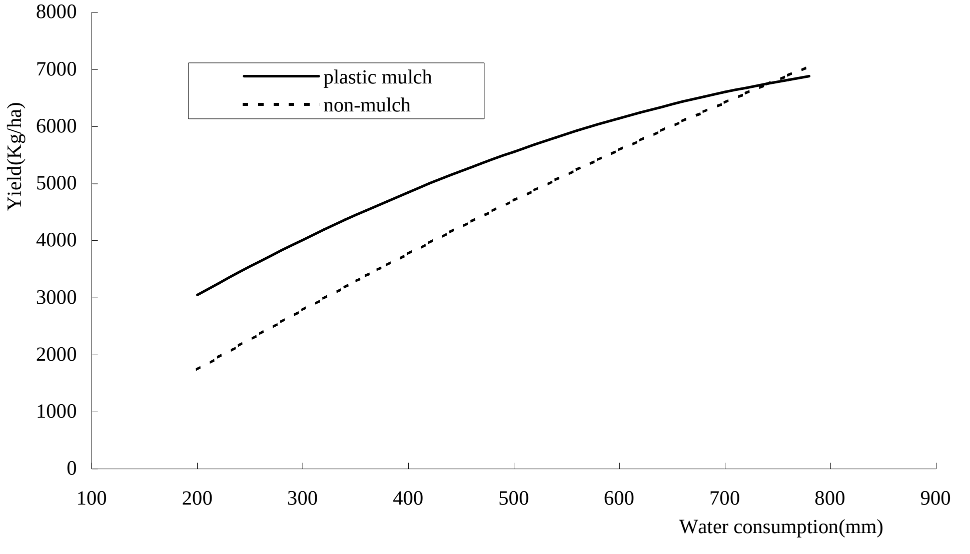

Fig.4 The comparion between Yield in the plastic-mulched plot with that of the non-mulched plot under different water consumpation condition

With little rain and irrigation, soil moisture associated with plastic-mulching was higher than that of non-mulched plots before tillering of spring wheat and in the elongation stage of winter wheat (Fan et al, 1997). While in the later growing period, with increased water consumption so the soil water content for plastic-mulched treatment rapidly decreased, until the ripening stage when soil water content of plastic-mulched plots was far lower than that of non-mulched plots, especially below 60 cm. Fan et al (1997) have studied plastic-mulching for winter wheat in semi-arid fields. Results showed that plastic-mulching for winter wheat could improve root weight. Dry root weight in the 0~100 cm soil layer of both high- and no-fertilizer treatments were 17.3% and 10.8% higher than those of the non-mulched crop and roots penetrated deeper. Ma (1999) determined dry root weight in a 0~80 cm soil layer receiving 225 mm of irrigation and in non-irrigated plots of plastic-mulched and non-mulched wheat. Results showed that dry root weight increased 30.3% and 48.6% respectively for the irrigated and non-irrigated plastic-mulched plots. Since plastic-mulching could improve wheat root weights and extend root distribution, so wheat crops under plastic-mulching could absorb more water and maintain growth under lower soil water conditions. So, PMBS could adequately use soil water and gain higher yield. Some researchers thought that plastic-mulching could reduce irrigation quota, assuming that soil water rather than irrigation would meet the water requirements. However, relative to non-mulched wheat, actual water use did not reduce.

5 Conclusions

Prior to and during the seedling stage, soil water contents in plastic-mulched plot were higher than that in non-mulched plot. The maximum leaf area index (LAI) of spring wheat in plastic-mulched field was about 1.5 higher than in the non-mulched treatment. After the tillering stage, soil moisture of PMBS became less than that of non-mulched plots. At the ripening stage, soil water content for non-irrigated treatments of plastic mulched plots was about 4% lower than that of the non-irrigated, non-mulched plots. It indicated that PMBS could use more soil water at depth.

A combination of plastic mulching and bunch seeding for spring wheat could decrease soil evaporation by 55% relative to non-mulched plots. Prior to and during the seedling stage, reduced evaporation meant higher soil water contents than the non-mulched plots. But PMBS could greatly increase LAI of spring wheat, creating a larger water consumption so that soil water content fell below that of the non-mulched plots. So total water consumption of PMBS for various supply irrigation treatments was higher than that of non-mulched treatments.

Plastic-mulching could improve spring wheat yield with the scale of yield improvement reducing with irrigation or increased soil water. Under limited-irrigation conditions, the largest yield improvement was above 100% and WUE was far higher than that without mulching. In adequate irrigation conditions, the range of yield improving was slight and WUE was not higher. So, PMBS is adapted to limited irrigation circumstances. Under limited-irrigation conditions, PMBS could effectively improve yield with dry matter accumulation rising, head number per ha and seed number per head going up, and having little effect on the 1000-seed weight.

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Effects of no-till straw mulch on wheat yields and soil environment in semi-humid dry area

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Abstract

Effects of no-till straw mulch practices on winter wheat yield and the soil environment were studied from 1996 to 2000 in the semi-humid, dryland region near to Heyang, Shaanxi Province, China. The average yield of dryland wheat in this part of China is 2900 kg/ha. The experiment consisted of three main plot treatments: 1) conventional tillage, 2) no tillage + straw mulching, and 3) no-tillage + irrigation. The subplot treatments were different levels of fertilization. In our experiment, wheat yield in the no-tillage + straw mulch + NP fertilizer ranged between 3750 -5250 kg/ha. Soil organic matter in the 0-60 cm layer increased by 3.05 g/kg after four years of no tillage + straw. Numbers of bacteria, fungi, and actinomycetes in the soil increased by 21%, 54% and 108%, respectively. Compared to conventional tillage practices, the no tillage + straw mulch technique is an economically and environmentally sound choice for farmers in this area.

Key words: Dry land farming, no till, straw mulch, wheat, fertilizer.

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1 Introduction

Water shortage and poor soil fertility are the two main limiting factors for winter wheat (Triticum aestivum) production in dryland areas of northern China. Fertilization plays an important role for increasing winter wheat yield in this area. Under normal rainfall conditions, the soil water content influences the response of wheat to chemical fertilizer and manure (Kavitha and Wahab, 2001; Baumhardt and Jones, 2002).

Wheat production using no-tillage is becoming an increasing accepted management technology (Oio et al.1991). Zero tillage can increase yield and conserve both moisture and soil nutrients, however some land preparation cost and time are consumed during operation (Singh and Kharub, 2001). To improve dryland agricultural production in the semi-humid area of northern China, new ways to conserve water and raise fertilizer use efficiency must be developed. The objective of our research was to determine the effect of no tillage, straw mulching, and fertilization on wheat yield and soil environment of a field experiment in a semi-humid area of China. Specifically, we examined the effect of no-tillage and straw mulch on (1) wheat yield, (2) soil fertility, and (3) soil microbial biomass. We believe that this work will be an important reference for future studies on dryland wheat production in semi-humid areas.

2 Materials and methods

2.1 Experimental site

The field experiment was conducted at the Heyang Dryland Experiment Station of the Northwest Science and Technology University of Agriculture and Forestry in Heyang, Shaanxi Province, China (34°16?21? N, 109.°30?27? E). The climate is classified as semi-humid. Average annual precipitation is 530 mm and the aridity index is 1.5. Temperatures range between –20℃ in the winter and 40℃ in the summer. The average temperature is 10.5 ℃ and there are 169-180 frost-free days per year. Common crops in the area are winter wheat, millet, soybean and oil sunflower. There is generally one harvest per year.

The experiment was conducted from 1996-2000. Rainfall during the experimental period is shown in Table 1. Rainfall was near normal in 1999, above normal 1996 and 1998, and below normal in 1997 and 2000. Basic soil characteristics at the experimental site are as follows: organic matter 9.22g kg^{-1}, total N 0.59 g kg^{-1}, available N 45.9 mg kg^{-1}, available P_2O_5 7.71 mg kg^{-1}, available K_2O 70.7 mg kg^{-1}, slowly available K_2O 840 mg kg^{-1}.

The experiment was a split plot design. The main plot had three treatments: 1) no tillage + straw mulch, 2) no tillage + irrigation and 3) conventional tillage. The split plot treatments were different levels of fertilization (Table 2). Details are given below.

2.2 Main plot treatments

Conventional tillage (CCM) included a

combination of offset disking, deep-plowing, and harrowing. Normally farmers ploughed the land after wheat harvest, and then harrow the land after a rain to conserve soil moisture and nutrients. In the no tillage + straw mulch treatment (NTSM), we left about 10cm of stubble on the field at wheat harvest, then added an additional 7500-9750 kg straw/ha to the soil surface as mulch. The soil was not tilled from June to September. Weeds were killed with a herbicide. At sowing time, the straw mulch was taken up, the soil was cultivated and fertilized, and the wheat was sown as normal. Then, the straw mulch was returned to the plots. In the no tillage + irrigation treatment (NTSI), the plots were left undisturbed between June and September. At sowing time, the soil was cultivated, fertilized, and planted as normal. The wheat was irrigated in January with 1200m^3 /ha of water.

The plots were replicated four times and randomly arranged. Plot size was 5m x 3.5m with a total area of 17.5m^2. Each plot had 16 rows, with 12.5g of wheat seed planted in each row. The wheat variety was Shi-86-5144. Sowing dates were September 21, 1996, September 20, 1997, September 23, 1998 and September 24, 1999. Harvest dates were June 15, 1997; June 21, 1998; June 25, 1999 and June 28, 2000.

Table 1. Precipitation (mm) at the experiment station from 1996-2000

Month	Year				
	1996	1997	1998	1999	2000
January	6	9	5	0	12
February	9	14	4	0	5
March	13	20	45	22	28
April	22	30	43	58	19
May	33	13	192	83	93
June	120	0	30	49	36
July	94	68	220	50	126
August	141	12	108	63	33
September	67	89	24	103	53
November	58	0	14	57	41
December	56	32	0	11	10
October	0	0	0	2	0
Total	617	287	682	498	364

Table2. Fertilizer treatments.

Treatment	Treatment content	Fertilizer Rate (kg/ha)				
		Urea	$(NH_4)_2$-HPO_4	K_2SO_4	Micro-nutrients	Manure
1	Control	0	0	0	0	0
2	NP	300	300	0	0	0
3	NPK	300	300	300	0	0
4	NP+ micro*	300	300	0	45	0
5	NPM	300	300	0	0	75000
6	NP (N2/3+N1/3)	158 + 142	300	0	0	0
7	NP + spray **	300	300	0	3.25	0

*Borax (7.5kg/ha)**,** Boron (1%) Fe (Vitriol inferior iron 15 kg/hm^2**,** Fe19%) $MnSO_4$ (22.5 kg/ha), Mn 12%.
** spray B, Fe, K.

2. 3 Soil analysis

Soil moisture was determined on a dry weight basis. Soil microbial populations were determined by dilution plate counting. The following media were used: bacterium - beef cream peptone and agar-agar; fungus - bean sprout and agar-agar; actinomycete - Gao's Number 1. Organic matter was determined by oxidation with potassium dichromate. Total N was determined by the Kjeldahl method (digested with sulfuric acid); Total P and available P were determined by acid soluble–molybodeum colorimetry and acid extracted-molybdenum methods respectively. Total K and available K were determined with the acid soluble-flame photometric method and the neutral ammonium acetate extracted-flame photometric method respectively.

3 Results and discussion

3.1 Wheat yield

Winter wheat yields during the experimental period are shown in Table 3. The highest yield (5760 kg/ha) occurred in 1999/2000 in the NTSM + NP + micronutrient treatment. The lowest winter wheat yield (1270 kg/ha) occurred in 1998/99 in the CCM + no fertilizer treatment.

The yield of winter wheat in wet years was 1-3 times greater than in dry years. These results demonstrate the large fluctuations in yield that commonly occur in semi-humid conditions. Statistical analysis indicated that wheat yields varied significantly between years as well as between soil management techniques and fertilization treatments (Table 4).

Table 3. Effects of soil management technique and fertilizer treatment on wheat yield from 1996-2000.

Year	Soil management technique	Average yield (ton/ha)					
		CK	NP	NPK	NP+ micro*	NPM	NP (N2/3+N1/3) P
	NTSM	3.02	4.10	4.15	4.65	4.33	4.20
1996-1997	NTSI	4.45	5.42	5.66	5.30	5.18	5.69
	CCM	2.90	3.85	3.75	4.29	3.41	4.08
	NTSM	2.65	3.88	3.97	3.90	3.67	3.86
1997-1998	NTSI	3.15	3.85	3.98	4.11	4.19	3.89
	CCM	1.70	2.53	2.41	2.47	2.59	2.42
	NTSM	1.27	1.56	1.52	1.48	1.42	1.63
1998-1999	NTSI	1.85	2.24	2.13	2.16	1.73	2.02
	CCM	-	-	-	-	-	-
	NTSM	4.14	5.16	5.33	5.76	5.01	5.32
1999-2000	NTSI	3.95	5.07	5.46	5.24	4.97	5.20
	CCM	-	-	-	-	-	-

Table 4. Statistical analysis of wheat yields for different management techniques, years and fertilizer applications

Source	DF	Sum of square	Mean square	F value	Pr>F
Years	1	27943094	27943094	158.99**	0.01
Management	2	45286908	22643454	128.84**	0.01
Treatment	5	16551517	3310303	18.83*	0.01
Method×Treat.	10	689843	68984	0.39	0.9468
Error	87	15290692	175755		

*, ** Significant at $P < 0.05$ and 0.01, respectively.

Table 5. Analysis of variance table for data from 1996-1998

Years	Yield	Management Technique	Yield	Treatment	Yield
1996-1997	4.34 a	No tillage + Irrigation	4.62 a	NP+ manure	4.72 a
				NP+ micro	4.06 ab
				NPK	3.97 ab
1997-1998	3.33 b	No tillage + straw mulch	3.86 b	NP	3.95 ab
				N (2/3+1/3) P	3.87 b
		Conventional cultivation	3.03 c	CK	2.99 c

Significant at $P < 0.05$,$LSD_{0.05} = 380.7$

Table 6. Analysis of data for 1998-2000

Year	Yield	Method	Yield	Treatment	Yield
1999-2000	5.05±1.55 a	No tillage + straw mulch	3.50±1.55 a	NP+ manure	3.66±1.94 a
				NPK	3.61±1.87 a
				NP+ micro	3.54±1.78 a
1998-1999	1.75±0.35 b	No tillage + Irrigation	3.30±1.89 b	NP	3.51±1.69 ab
				N (2/3+1/3) P	3.28±1.79 b
				CK	2.80±1.78 c

Significant at $P < 0.05$,$LSD_{0.05} = 427.4$

The analysis of variance for 1996-1998 is given in Table 5. Wheat yield in the NTSI treatment was significantly higher than in the NTSM and CCM treatments. Wheat yield was lowest in the conventionally tilled plots. Wheat yields were significantly higher in the fertilized compared to unfertilized treatments. There was no significant difference in yield between the NP, NPK, and NP + micro-nutrient treatments. This indicated that K, Mn, Zn, and Fe had no effect on yield. One-time N application yielded more than a split application of N.

The response of wheat to cultivation was different during the period 1998-2000 compared to 1996-1998 (Table 6). Wheat yield was significantly higher in the NTSM treatment compared to the NTSI treatment. This indicates that the straw mulch conserved enough water so that high wheat yield could be achieved without the application of irrigation water. These results demonstrate that the no-till straw mulch techniques are effective for dryland wheat production.

3.2 Soil nutrients and microorganisms

The NTSM treatment not only raised the soil moisture content, it also supplied crop nutrients (Table 7). Soil organic matter was higher in the NTSM treatment compared to the CCM treatment throughout the entire soil profile. The effect was especially pronounced in the plow layer where NTSM increased soil organic matter by 1.1 g/kg. NTSM increased total N and total P by 0.46 g/kg and 0.01 g/kg respectively. NTSM also influenced K cycling. Because of the high yield, wheat absorbed more K from the soil. Without the application of K fertilizer, available K and slowly available K decreased by 84 mg/kg and 160 g/kg respectively.

Soil microbial biomass plays an integral part in determining soil fertility. The measurement of soil microbes in the 0~20 cm soil layer is important for evaluating soil fertility and determining the ability of the soil to supply nutrients. Compared to the conventionally tilled treatment, NTSM increased the number of bacteria, fungus and actinomycetes by 21%, 54%, and 108% respectively (Table 8).

Table7. Effects of NTSM and CCM on soil nutrients

Treatments	Depth cm	Available N mg/kg	Available P_2O_5 mg /kg	Available K_2O mg/kg	Slow Available K_20 mg/kg	Total N g/kg	Total P g/kg	Organic matter g/kg
CCM	0-20	51.5	14.5	176	1140	1.07	0.72	10.9
	20-40	34.5	4.3	81	900	0.68	0.56	6.6
	40-60	17.2	0.4	60	660	0.66	0.51	4.2
NTSM	0-20	63.5	25.9	92	980	1.52	0.73	12.1
	20-40	47.3	6.4	71	780	0.84	0.60	7.5
	40-60	39.4	4.8	61	860	0.74	0.58	5.2
Nutrients added	0-20	+12.1	+11.4	-84	-160	+0.46	0.01	+1.1
	20-40	+12.8	+2.4	-11	-121	+0.16	+.04	+0.7
	40-60	+22.1	+4.4	0	+200	+0.08	+.06	+1.0

Table 8. Effects of NTSM and CCM on the number of microbes in different soil layers

Treatment	Depth cm	Bacteria ($\times 10^7$)	Fungi ($\times 10^3$)	Actinomycetes ($\times 10^4$)
NTSM	0-15	2900	4.0	25.0
	15-40	90	3.1	5.1
	40-60	0	2.7	5.1
CCM	0-15	2400	2.6	12.0
	15-40	310	3.4	4.6
	40-60	20	1.4	5.5

4 Conclusions

Normal winter wheat yield is only 2.90 ton/ha in the semi-humid dryland region of Shaanxi Province. In our experiment, the combination of no-tillage, straw mulch, and NP fertilization increased yield to 3.75-5.25 ton/ha compared to the conventionally tilled treatment. During the final year of the study, yields were higher in the no-till straw mulch treatment compared to the irrigated treatment. These results and those from other studies indicate that the combination of no-tillage and straw mulching can conserve water, improve soil fertility, and increase yield in dryland areas. At the current time, the major major obstacle to its adoption in Shaanxi Province, China, is that the wheat straw is often removed from the field and used for other purposes.

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Modeling crop yield response to water and nitrogen with artificial neural networks based on genetic algorithms

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Abstract

A model of crop response to water and nitrogen is the basis for rational regulation of field water and nitrogen regimes and improvement of water and nitrogen use efficiency. The relationship between soil water, nitrogen and crop yield is very complex. Since artificial neural networks (ANN) are powerful in uncovering casual links, they can be used to model water-nitrogen-yield relationships for particular sites. A real number coding genetic algorithm and gradient- descending algorithm were combined for the purpose of weight training in an ANN. The model was calibrated and tested with field experiment data for winter wheat at Yongledian Station in Beijing. Results showed that the ANN was effective in modeling the water-nitrogen-yield relationship. Then the impact of water stress and fertilizer on wheat yield was analyzed using the ANN model.

Key words: Winter wheat; model of crop response to water and nitrogen; artificial neural networks; genetic algorithm; back propagation algorithm.

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1 Introduction

Crop yield is closely related to field evapotranspiration and fertilizer. The relationship can be expressed as

$$Y = f(ET_i/ET_{im}, FE/FE_m) \qquad (1)$$

Where Y is crop yield, ET_i and ET_{im} are actual and potential evapotranspiration in growing stage i, FE and FE_m are fertilization amount and the maximum, respectively. Much research have been carried out about the impact of water stress on crop yield, with a number of models of crop water production function being proposed and applied in practice (Shen, 1995). To assess impacts of water and fertilizer on crop yield, regression analysis of crop yield, total evapotranspiration and fertilizer use has been the main method used, based on field experiments (Liu, 2000). Since there are interactions between water and fertilizer, so relationships between water, fertilizer and yield are complex. Models of crop response to water and fertilizer (MCRWF) or crop - water - fertilizer production functions (CWFPF) should be further studied.

Artificial Neural Networks (ANN) provide an alternative approach based on theories of the massive interconnection with neurons or nodes and parallel processing (Hetch,1989; Wen,2003). Since it is powerful in mapping nonlinear relationships and has some intelligent properties such as self-organizing, adaptation and self-learning, it has been widely used in many science and engineering disciplines. Among many ANN architectures proposed and explored in the literature, the most commonly used one is a multi-layer feed forward network based on a back-propagation algorithm (BPA). It has been used to model a crop-water production function (Wei, 2002) and a crop-water-fertilizer production function (Zhou, 2003). However, the basis of BPA is the gradient descending algorithm (GDA), which is liable to converge to local optima of error functions, limiting the use of BPA. A Genetic Algorithm (GA) is a global optimization method and can effectively overcome the deficiencies of BPA.

Based on experimental results for winter wheat at Yongledian Station in Beijing, an ANN was established for the crop-water-fertilizer production function. ANN parameters were obtained from experimental results with an improved GA (combination of Real number coding GA and GDA). Impacts of water and fertilizer on wheat yield were analyzed based on the model.

2 Design of ANN for CWFPF and parameter optimization

2.1 Design of ANN for CWFPF

An ANN with a BPA is usually composed of several consecutive layers, including an input layer, a number of hidden layers and an output layer. Each node is connected with nodes in the subsequent layer by weighted connections to produce a nonlinear relationship between input and output. The number of input nodes N and output nodes M are determined by problem requirements. The number of hidden layers (usually one) and the number of nodes Q in these layers are chosen arbitrarily.

For an ANN for CWFPF shown in Fig. 1, only one hidden layer was considered. The input nodes were water and fertilizer factors, including relative evapotranspiration of each growing stage and amount of fertilizer use. The number of the input nodes was $N=N_w+N_f$, where N_w and N_f were numbers of crop growing stages and times of fertilizer use, respectively. The output layer included only one node, namely relative crop yield. In Fig. 1, ω_{ij} refers to the weights between the input node j and the hidden node i, T_{li} refers to weights between the hidden nodes i and the output node, θ_i and θ_l are thresholds of the hidden nodes i and the output node, respectively. The above parameters were given random values at the beginning and updated by ANN training.

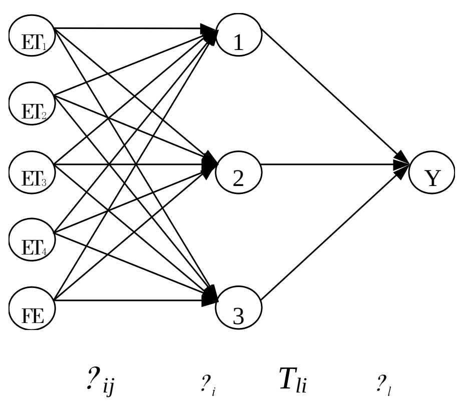

Fig. 1 Schematics of a three-layer ANN for CWFPF

2.2 Back-Propagation algorithm

A BPA is an essential algorithm for the ANN mentioned above. Input information is fed forward to the output layer through a hidden layer, so that output of nodes in the hidden layer y_i and output node O_l can be obtained (Wen, 2000):

$$y_i = f_1\left(\sum_j \omega_{ij} x_j - \theta_i\right) = f_1(net_i) \qquad (2a)$$

$$O_l = f_2\left(\sum_i T_{li} y_i - \theta_l\right) = f_2(net_l) \qquad (2b)$$

where f_1 and f_2 are transfer functions defined by:

$$f_1(x) = 1/(1 + e^{-x}), \quad f_2(x) = x \qquad (3)$$

If the calculated output differs from the expected output, an error will be propagated backward to modify the ANN parameters until the error reaches a minimum. The error E between the calculated output O_l and expected output t_l can be calculated from

$$E = \frac{1}{2}\sum_l (t_l - O_l)^2 \qquad (4)$$

Errors of the output node and hidden nodes are:

$$\delta_l = (t_l - O_l) f_2'(net_l) \qquad (5a)$$

$$\delta_i' = f_1'(net_i) \sum_l \delta_l T_{li} \qquad (5b)$$

Then ANN weights and thresholds can be updated using

$$T_{li}(k+1) = T_{li}(k) + \Delta T_{li} = T_{li}(k) + \eta \delta_l y_i \qquad (6a)$$

$$\omega_{ij}(k+1) = \omega_{ij}(k) + \Delta \omega_{ij} = \omega_{ij}(k) + \eta' \delta_i' x_j \qquad (6b)$$

$$\theta_l(k+1) = \theta_l(k) + \eta \delta_l \qquad (7a)$$

$$\theta_i(k+1) = \theta_i(k) + \eta' \delta_i' \qquad (7b)$$

where η is the learning velocity.

2.3 ANN design based on GA

Since the design and training of an ANN requires a global search and there may be many local optima in the search space, it is difficult for a BPA to search for a global optimum. A GA is a stochastic search algorithm that has higher probability of reaching the global optimum. The stochastic optimum strategy used in a GA can result in uncertainty in optimum effect and direction, while GDA is more favorable in this aspect. Therefore, the optimum effect can be better to combine GA with GDA in the evolution of initial generations. A combination of Real number coding GA and GDA was used in the training of this ANN. The main steps of this algorithm include:

(1) Real number coding. Each weight and threshold was expressed as a real number. The chromosome vector includes (N+2)×Q+1 variables, based on N×Q variables for weights between input nodes and hidden nodes, Q variables of thresholds of hidden nodes, Q variables of weights between hidden nodes and output node, and the threshold of the output node.

(2) Initial population. Population $V_1, V_2, \ldots, V_n$ were initialized randomly, where n is the population size.

(3) The fitness f. A value of f is obtained from:

$$f = 1/SS, \quad SS = \sum_{i=1}^{m} \left|(y_i' - y_i)/y_i\right| \qquad (8)$$

where y_i' and y_i are calculated and observed values of the training sample i, m is number of training samples.

(4) Local optima. During evolution of the first 100 generations, local optima was processed based on equations (2) to (7).

(5) Non-linear ranking selection. The population members were arranged in order of best to worse fit and selection probabilities were assigned using

the following equation:

$$p_i \ ? \ r(1 \ ? \ q)^{?1} \ ,i \ ? \ 1,2,? \ \ n \qquad (9)$$
$$r \ ? \ q/(1 \ ? \ (1 \ ? \ q)^{?})$$

where q was the selection probability of the best individual.

(6) Crossover operator. According to GA design experience, alternate use of several crossover operators can obtain a better effect (Pan, 1998). In this paper, arithmetic crossover, heuristic crossover (Wright, 1991) and discrete crossover were used in turn.

(7) Mutation operator. Four mutation operators were used, including boundary mutation, inconsistency mutation, multilevel inconsistency mutation and consistency mutation.

3 ANN models for CWFPF of winter wheat

3.1 Introduction to field experiment

A field experiment to determine the winter wheat yield-water-fertilizer relationship was carried out at Yongledian Station in Beijing for two growing seasons from 1998 to 2000. This is one of the main crops in the North China Plain. Experimental plots were 10 m *5 m. Irrigation and fertilization treatments from seeding to greening were all the same for different plots, since the impact of water and nitrogen fertilizer was to be determined after greening. Four stages were identified, namely, greening to shooting, shooting to heading, heading to milking and milking to maturing. Water treatments include from 0 to 4 irrigations. Fertilizer (carbamide) was applied once at 3 different rates in 1999 and at 4 rates in 2000. The main items monitored included meteorological data, soil water and nutrition, crop growth and yield. Values for evapotranspiration at different plots were estimated from experimental results and a soil water balance model.

3.2 Training results of ANN

From the experimental design, 5 ANN input nodes were required for a CWFPF of winter wheat, including relative evapotranspiration for four growing stages and relative fertilizer amount. The output node was relative yield. In ANN training, 35 data sets were used and 9 others were used for ANN testing. From the ANN training results, an optimal ANN structure was found to be 5-3-1, with one hidden layer containing nodes, as shown in Fig. 1.

The main controlling parameters used in the GA were: maximum number of evolutionary generations = 200, population size = 500, tolerance error between two consecutive generations = 10^{-5}.

After training, parameters in the ANN model for CWFPF of winter wheat were obtained as shown in Tab. 1. With these parameters, yield of winter wheat for different water and fertilizer regime could be estimated from equation (2).

Table 1. ANN weights and thresholds for CWFPF

编号	i=1	i=2	i=3	Note
0	0.3364	-0.4489	0.9461	θ_i
j=1	-0.5716	-0.6228	-0.2871	? i j
j=2	-0.0481	0.3526	-0.5144	? i j
j=3	-0.4535	0.907	-0.2872	? i j
j=4	-0.8484	0.9122	-0.3825	? i j
j=5	0.8642	-0.0026	-0.7029	? i j
l=1	-0.5786	0.7359	-0.9900	T_{li}
l=0	0.8397			θ_l

3.3 Testing the ANN model for CWFPF of winter wheat

Using the above ANN parameters, winter wheat yield of the training and testing samples were calculated and compared with the observed ones, as shown in Fig. 2. All the data is distributed near

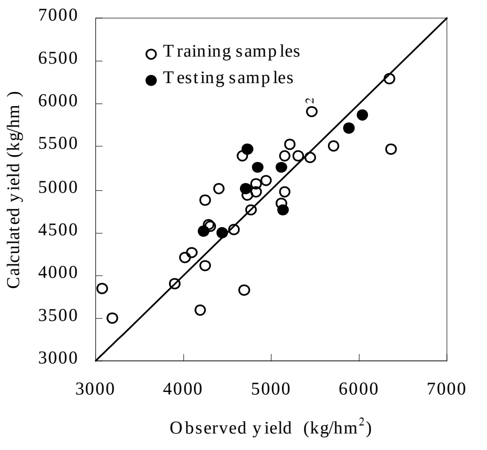

Fig. 2 Comparison of observed winter wheat yield and ANN model calculation

the 1:1 line. For the 35 training samples, the average value of relative errors between calculated and observed yields is 6.4% and the proportion of relative errors less than 10% and 20% are 77% and 97%, respectively. For the 9 testing samples, the above three values are 6.1%, 89% and 100%, respectively. So results indicate that the proposed ANN model is effective in modeling the relationship between crop yield and water-fertilizer.

4 Results

4.1 Impact of water stress in one growing stage on winter wheat yield

Crop yield with different water stress can be estimated, based on the ANN model above. Fig. 3 shows the relationships between relative yield, expressed as ratio of calculated yield Y_c to maximum yield Y_{mF} at the given fertilizer, and water stress for one growing stage when using 400 kg/hm^2 of N fertiliser. The relationships can be expressed with a D-K linear model (Li, 1999):

$$(1-Y_c/Y_{mF})=K_{yi}(1-ET_a/ET_m) \qquad (10)$$

where K_{yi} is the sensitivity coefficient of stage i.

From Fig. 3, the sensitivity coefficients for the four stages are 0.045, 0.165, 0.252 and 0.324, respectively. The order of sensitivity coefficients is milking to maturing > heading to milking > shooting to heading > greening to shooting.

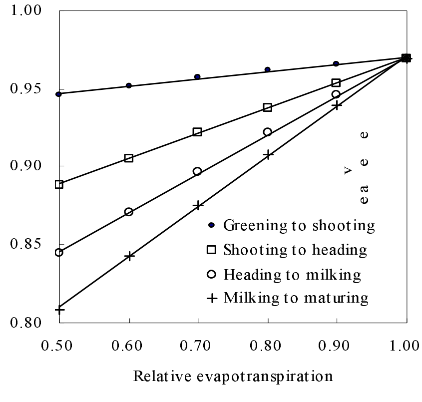

Fig. 3 Impact of water stress on winter wheat yield

4.2 Impact of fertilizer amount on winter wheat yield

The impact of fertilizer amount on crop yield is shown in Fig. 4, with water stress during a single stage being set to a relative evapotranspiration value of 0.75. The larger the amount of fertilizer, the larger the crop yield, for amounts of fertilizer between 0～600 kg/hm^2, as used in this experiment. At the same time, the incremental benefit of fertilizer on yield declines.

5 Conclusions

An ANN model was established to describe the relationship of water-fertilizer and winter wheat yield, with the relative evapotranspiration in each stage, relative fertilization as input and the relative crop yield as output. The training and testing results showed that this ANN model could effectively describe the relationship. Impact of water and fertilizer on crop yield was analyzed with this model. It showed that the crop yield under water stress in a single stage could be described by linear relationship. The order of the sensitivity of crop yield to the water stress is milking to maturing > heading to milking > shooting to heading > greening to shooting. The larger the amount of fertilizer, the larger the crop yield, for amounts of fertilizer between 0～600 kg/hm^2, as used in this experiment. At the same time, the incremental benefit of fertilizer on yield declines.

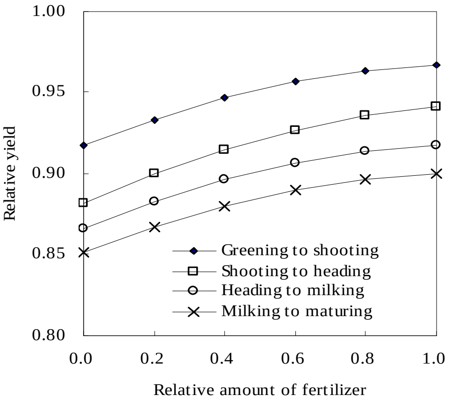

Fig.4. Impact of fertilizer on yield of winter wheat

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