

Optimizing water and nitrogen inputs for winter wheat cropping system on the Loess Plateau, China

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Abstract: Optimal use of water and fertilizers can enhance winter wheat yield and increase the efficiencies of water and fertilizer usage in dryland agricultural systems. In order to optimize water and nitrogen (N) management for winter wheat, we conducted field experiments from 2006 to 2008 at the Changwu Agro-ecological Experimental Station of the Chinese Academy of Sciences on the Loess Plateau, China. Regression models of wheat yield and evapotranspiration (ET) were established in this study to evaluate the water and fertilizer coupling effects and to determine the optimal coupling domain. The results showed that there was a positive effect of water and N fertilizer on crop yield, and optimal irrigation and N inputs can significantly increase the yield of winter wheat. In the drought year (2006–2007), the maximum yield (Y_{\max}) of winter wheat was 9.211 t/hm² for the treatment with 324 mm irrigation and 310 kg/hm² N input, and the highest water use efficiency (WUE) of 16.335 kg/(hm²·mm) was achieved with 198 mm irrigation and 274 kg/hm² N input. While in the normal year (2007–2008), the maximum winter wheat yield of 10.715 t/hm² was achieved by applying 318 mm irrigation and 291 kg/hm² N, and the highest WUE was 18.69 kg/(hm²·mm) with 107 mm irrigation and 256 kg/hm² N input. Crop yield and ET response to irrigation and N inputs followed a quadratic and a line function, respectively. The optimal coupling domain was determined using the elasticity index (EI) and its expression in the water-N dimensions, and was represented by an ellipse, such that the global maximum WUE (WUE_{\max}) and Y_{\max} values corresponded to the left and right end points of the long axis, respectively. Considering the aim to get the greatest profit in practice, the optimal coupling domain was represented by the lower half of the ellipse, with the Y_{\max} and WUE_{\max} on the two end points of the long axis. Overall, we found that the total amount of irrigation for winter wheat should not exceed 324 mm. In addition, our optimal coupling domain visually reflects the optimal range of water and N inputs for the maximum winter wheat yield on the Loess Plateau, and it may also provide a useful reference for identifying appropriate water and N inputs in agricultural applications.

Keywords: water-fertilizer coupling; water use efficiency; optimal coupling domain; yield; winter wheat

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The unbalanced distribution of water and nutrients can significantly limit crop production (Tang, 1999; Zhu, 2000; Xie, 2001; Gao and Li, 2003). The efficient coupling of soil water and fertilizer use is, therefore,

an important issue for improving the economic and ecological outcomes of crop production and ensuring the sustainable development of dryland agriculture (Hou et al., 2012).

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The coordination of soil water content, soil nutrients and their crop demand greatly influences winter wheat yield on the dry and infertile Loess Plateau in Northwest China (Sharma et al., 1992; Wang, 1995; Chen, 1996), where precipitation is scarce and unevenly distributed (Huang et al., 2002). On the plateau, over 55% of the regional rainfall occurs from July through September, while the winter wheat grows fastest during its peak growth period from April through June, which significantly inhibits fertilizer absorption. The use of large amounts of nitrogen (N) fertilizer can significantly improve crop yield, but overuse of it can also lead to environmental problems (Guo et al., 2003). Liu et al. (2000) indicated that irrigation and fertilization can result in a high crop yield in the drought-prone and infertile regions. An appropriate irrigation scheme can significantly improve water use efficiency (WUE) and may eventually increase crop yield and conserve water resources (Li et al., 2004; Gu et al., 2012). The yield of winter wheat increases with the increasing amounts of N fertilizer within an appropriate range (Cai et al., 1994; Huang et al., 1999). Generally, water and fertilizer have a synergistic effect on crop growth. On the one hand, water deficiency restricts the effect of fertilizers on crop yield increasing, while too much water input also leads to a reduction of crop yield and N loss through leaching. On the other hand, both excessive and deficient N fertilizer use can limit the efficiency of water use, which in turn affects the crop yield (Tang and Yang, 1994; Zhen and Liu, 1995; Miao, 1997; Zhai and Li, 2003). In general, the amount of nutrients for a crop to produce a maximal yield varies with the variation of water inputs, and vice versa (Gajri et al., 1993; Sandhu et al., 2002). Many researches have suggested that, at fixed water inputs, the optimal inputs of fertilizer can produce a maximum crop yield; the same is true that fixed fertilizer inputs determine the optimal water inputs (Balasubramanian and Chari, 1983; Sharma et al., 1990; Shen et al., 2001). Therefore, optimizing water and fertilizer coupling levels may be the best way to improve the efficiencies of both fertilizer and water use (Zhai and Li, 2005).

After Arnon (1975) proposed that the basic prob-

lems of dryland agriculture are reasonable fertilizer inputs and high WUE under limited water conditions, researches on the influence of water-fertilizer coupling on crop yields were widely conducted (Balasubramanian and Chari, 1983; Sharma et al., 1990, 1992; Wang, 1995; Li et al., 2000; Liu and Zhang, 2007; Kong et al., 2008). However, the results were different by regions, crop varieties and fertilizer levels (Meng et al., 1998; Li et al., 2000; Liu et al., 2000; Shen et al., 2001; Wu et al., 2001; Li et al., 2005; Kong et al., 2008). High WUE and crop yield are two important objectives for the development of dryland agriculture. Analyzing the optimal inputs of water and fertilizer for increasing WUE and crop yield is an important issue in water-saving agriculture (Liu, 1997, 1998; Liu et al., 2002; Liu and Zhang, 2007).

The objectives of this study are to: (1) analyze the effects of water and N fertilizer coupling levels on winter wheat yield and the indicators associated with the yield; (2) establish regression equations to describe the relationships between crop yield, irrigation and N fertilizer use; and (3) determine a reasonable amount of irrigation and N inputs for the maximum winter wheat yield.

1 Materials and methods

1.1 Study area

Field experiments were conducted from October 2006 to June 2007 and from October 2007 to June 2008 at the Changwu Agro-ecological Experimental Station of the Chinese Academy of Sciences, which is located in a typical semi-arid area of the Loess Plateau, Shaanxi province, Northwest China (107°40'30"E, 35°14'30"N; 1,200 m asl). A long-term (1956–2008) average annual precipitation in this region is 584 mm. The annual mean temperature is 9.1°C and the mean annual accumulative temperature above 10°C is 3,029°C. The average annual frost-free period is 171 days. Precipitation and temperature data in this study (Fig. 1) were from a weather station of Chinese Ecological Research Network, 100 m away from the east of the experimental site. According to the division standard for different precipitation years (Hao et al., 2003), we divided a year into two periods, i.e. the fallow period

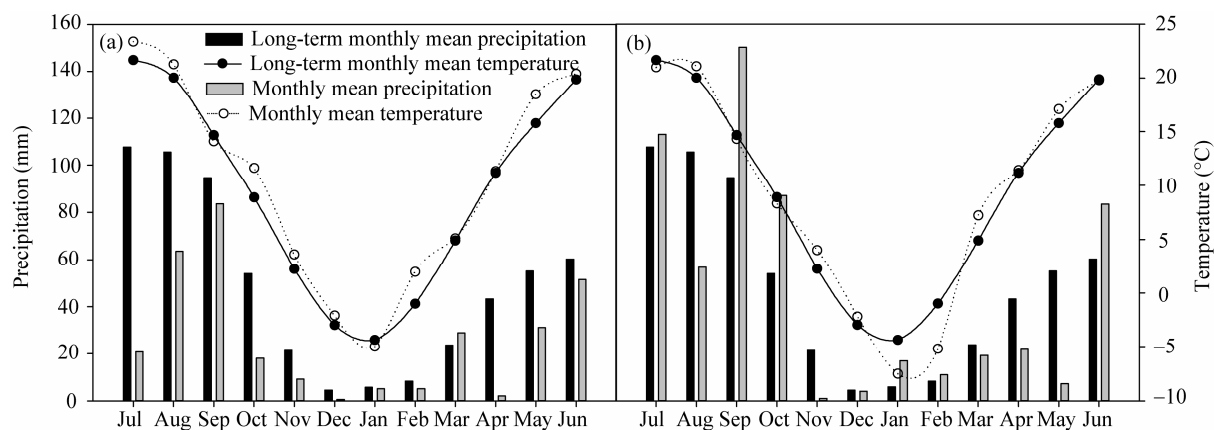


Fig. 1 Monthly mean precipitation and temperature from July 2006 to June 2007 (a) and July 2007 to June 2008 (b) compared with the long-term monthly means (1956–2008) at the experimental site

before sowing (from July through September) and the growing period (from October through the next June). The year with ‘normal precipitation’ is defined as the normal year, while the wet year is considered having 10% more or above precipitation compared with the long-term average, and the drought year having 10% less or below precipitation compared with the average value. During our experiments, the mean temperatures in the two growing seasons were similar and close to the long-term annual average. The precipitation from July 2006 to June 2007 was less than 10% of the long-term mean annual amount, while from July 2007 to June 2008 it approached the long-term mean value. Therefore, 2006–2007 and 2007–2008 in this study were considered to represent the drought and normal year, respectively.

The soil of the experimental site is Heilu soil (Calcic Kastanozems, FAO) with a field capacity of 23% and a permanent wilting coefficient of 10% in gravimetric content. The pH value of topsoil (0–20 cm) was 8.2. The organic matter, total N, hydrolysable N, available phosphorous (AP) and available potassium (AK) contents were 11.2 g/kg, 0.89 g/kg, 42.9 mg/kg, 5.8 mg/kg and 172.6 mg/kg, respectively.

1.2 Experimental design

The study was carried out by using an incomplete factorial design. The treatments were combinations of irrigation water and N application with 3 replications (Table 1). Totally, 27 treatments were assigned into 81 plots in a randomized block design. Every plot has an area of 16 m², and was surrounded by 1-m wide vege-

tated buffer strips.

The numbers of N and irrigation treatments in this study were designed as arithmetic progressions. In order to facilitate the calculation, we used the numerical designators (levels) to represent the amounts of N and irrigation water rather than their actual quantities. The lowest level of N or irrigation water was expressed using the number 0, and increasing numbers were given in the order of increasing N or irrigation water quantities as 1, 2, 3, 4 and 5.

Irrigations were conducted at five growing stages of winter wheat, i.e. over-wintering, turning green, jointing, heading and filling. About 75-mm equivalent water was piped and irrigated to every plot at every irrigation treatment. The treatment W0 (0) received no irrigation at the whole growing stage, W1 (75 mm) received 1 irrigation at the over-wintering stage, W2 (150 mm) received 2 irrigations at the over-wintering and turning green stages, and so forth for W3 (225 mm), W4 (300 mm) and W5 (375 mm; Table 1). N rates in this study were 0 (N0), 75 (N1), 150 (N2), 225 (N3), 300 (N4) and 375 (N5) kg/hm², respectively. All the N fertilizers, in forms of urea and 120 kg phosphorous pentoxide (P₂O₅) per hectare, were applied once when sowing according to the local cropping system. The cultivar of winter wheat (*Triticum aestivum* L.) used in the experiments is ‘Changhan 58’, which is widely cultivated in the study area. Wheat seeds were sown in 5-cm soil depth with the row spacing of 20 cm and the seeding rate of 150 kg/hm² on 14 September 2006 and 22 September 2007, respectively. Crops were harvested at the end of June in both years.

Table 1 Treatments of water-N combinations and irrigations

Treatment of water-N combination							Treatment of irrigation in growing period (mm)					
	N0	N1	N2	N3	N4	N5	Over-wintering	Turning green	Jointing	Heading	Filling	Whole growing
W0	W0N0	W0N1	W0N2	W0N3	W0N4	W0N5	0	0	0	0	0	0
W1	W1N0		W1N2			W1N5	75	0	0	0	0	75
W2	W2N0		W2N2			W2N5	75	75	0	0	0	150
W3	W3N0	W3N1	W3N2	W3N3	W3N4	W3N5	75	75	75	0	0	225
W4	W4N0		W4N2			W4N5	75	75	75	75	0	300
W5	W5N0	W5N1	W5N2	W5N3	W5N4	W5N5	75	75	75	75	75	375

1.3 Methods

1.3.1 Plant and soil sampling

Sampling and measurement procedures were respectively the same in the two growing seasons. Soil water content in each plot was measured at a depth of 300 cm and at an interval of 20 cm using the gravimetric method at sowing and harvesting times. Wheat spikes were investigated at a fixed position before harvesting. Grains per spike were measured by harvesting 20 spikes from each plot. Wheat plants in an area of 1 m² in the center of each plot were harvested for measuring grain yields and determining 1000-grain weight.

1.3.2 Evapotranspiration (ET) and WUE

Field ET (mm) was estimated by water balance method:

$$ET = P + I + \Delta SWS - R - D. \quad (1)$$

Where, P is the precipitation amount during the growing season (mm); I is the amount of irrigation (mm); ΔSWS is the net decrease of soil water storage in the upper soil layer of 300 cm from the beginning to the end of the growing season (mm); R is the surface runoff (mm); and D is the deep leakage (mm). For the little precipitation and deep groundwater table in this region, R and D were very small and could be neglected here.

Then, the equation for ET can be simplified as Eq. 2.

$$ET = P + I + \Delta SWS. \quad (2)$$

This equation indicates that ET is the sum of precipitation, irrigation and net decrease of soil water storage during the whole growing season.

The equation for soil water storage is given as below:

$$SWS = h \times a \times \theta \times 10. \quad (3)$$

Where h is the soil depth (cm), a is the soil bulk den-

sity (g/cm³), and θ is the soil water content change (%).

The WUE for wheat in our experiments was calculated by the grain yield divided by the total ET during the whole growing season.

1.3.3 Elasticity index (EI) and relationships with water-N inputs

When water and N inputs change linearly or only one factor of them varies, EI can illustrate the relationships between crop yield, water consumption and WUE in two-dimensional coordinates (Liu, 1998). However, if the amounts of water and N change randomly at the same time, the relationships between crop yield, water and fertilizer inputs can't be presented in two-dimensional coordinates. The yield (Y) and ET should be described as a function of water (x_1) and N (x_2) inputs in three-dimensional coordinates.

$$Y = Y(x_1, x_2), \quad (4)$$

$$ET = ET(x_1, x_2). \quad (5)$$

So, EI would be calculated as Eq. 6 (Liu and Zhang, 2007).

$$EI = \frac{\frac{\partial Y}{\partial x_2} \frac{dx_2}{dx_1} + \frac{\partial Y}{\partial x_1}}{\frac{\partial ET}{\partial x_2} \frac{dx_2}{dx_1} + \frac{\partial ET}{\partial x_1}} \times \frac{ET}{Y}. \quad (6)$$

After selecting a direction of dx_2/dx_1 in the water-N (x_1 - x_2) plane, the relationships between crop yield, ET and WUE, and the characteristics of which can be analyzed at the thresholds of EI (1 or 0). Then, Eq. 6 could be used to describe the optimal range of water and N coupling based on the observed yield data. Liu et al. (2002) also reported their results using the direction of dx_2/dx_1 , which can be represented by the following two directions.

(1) One direction is the line from a local point (x_1, x_2)

to the point (x_{1m}, x_{2m}) with global maximum yield (Y_{\max}):

$$\frac{dx_2}{dx_1} = \frac{x_2 - x_{2m}}{x_1 - x_{1m}}. \quad (7)$$

The physical meaning of Eq. 7 implies that the global Y_{\max} can be identified when the shortest distance of x_1 and x_2 is reached.

(2) The other direction is the greatest gradient direction of the point on the Y surface:

$$\frac{dx_2}{dx_1} = \frac{\partial Y / \partial x_2}{\partial Y / \partial x_1}. \quad (8)$$

The physical meaning of Eq. 8 is that the greatest yield increase can be determined at certain levels of x_1 and x_2 .

Using Eq. 6, the EI in the direction of dx_2/dx_1 can be calculated based on the expression of dx_2/dx_1 .

2 Results

2.1 Effects of water and N coupling on crop yield

The grain yield elements of winter wheat varied greatly under different levels of water and N coupling from the over-wintering to the heading period (Figs. 2–4). Under the same irrigation conditions (except for W5), spikes increased with the increase of N inputs (Fig. 2). Spikes reached the maximum

values of 638.125×10^4 ears/hm² for the treatment W5N4 in 2006–2007 and 698.125×10^4 ears/hm² for W4N5 in 2007–2008. The variation in grains per spike was similar to that in spikes (Fig. 3). The largest grains per spike in 2006–2007 and 2007–2008 were 38.85 for W5N2 treatment and 41.49 for W3N5 treatment, respectively. The 1000-grain weight decreased with the increase of N inputs or irrigation amounts (Fig. 4). The treatment W3N0 in 2006–2007 had the maximum 1000-grain weight value of 45.6 g, while the treatment W5N0 in 2007–2008 had the maximum value of 49 g.

Notably, the yield of winter wheat can be improved using the appropriate amounts of water and N, because we identified a positive relationship between water and N inputs (Fig. 5). In 2006–2007, as the amount of irrigation increased and the N levels were between N0 to N3, the yield increased significantly. However, when the N levels were between N4 and N5, the yield increased slightly with the increase of irrigation inputs. In 2006–2007, the highest yield of winter wheat (8.87 t/hm^2) was obtained for the treatment W3N4 (Table 2 and Fig. 5). The variation trend of winter wheat yield in 2007–2008 was similar to that in 2006–2007, and the highest winter wheat yield in 2007–2008 (10.09 t/hm^2) was also obtained for the treatment W3N4.

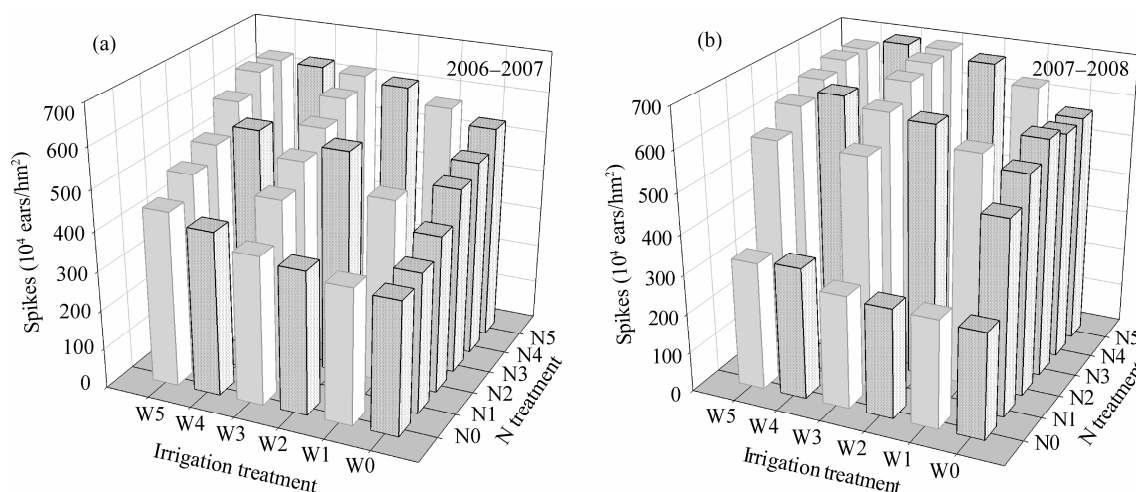


Fig. 2 Effects of water and N coupling on spikes in 2006–2007 (a) and 2007–2008 (b)

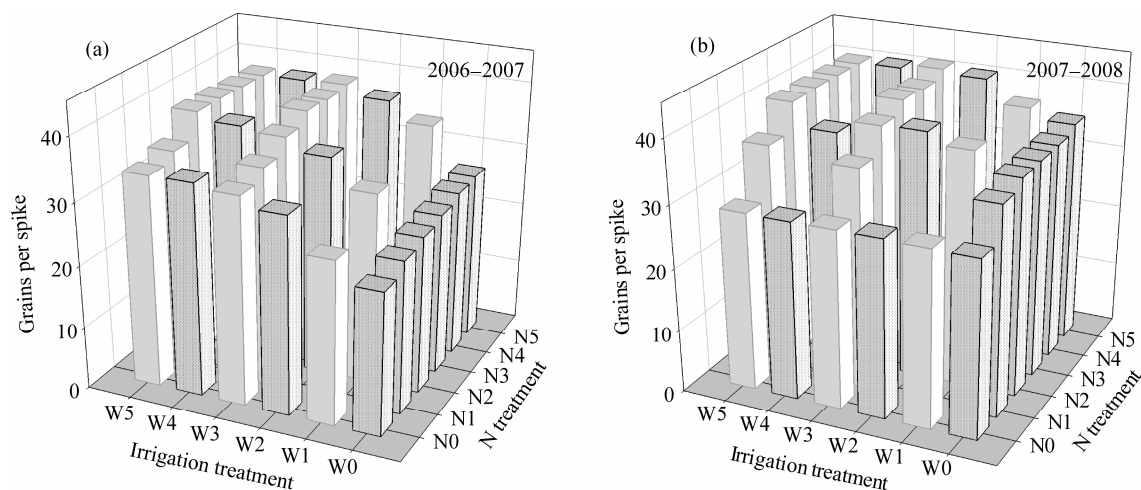


Fig. 3 Effects of water and N coupling on grains per spike in 2006–2007 (a) and 2007–2008 (b)

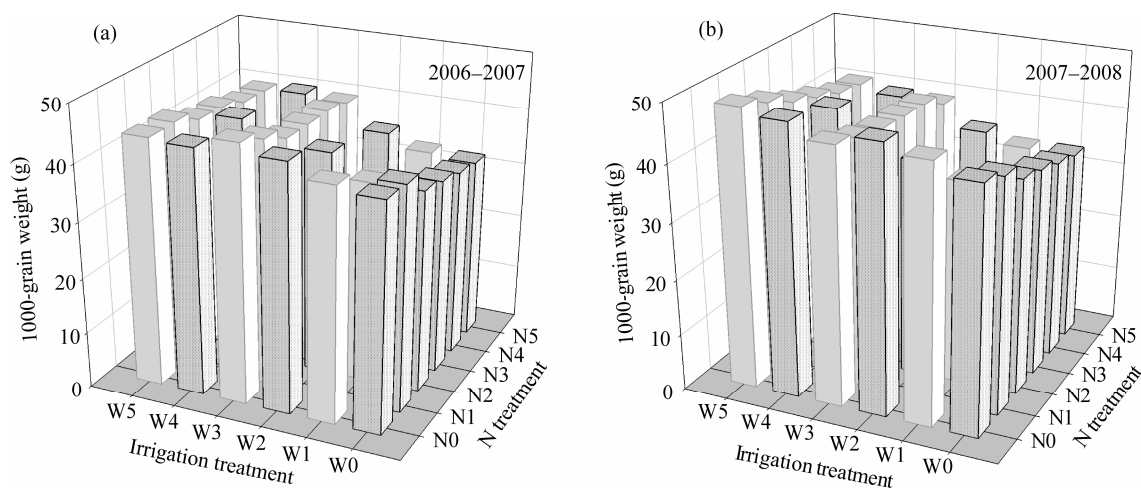


Fig. 4 Effects of water and N coupling on 1000-grain weight in 2006–2007 (a) and 2007–2008 (b)

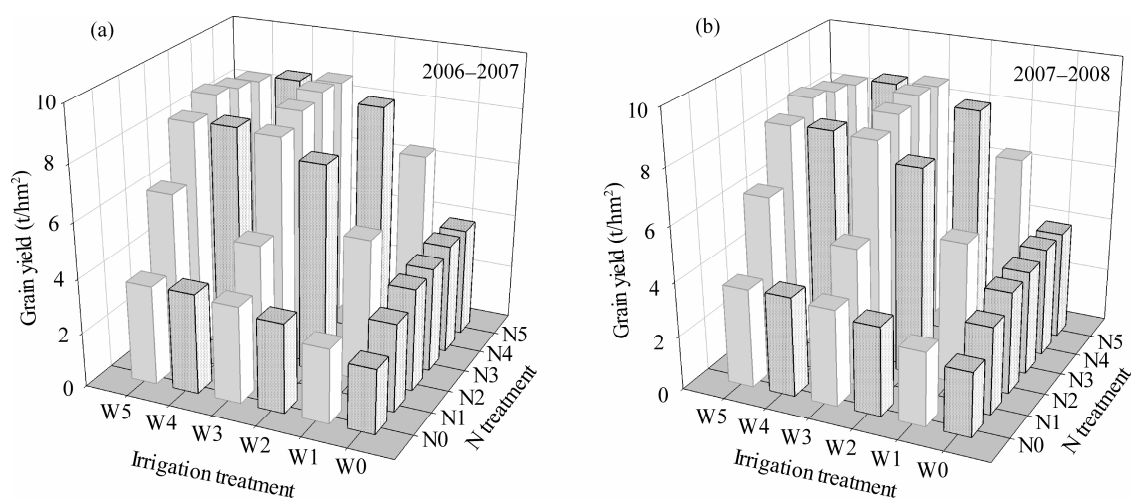


Fig. 5 Effects of water and N coupling on grain yield in 2006–2007 (a) and 2007–2008 (b)

Table 2 Yield (Y), evapotranspiration (ET) and water use efficiency (WUE) for different water-N combination treatments in 2006–2007 and 2007–2008

Treatment	2006–2007			2007–2008		
	Y (t/hm ²)	ET (mm)	WUE (kg/(hm ² ·mm))	Y (t/hm ²)	ET (mm)	WUE (kg/(hm ² ·mm))
W0N0	2.38	358.73	6.64	2.91	388.29	7.49
W0N1	3.24	366.81	8.83	4.46	396.08	11.27
W0N2	3.77	370.90	10.17	5.82	393.35	14.79
W0N3	3.84	377.03	10.18	6.33	401.59	15.76
W0N4	4.03	382.02	10.54	6.38	400.51	15.94
W0N5	3.98	386.06	10.32	6.24	405.75	15.37
W1N0	2.75	424.33	6.47	2.92	432.57	6.74
W1N2	5.23	439.88	11.89	7.64	455.91	16.77
W1N5	6.49	451.23	14.39	8.13	466.58	17.42
W2N0	3.30	472.83	6.99	3.11	484.34	6.43
W2N2	7.59	486.42	15.60	8.81	513.35	17.17
W2N5	8.07	501.30	16.09	9.76	521.30	18.73
W3N0	3.57	509.31	7.01	3.22	543.78	5.91
W3N1	5.08	538.53	9.43	6.83	556.48	12.28
W3N2	8.29	554.62	14.94	9.32	577.50	16.13
W3N3	8.68	558.17	15.56	10.01	581.97	17.19
W3N4	8.87	563.10	15.75	10.09	580.71	17.38
W3N5	8.73	567.16	15.40	10.00	597.21	16.74
W4N0	3.69	552.18	6.68	3.35	593.83	5.64
W4N2	8.38	584.06	14.34	9.46	660.11	14.33
W4N5	8.61	619.60	13.89	9.85	683.02	14.42
W5N0	3.65	600.27	6.08	3.38	632.65	5.34
W5N1	6.32	609.61	10.36	7.72	663.65	11.63
W5N2	8.32	612.46	13.58	9.47	682.79	13.87
W5N3	8.81	614.62	14.33	10.06	694.19	14.49
W5N4	8.57	617.21	13.89	10.00	705.84	14.16
W5N5	8.37	619.52	13.50	9.67	711.52	13.59

2.2 Responses of yield to water and N coupling

2.2.1 Analysis of yield responses to water and N coupling

According to the yields of winter wheat under different water and N combination conditions, the relationships between yield, water and N fertilizer inputs in 2006–2007 and 2007–2008 were simulated as Eq. 9 and Eq. 10, respectively.

$$Y = 1225.569 + 23.072W + 27.386N + 0.019WN - 0.0451W^2 - 0.054N^2 \quad (F=71.679, R^2=0.945, P<0.001), \quad (9)$$

$$Y = 1740.825 + 18.085W + 41.811N + 0.016WN - 0.036W^2 - 0.08N^2 \quad (F=102.788, R^2=0.961, P<0.001). \quad (10)$$

Where, Y is the yield of winter wheat (kg/hm²); W is

the irrigation quantity (mm); and N is the N amount (kg/hm²). These results showed that the simulated yield of winter wheat from Eq. 9 and Eq. 10 agreed well with the observed data in the growing seasons of 2006–2007 and 2007–2008, respectively (Fig. 6).

The regressive equations (Eqs. 9 and 10) from the two-year study suggested: (1) The yield of winter wheat first increased with the increase of water and N inputs, as evidenced by the positive first order coefficients in the regression equations; and (2) All the quadratic coefficients in the regression equations were negative, indicating a downward parabola and implying that excessive irrigation and N inputs may result in higher costs and lower yields.

2.2.2 Analysis of the marginal yield

In a multiple regression model, the marginal yield represents the increase in total yield as one variable changes while the other variables remain unchanged (Li et al., 2000). The effects of water and N inputs on winter wheat yield followed the law of diminishing returns. At this point, the associated amounts of water and N can be considered the optimal values as shown in Fig. 7. From Fig. 7, we can get two conclusions: (1) The slope of Y_N' in the normal year (2007–2008) was larger than that in the drought year (2006–2007), which indicated that the amount of N had a greater effect on winter wheat yield as the amount of water increased; and (2) The slope of Y_w' in the drought year (2006–2007) was larger than that in the normal year (2007–2008), which showed that the wheat yield was more sensitive to irrigation in the drought year.

2.2.3 Inputting amounts of water and N fertilizer for the maximum crop yield

The maximum crop yield scheme shows the input levels of water and N for achieving the maximum crop yield without considering the costs. In this study, the partial derivatives of water and N in 2006–2007 and 2007–2008 were calculated based on Eq. 9 and Eq. 10, respectively.

In 2006–2007:

$$\frac{\partial Y}{\partial W} = 23.072 + 0.019N - 0.0902W, \quad (11)$$

$$\frac{\partial Y}{\partial N} = 27.386 + 0.019W - 0.108N. \quad (12)$$

In 2007–2008:

$$\frac{\partial Y}{\partial W} = 18.085 + 0.016N - 0.072W, \quad (13)$$

$$\frac{\partial Y}{\partial N} = 41.811 + 0.016W - 0.16N. \quad (14)$$

When $\partial Y/\partial W$ and $\partial Y/\partial N$ (Eqs. 11–14) are considered to be zero, the amounts of water and N required for achieving the Y_{\max} in different years can be calculated (Table 3).

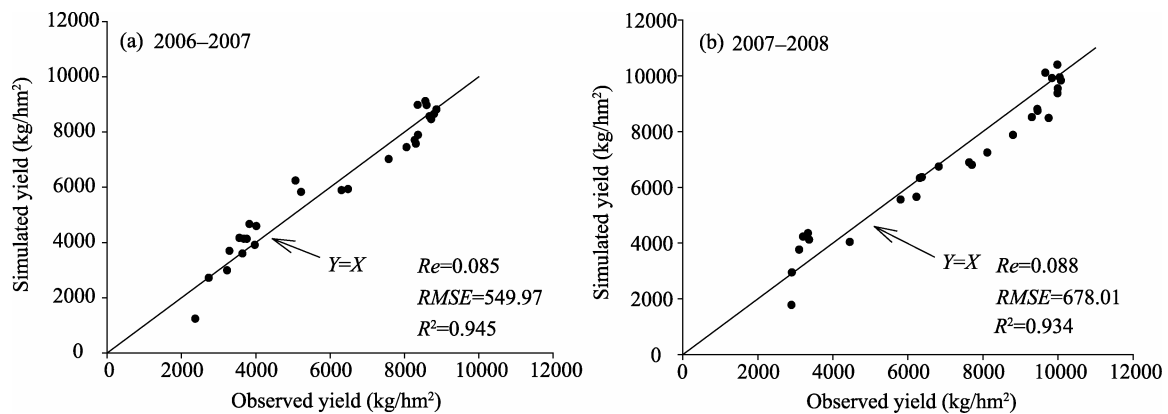


Fig. 6 Relationships between the observed and simulated yields in 2006–2007 (a) and 2007–2008 (b). $Y=X$, 1:1 line.

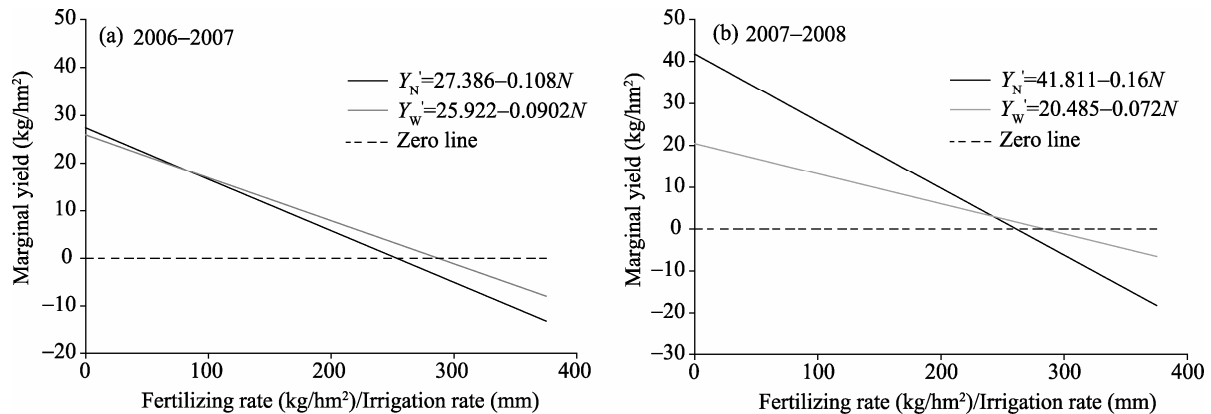


Fig. 7 Relationships between the amounts of irrigation water, N fertilizer and marginal yield in 2006–2007 (a) and 2007–2008 (b)

Table 3 Amounts of water and N inputs for achieving the maximum yield (Y_{\max})

Year	Irrigation amount (mm)	N addition (kg/hm ²)	Y_{\max} (t/hm ²)
2006–2007	321.10	310.00	9.18
2007–2008	316.28	292.95	10.72

2.3 Optimal coupling domain for water and N inputs

Although we have calculated the amounts of water and N inputs to achieve the maximum winter wheat yield, it is more practical to consider a suitable range for water and N inputs, i.e. the ‘optimal coupling domain’ of water and N inputs. Within this coupling domain, we can determine the water and N inputs that satisfy the high WUE and crop yield. This would allow our study to have a higher relevance in practical application.

2.3.1 Response functions of yield and ET to water and N input levels

The regression equations representing yield and ET were described by N and water inputs for 2006–2007 (Eqs. 15 and 16) and 2007–2008 (Eqs. 17 and 18) based on simplified water and N input levels, and the observed yield and ET values were from Table 2.

$$Y = -3.006 + 2.553x_2 + 2.125x_1 + 0.108x_1x_2 - 0.304x_2^2 - 0.252x_1^2, \quad (15)$$

$$ET = 312.438 + 7.025x_2 + 48.425x_1 \quad (F=433.38, R^2=0.973, P<0.001), \quad (16)$$

$$Y = -3.316 + 3.953x_2 + 1.669x_1 + 0.088x_1x_2 - 0.452x_2^2 - 0.2x_1^2, \quad (17)$$

$$ET = 305.236 + 9.674x_2 + 58.164x_1 \quad (F=791.93, R^2=0.985, P<0.001). \quad (18)$$

In three-dimensional coordinates, the yield was represented by a quadratic paraboloid whereas the ET formed a plane, based on Eqs. 15–18. In 2006–2007, the maximum winter wheat yield was 9.211 t/hm² when $x_1=5.319$ and $x_2=5.144$, and the maximum WUE (WUE_{\max}) of 16.335 kg/(hm²·mm) was achieved when $x_1=3.645$ and $x_2=4.658$. With the same method, in 2007–2008, the maximum winter wheat yield of 10.715 t/hm² was achieved when $x_1=5.247$ and $x_2=4.880$, and the WUE reached its maximum value of 18.69 kg/(hm²·mm) with $x_1=2.425$ and $x_2=4.410$.

2.3.2 Optimal coupling domain for water and N inputs

Equation 6 can be used to delineate an optimal coupling domain for water and N inputs using our experimental data. Firstly, we considered the line direction using Eq. 7, in search of a global Y_{\max} . In 2006–2007, substituting the values of x_{1m} , x_{2m} , Eqs. 15–16 and their corresponding derivatives with respect to x_1 and x_2 into Eq. 6, and then setting EI equals to 1 (Liu, 1998) resulted in the x_1 - x_2 relationship (Fig. 8). The relationship between water and N levels can be represented by an ellipse, and the edge points of the ellipse represent the local maxima of WUE because EI is always equal to 1. The value of dx_2/dx_1 at the point of the global Y_{\max} does not exist, so the values of x_1 and x_2 can not reach the Y_{\max} point when EI is set to 1. When the yield reaches its global maximum value, EI equals zero. The values of x_1 and x_2 at the Y_{\max} point are shown in Fig. 8. The point representing the Y_{\max} is also shown on the trend line, although it does not exist when $EI=1$. Hence, the ellipse region is surrounded by a series of Y_{\max} points at $EI=0$ and $EI=1$ for different soil water and N levels. This ellipse region is therefore considered to be the feasible region of water and N inputs. The lower limit of the feasible region is the point at which the WUE reaches a global maximum value, and the upper limit of the feasible region is the point at which the yield reaches its global maximum value. As shown in Fig. 8, Y_{\max} and WUE_{\max} are located at the two end points of the long axis in the ellipse. The ellipse equations for 2006–2007 and 2007–2008 were shown as Eq. 19 and Eq. 20, respectively. This equation for the ellipse was called the first species ellipse.

$$0.749x_2^2 + 0.638x_1^2 - 0.071x_1x_2 - 7.027x_2 - 5.368x_1 + 28.773 = 0, \quad (19)$$

$$2.01x_2^2 + 0.777x_1^2 - 0.423x_1x_2 - 17.05x_2 - 3.99x_1 + 45.744 = 0. \quad (20)$$

Both equations (Eqs. 19 and 20) for 2006–2007 and 2007–2008 had the same form, in which the global Y_{\max} and WUE_{\max} located at the two end points of the long axes in the ellipse, and their gradients, were also similar. This water-N coupling area was found to be similar for both the dry and normal years, which implies that this method is credible.

When selecting the greatest gradient direction of

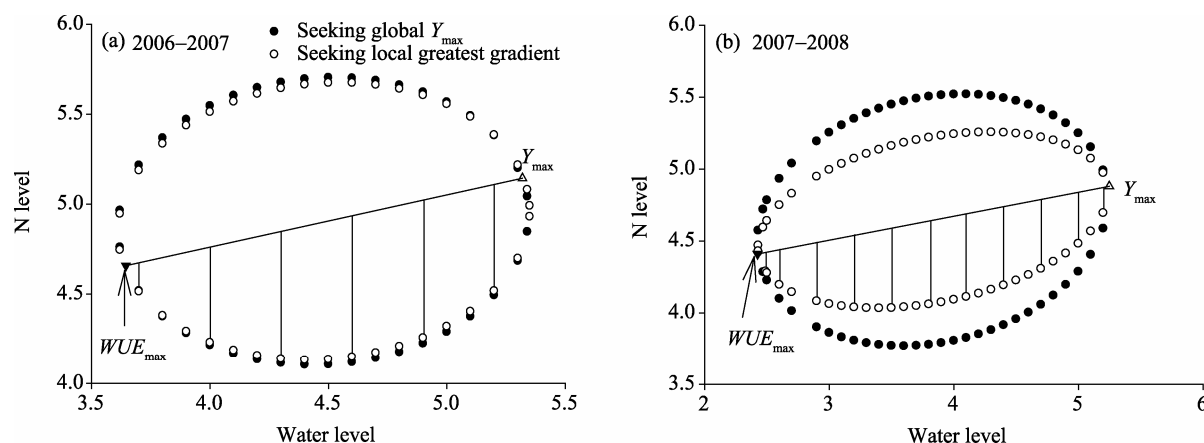


Fig. 8 Optimal coupling domains for water and N inputs in 2006–2007 (a) and 2007–2008 (b)

the point on the Y surface (Eqs. 8), we derived another set of ellipses that were also shown in Fig. 8. The ellipse equations for 2006–2007 and 2007–2008 were represented as Eq. 21 and Eq. 22, respectively.

$$0.745x_2^2 + 0.589x_1^2 - 0.099x_1x_2 - 6.861x_2 - 4.794x_1 + 27.118 = 0, \quad (21)$$

$$1.999x_2^2 + 0.378x_1^2 - 0.555x_1x_2 - 16.438x_2 - 0.322x_1 + 38.115 = 0. \quad (22)$$

These two equations were of the second species ellipse. Compared with the first species ellipse (used to determine Y_{\max}), the two end points on the long axis of the second species ellipse still represented Y_{\max} and WUE_{\max} , but the length of their short axes were smaller.

As mentioned above, the equation for describing the yield responses to water and N inputs was a smooth parabola. The global and local maximum yields under each water or N treatment existed on the parabola. The right end point on the long axis of the ellipse was the projected point for the global and local maximum yields. In other words, the yield reaches its local maxima on the long axis of the ellipse. The left end point on the long axis of the ellipse represented the local maxima of WUE. In practice, it is always desired that increasing the inputs of water and N results in the maximum increase in yield, and the second species ellipse was constructed to reflect conditions just in this case. Therefore, the lower half of the ellipsoid (the hatched area in Fig. 8) represents the optimal coupling domain for water and N inputs in practical agriculture of our study area.

3 Discussion and conclusions

Water and fertilizer, which restrict or promote the growth of winter wheat, are two key factors relating to crop yield (Shangguan et al., 1999). Some studies have shown that improving irrigation and fertilizer conditions significantly affected the yield of winter wheat (Meng et al., 1998; Li et al., 2000; Li et al., 2005; Kong et al., 2008). Positive effects on wheat yield have been documented for a certain range of water and fertilizer inputs, such that greater amounts of water were matched with higher amounts of fertilizer, and vice versa (Zhao et al., 2009). However, winter wheat yields have also been reported to be decreased when the inputs of water and fertilizer exceeded a certain range (Li et al., 2000; Zhang et al., 2005). Similar results were also found in our study.

Spikes, grains per spike and 1000-grain weight are considered to be the three key elements that have the greatest effect on grain yield of winter wheat. Zhao et al. (2009) found that the spikes and 1000-grain weight increased with the increase of irrigation frequencies, while no significant relationship existed between N inputs and 1000-grain weight. In addition, Li et al. (2005) reported that within a certain inputs range, spikes of winter wheat increased with the increase of water and N amounts, following the shape of a quadratic parabola under different water conditions. The 1000-grain weight decreased with the increase of N inputs under a certain water level, while it was not significantly affected by water inputs when the N input was fixed. Zhang et al. (2005) found that both

spikes and grains per spike increased as N inputs were coupled with a high water level. However, the 1000-grain weight was negatively correlated to water quantity, and no significant relationship was found between 1000-grain weight and fertilizer inputs.

In our study, spikes increased with the increase of both water quantities and N inputs. In addition, the variation of grains per spike was similar to that of spikes, which also increased with the increase of water and N inputs. We also found that the 1000-grain weight decreased with the increase of N inputs, and there was no significant relationship between 1000-grain weight and increased irrigation levels. Our results, concerning spikes, grains per spike and 1000-grain weight of winter wheat for different amounts of water and N, were different from those reported in other studies. The reason may be the differences in plot scales, and related water and fertilizer conditions.

The equation describing yield responses to water and N inputs directly reflected the interactions between these factors. In this study, the increase of water and N levels improved the winter wheat yield and promoted each other, but only to a certain range. Excessive inputs of water and N not only increased production cost but also decreased crop yield. According to our marginal yield analysis, the effect of water and N inputs on crop yield was associated with diminishing returns, whereby the winter wheat yield reached its maximum value when the marginal yield was equal to zero. The result was similar to that reported by Zhang et al. (2005), Liu et al. (2000) and Li et al. (2005).

We also observed that the yield response surfaces were quadratic parabolas, while the ET response surfaces were planar in three-dimensional coordinates. These surfaces were obtained from the responding equations for yield and ET in 2006–2007 (Eqs. 15 and 16) and 2007–2008 (Eqs. 17 and 18). The results showed that, in the drought year, the maximum winter wheat yield was 9.211 t/hm^2 for the treatments with 324 mm irrigation and 310 kg/hm^2 N rate, and the highest WUE was $16.335 \text{ kg}/(\text{hm}^2 \cdot \text{mm})$ with 198 mm irrigation and 274 kg/hm^2 N rate. However, in the normal year, the maximum winter wheat yield was 10.715 t/hm^2 with the treatments of 318 mm irrigation

and 291 kg/hm^2 N input, and the highest WUE was $18.69 \text{ kg}/(\text{hm}^2 \cdot \text{mm})$ corresponding to the treatments with the irrigation of 107 mm and the N input of 256 kg/hm^2 . The global Y_{\max} and WUE_{\max} were all higher in the normal year than in the drought year.

The useful range of water and fertilizer inputs was directly described by the optimal coupling domain derived from crop yield and WUE. In this domain, when the irrigation amount is below the level required to produce the WUE_{\max} , both crop yield and WUE increase with an increased irrigation amount. When the irrigation level is within the range that strikes a balance between the Y_{\max} and WUE_{\max} , any additional increase in irrigation amount will cause the crop yield to increase while the WUE to decrease. Consequently, the crop yield and WUE decrease when the irrigation level is higher than the optimal amount for producing the maximum winter wheat yield. These results suggested that the irrigation amount should not exceed 324 mm for a high winter wheat yield and WUE in the region studied.

In general, the levels of water and fertilizer inputs should be optimized according to different water and fertilizer conditions in a particular region. In regions with limited water resources, the decision about the amount of fertilizer to use should be made by taking into consideration the global WUE_{\max} ; while in regions with sufficient water resources, this decision should consider the global Y_{\max} . Also, the amount of fertilizer required in rain-fed agriculture should be calculated using an optimal water-N coupling domain which accounts for precipitation levels. Moreover, the amount of fertilizer used should be calculated according to the precipitation in a region and its predefined irrigation program. The fertilizer input should be balanced for achieving the best WUE and the highest crop yield.

Considering the two major objectives of crop yield and WUE in dryland agriculture, we determined an optimal coupling domain for applying water and N to winter wheat in a semi-arid region on the Loess Plateau. This optimal coupling domain directly reflects the best levels of irrigation and N fertilizer that should be supplied to winter wheat, and also provides a reference for applying reasonable levels of water and fertilizer in practice.

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