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Original Research Paper

Quantifying the Impact of Climate, Irrigation and Nitrogen on Winter Wheat Yield in Guanzhong Plain of Northwest China

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ABSTRACT

Wheat (*Triticum durum*) yields have increased significantly because of the increasing higher irrigation and fertilizer inputs since the last half of 20th century. With varying climate and rising population, increasing focus is being given to enhancing resource use efficiency while increasing yields. This study utilized the CERES (Crop Estimation through Resource and Environment Synthesis) - Wheat model to analyse the impact of irrigation, nitrogen (N) and climate on wheat yield, using 58-year climate data. Analyses were conducted using four assumed scenarios with step-by-step method. Results showed that the optimum irrigation and nitrogen ranges were not uncertain when taking into account a single factor. When considering both irrigation and nitrogen, the impact of irrigation on simulated grain yield was greater than that of nitrogen, which was similar to the results obtained from the experiments. The average variation in grain yield was attributed to irrigation (46.8%), nitrogen (5.5%) and climate (2.4%). Besides, relative humidity and maximum temperature were consistently and significantly correlated with grain yield under all conditions, while precipitation had a significant correlation with grain yield when no irrigation or N was applied, or one of them was applied. However, solar radiation was significantly correlated with grain yield when both irrigation and N were available.

INTRODUCTION

Wheat (*Triticum durum*), a basic staple food for humans, is grown in most parts of China. This crop grows in warmer places and its optimal production needs adequate moisture in its entire growing season. However, precipitation distributes unevenly with great variation and mainly concentrates in summer and autumn in China. In spite of this, its yield has increased by 6.5-fold in the past 60 years (data obtained from http://zzys.agri.gov.cn/nongqing.aspx) because of higher irrigation, fertilizers and pesticide applications. These applications have an adverse impact on the ecosystem services and environmental quality if not used appropriately (Gregory et al. 2002, Matson et al. 1997). Yield increase ceases or declines after irrigation and fertilizer applications reach a certain amount (Cassman et al. 2003). Thus, irrigation and fertilizer applications need to be restricted as a consequence of inadequate resources and environmental protection.

Deficit irrigation is, therefore, applied to allow yield reduction within limited ranges and to allocate limited water properly on some growth stages (Fereres & Soriano 2007, Kang et al. 2002, Payero et al. 2006). It has been practiced in several areas, where it has been proven to considerably increase water use efficiency (WUE) and decrease grain yield by only a small margin, or sometimes even has no effect on grain yield compared to rainfed winter wheat (Eck 1988, Oweis et al. 2000, Yu Kun et al. 2009). These findings only establish the direct relationship between irrigation application, WUE and grain yield. In fact, an underlying mechanism of varying WUE and yield under deficit irrigation (Kobata et al. 1992, Xue et al. 2006), may provide evidence of these yields or WUE under various irrigation conditions. Nitrogen (N), another key factor in wheat growth, is overused in most parts of China. Excessive nitrogen fertilization rates increase the overall costs and potential environmental effect caused by soil acidification and nitrate leaching (Guo et al. 2010, Ju & Zhang 2003, Lv et al. 1998, Tong et al. 2005, Zhang et al. 1995). Nitrogen fertilizer supply to wheat has a positive impact on the wheat growth and development (Blacklow & Incoll 1981, Frederick & Camberato 1994), therefore, N fertilizer supply cannot be inadequate.

Crop yields are not affected by water or N independently, and the extent of influences varies in different regions. These factors are constrained by N in developing regions, and in developed regions, precipitation and water availability have a considerable limitation on yield increase (Sinclair & Rufty 2012). This does not mean that yields affected mainly by water or N is only related to the regions, but is also related to the amount and growth stages. For example, the N application impact on yield in the early stage is larger than that in the later stage under non-irrigated conditions, in which lower N rates are more helpful for higher yield gained than higher N rates. The N effect on grain yield is more significant under irrigated conditions than under non-irrigated conditions. The jointing stage is a key and sensitive stage of winter wheat responses to water and N coordination, and grain yield increases when water and N fertilizer are applied at this stage (Zhai & Li 2006).

The greater extent of yield variability is not only related to irrigation and fertilizer, but also to climate (Mueller et al. 2012). Climate variation is reported to be anticipated, to make crop production increase in high and mid-latitudes, and decrease in lower latitudes, as time progresses. Until the year 2080, climate change will lead to hunger, and about 80 million people will be affected (Parry et al. 1999). Among climatic events, increasing levels of atmospheric carbon dioxide (CO_2) is significant, which causes temperature to increase. Increased temperature leads to a shorter growing period (He et al. 2015), and has a multiple linear relationship with the wheat yield (Rao et al. 2015).

Despite many studies associated with the response of wheat growth to climate, irrigation, or N, few studies focus on the interactions between irrigation, N, climate and wheat yield. During the 2009-2012 period, experiments related to irrigation and N were conducted in Yangling of the Guanzhong region. Experimental comparisons are extremely necessary, but these methods are confined to comparatively a small number of sites, years and management practices. Crop growth models are, therefore, developed to assess management practices (Bergez et al. 2010, Boote et al. 1996). In this study, CERES (Crop Estimation through Resource and Environment Synthesis) - Wheat model was employed to run the assumed scenarios related to irrigation, N and climate based on the 2009-2012 experiments. The main purpose of this study is to (1) determine the contributions of climate, irrigation and N on wheat yields, (2) evaluate the impact of irrigation and N on wheat yields in the Guanzhong plain environment, where high production required irrigation and N fertilizer application, and (3) have a quantitative understanding of the relationships among climate factors, irrigation, N and wheat grain yield.

MATERIALS AND METHODS

The Model and Dataset

Detailed information on the experiments of 2009-2012 in Yangling, Guanzhong Plain of Northwest China (latitude 34°17'59"N, longitude 108°04'E, 506 m elevation) has been described in detail in our previous paper (Ji et al. 2014), we therefore give a brief description about them here. Three levels of irrigation (flood irrigation) (70%-80% (I_1), 60%-70% (I_2) and 50%-60% (I_3) field capacity) were set. The whole growing season was divided into 10 growing stages using the cereal scale of Zadoks et al. (1974). According to the water sensitive indexes summarized by SAIEID (1982), four stages (tillering, stem elongation, dough development and ripening) were involved in the experiments for the period 2009-2010. Irrigation control was exerted for the three periods (01/12/2009-30/12/2009 (I), 20/03/2010-05/04/2010 (II) and 15/05/2010-05/06/2010 (III)) in these stages. The experiments for the period 2010-2012 added three levels of N (180 (N_1), 135 (N_2) and 90 (N_3) kg N ha^{-1}). Nine treatments were designed using the orthogonal design with three replicates (Table 1).

CERES-Wheat model (Hundal & Kaur 1997, Ritchie et al. 1988, Wang et al. 2009) is a well-known wheat simulation model, which many researchers have applied worldwide, related to water and nutrient managements in wheat production and climate impact (Sadras & Monzon 2006, Subash & Ram Mohan 2012, Yang et al. 2006). The model, which is a sub-module of the Decision Support System for Agrotechnology Transfer (DSSAT) version 4.5, was therefore employed for simulations. DSSAT contains a weather module, soil module, plant module, management module, etc. (Hoogenboom et al. 2012). Weather records for the 2009-2012 experiments were from the weather station, approximately 100 m away from our experimental plots; whereas,

Table 1: Different irrigation levels at different growth stages and different N levels at sowing dates [a] of winter wheat during the period of 2009-2012 in Yangling[b].

Treatment	CK	T2	T3	T4	T5	T6	T7	T8	T9
N	N_1[d]	N_2[d]	N_3[d]	N_1	N_2	N_3	N_1	N_2	N_3
I[c]	I_1[e]	I_1	I_1	I_2	I_2	I_2	I_3	I_3	I_3
II[c]	I_1	I_3[e]	I_2	I_2	I_3	I_1	I_1	I_2	I_3
III[c]	I_1	I_2[e]	I_3	I_1	I_3	I_2	I_3	I_2	I_1

[a] Sowing dates: Oct 17, 2009; Oct 18, 2010; Oct 19, 2011.

[b] *N* application of all treatments in the period 2009-10 was N_1.

[c] I: December 1-December 30, II: March 20-April 5, III: May 15-June 5

[d] N_1 180 kg ha^{-1}, N_2 135 kg ha^{-1}, N_3 90 kg ha^{-1}.

[e] I_1: 70%-80% field capacity, I_2: 60%-70% field capacity, I_3: 50%-60% field capacity.

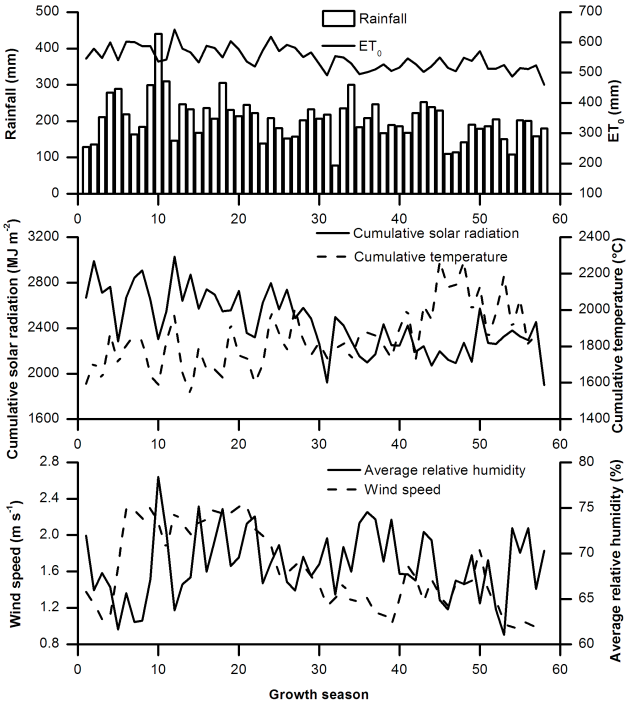

Fig. 1: 58-growth season weather data from Wugong weather station.

the 1954-2012 weather records (Fig. 1) used for simulating assumed scenarios were from Wugong weather station (Yangling, originally a town of the Wugong county) (CMA 2013). Weather variables contained daily precipitation (mm), maximum, average and minimum temperature (°C), sunshine duration (h) (changed into solar radiation by the method of Ampratwum & Dorvlo (1999) and Black et al. (1954)), relative humidity (%) and wind speed ($m\ s^{-1}$). The soil type in the experimental site was silty clay loam. All soil related data were gained from the experiments and in part from literature (Ji et al. 2014). The management module determines, when the field operations such as planting, applying inorganic fertilizer, irrigating, and harvesting are performed. Planting and harvesting related data for simulations was consistent with the data from the 2009-2010 experiment. However, both irrigation and inorganic fertilizer in the assumed scenarios were not always identical to the experiment. Plant module is designed to link other modules like weather module, soil module and management module to describe the growth, development and yield of individual crops (Hoogenboom et al. 2012, Jones et al. 2003).

It is essential for us to evaluate the adaptability of the model before using it in one region. The primary purpose of the evaluation is to calibrate the genetic coefficients of the wheat cultivar 'Xiaoyan 22'- P1V (vernalization coefficient), P1D (photoperiod coefficient), P5 (thermal time from the onset of linear fill to maturity), G1 (kernel number), G2 (potential kernel growth rate), G3 (tiller death coefficient), PHINT (interval between successive leaf tip appearances). They were determined as 25.53 days, 32.01%, 610.6 °C day, 24.16 #/g, 35.54 mg/(kernel.day), 1.592 g and 95.00°C day, respectively. Model evaluation showed that CERES-Wheat model was adapted for use in the region (Ji et al. 2014). It should be noted that CO_2 concentration in the model was set as the default value 380 vpm according to the actual values measured with a photosynthetic apparatus.

Climate, Water and Nitrogen Scenarios

Crop growth models are usually used to answer the hypothetical questions users put forward from the experiments or the practical productions, which prevents agronomists from spending time and energy conducting experiments. The assumed experiments consisted of 5 irrigation dates - 15/12, 01/03, 01/04, 20/04 and 10/05, which represented irrigation applied at early tillering, late tillering, stem elongation, booting stage and milking stage. This study focused on assumed scenarios as mentioed below, in the environment of Yangling (2009-2010) based on the experiments of 2009-2012 conducted in Yangling, Shaanxi province of China.

Scenario 1: 5 irrigation levels i.e., 1- time irrigation, 2 - time irrigation, 3 - time irrigation, 4 - time irrigation and 5 - time irrigation with irrigation quota 60 mm using overall design plus no irrigation (Fig.2);

Scenario 2: 6 fertilizer nitrogen levels i.e., 0 kg N ha^{-1}, 60 kg N ha^{-1}, 120 kg N ha^{-1}, 180 kg N ha^{-1}, 240 kg N ha^{-1}, 300 kg N ha^{-1} applied at sowing date

Scenario 3: 5 irrigation levels i.e., 1- time irrigation, 2 - time irrigation, 3 - time irrigation, 4 - time irrigation and 5 - time irrigation with irrigation quota 60 mm; 6 fertilizer nitrogen levels i.e., 0 kg N ha^{-1}, 60 kg N ha^{-1}, 120 kg N ha^{-1}180 kg N ha^{-1}, 240 kg N ha^{-1}, 300 kg N ha^{-1} applied at sowing date; irrigation and nitrogen interaction using overall design.

Scenario 4: 5 irrigation levels i.e., 1- time irrigation, 2 - time irrigation, 3 - time irrigation, 4 - time irrigation and 5 - time irrigation with irrigation quota 60 mm; 6 fertilizer nitrogen levels i.e., 0 kg N ha^{-1}, 60 kg N ha^{-1}, 120 kg N ha^{-1}, 180 kg N ha^{-1}, 240 kg N ha^{-1}, 300 kg N ha^{-1} applied at sowing date; irrigation designed 5 different treatments (1st stage, 1st stage + 2nd stage, 1st stage + 2nd stage + 3rd stage, 1st stage + 2nd stage + 3rd stage + 4th stage, 1st stage + 2nd stage + 3rd stage + 4th stage + 5th stage), irrigation and nitrogen with 58 - year climate applied in the design.

RESULTS AND DISCUSSION

Impact of Climate, Irrigation and N on Observed Yield

Grain yield varied under different irrigation and N in the

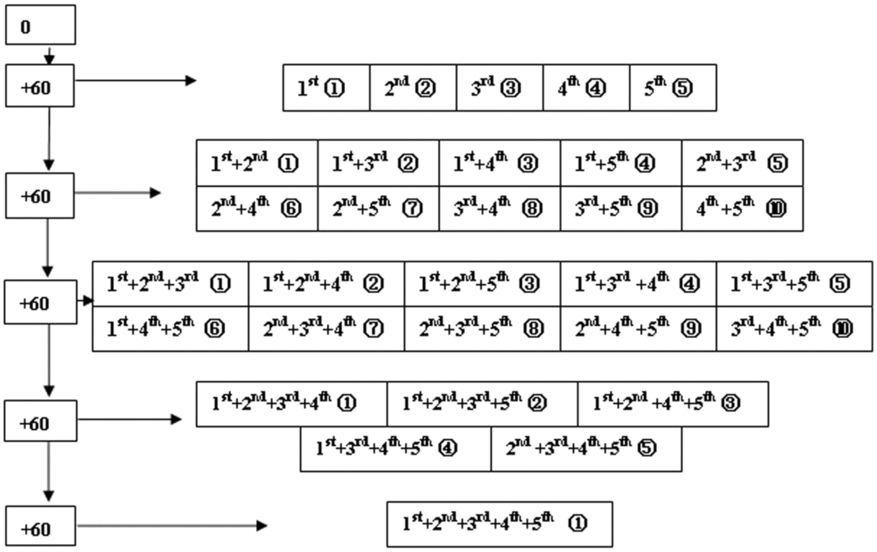

Fig. 2: Assumed irrigation treatments for simulation during the period 2009-2012.

three growing seasons (Table 2). It is apparent that grain yield in 2009-2010 differed from treatment to treatment just due to different irrigations applied. In spite of the corresponding treatment with the same irrigation level, grain yield showed the distinct variation due to three N levels included. The effects of irrigation, N, and irrigation and N interactions on grain yield were significant. Compared with N ($P < 0.1$), irrigation had a greater impact on grain yield ($P < 0.01$) in the periods of 2010-2011 and 2011-2012. Although CK was the same for the three growing seasons, its grain yield varied owing to climate variations (Tao et al. 2014).

Impact of Proposed Scenarios on Yield

Table 2: Response of observed yield to different irrigation (I) and nitrogen (N) levels during the period 2009-2012.

Treatment	Yield (t ha^{-1}) for 2009-2010	Yield (t ha^{-1}) for 2010-2011	Yield (t ha^{-1}) for 2011-2012
T1	6.78±0.12	7.59±0.13	6.69±0.11
T2	7.18±0.21	6.64±0.19	6.32±0.14
T3	6.55±0.21	5.55±0.20	5.37±0.13
T4	5.86±0.21	6.25±0.24	6.34±0.15
T5	5.79±0.16	5.31±0.13	5.50±0.26
T6	6.52±0.11	5.66±0.21	5.92±0.21
T7	6.29±0.19	6.14±0.12	5.60±0.12
T8	5.57±0.07	5.32±0.21	5.08±0.19
T9	4.75±0.16	4.90±0.20	4.05±0.13
I	0.059	0.001	0.004
N		0.045	0.091
I×N		<0.001	0.013

Response of grain yield to irrigation applications: Proper water application is usually judged by yield and WUE (yield/water consumption). Summaries of treatment evaluation of scenario 1 are given in Table 3.

The first five treatments (60 mm irrigation application for different growth stages) concerned yield and WUE prediction during the first wheat growing season of 2009-2010. Yield and WUE predictions averaged under different irrigation application dates. The values almost varied for all treatments because at every growth stage, wheat required different amounts of water. Furthermore, the standard deviation (SD), which measured the uncertainty, was different. For each treatment, the SD of both yield and WUE were in the order $I_{60} > I_{120} > I_{180} > I_{240}$ in the first growing season of 2009-2010. For instance, for I_{60} and I_{240}, the SD of yield was 0.92 and 0.06 t ha^{-1} mm^{-1}, and WUE was 2.01 and 0.30 t ha^{-1} mm^{-1}, respectively. This trend was also applicable for 2011-2012, but not for 2010-2011, which may be due to the climatic factors, parameter vector, and residual error that contributed to the uncertainty (Wallach et al. 2012). The 95% confidence intervals of I_{60} almost overlapped the 95% confidence intervals for other treatments during the growing seasons of 2009-2010 and 2011-2012, but was not fit for 2010-2011. This finding indicated that the optimum irrigation of different wheat growing seasons depended on the weather. The rainfed treatment had the lowest yield and WUE, which were completely below those of the irrigated treatments in the three periods.

Grain yield and WUE both increased with increasing irrigation in 2010-2011 (Table 3). First, high water input

Table 3: Results for evaluating irrigation treatments of winter wheat during the wheat growing seasons of 2009-2012.

Year	Scenario	Yield (t ha^{-1})			WUE (t ha^{-1} mm^{-1})		
		Mean	SD	95% credible interval	Mean	SD	95% credible interval
2009-2010	I_0	5.55			19.14		
	I_{60}	6.36	0.92	5.22-7.49	20.59	2.01	18.09-23.09
	I_{120}	6.90	0.73	6.37-7.42	21.71	1.63	20.54-22.87
	I_{180}	7.22	0.43	6.92-7.53	22.34	0.92	21.68-22.99
	I_{240}	7.38	0.06	7.30-7.46	22.52	0.30	22.14-22.89
	I_{300}	7.41			22.38		
2010-2011	I_0	3.72			15.56		
	I_{60}	5.36	1.58	3.40-7.32	18.52	4.49	12.95-24.09
	I_{120}	7.26	1.82	5.96-8.56	21.61	4.32	18.52-24.70
	I_{180}	8.79	2.08	7.30-10.28	23.93	3.65	21.32-26.54
	I_{240}	10.23	0.64	9.43-11.02	26.06	1.06	24.75-27.37
	I_{300}	10.73			26.89		
2011-2012	I_0	4.42			15.09		
	I_{60}	5.83	0.98	4.62-7.05	17.62	2.28	14.79-20.46
	I_{120}	6.90	0.57	6.49-7.30	19.76	1.30	18.83-20.69
	I_{180}	7.21	0.15	7.10-7.32	20.34	0.42	20.04-20.65
	I_{240}	7.26	0	7.26-7.26	20.39	0.10	20.27-20.51
	I_{300}	7.26			20.33		

(irrigation and precipitation) in the practice was related to a reduction in yield caused by reducing pollination and increased disease in wet years or soil conditions in practice. However, process-based models do not consider pollination dynamics and disease, which may result in considerable errors (Lobell et al. 2007). Second, wheat production is highly dependent on weather (Alexandrov & Hoogenboom 2000).

Response of yield variation to nitrogen: Grain yield and marginal product are utilized to determine the proper nitrogen fertilizer input. The marginal product of a given input can be expressed as follows:

$$MP = \frac{\Delta Y}{\Delta X}$$

Where, ΔX is the change in the firm's use of the input (an increase in N input) and ΔY is the change in quantity of grain yield produced.

Table 4 shows the tendency of yield and MP during the three growing seasons of 2009-2012. Yields show increased trend with rising N, which seems contradictory with practical conditions (Cui et al. 2008a, Cui et al. 2008b). However, the N input increase, greatly reduces MP when the N application was over 240 kg ha^{-1} in the period of 2009-2011. Therefore, N applications of more than 240 kg ha^{-1} were not considered. As for 2009-2010, yield increase rate increased from 9.67% (120 kg ha^{-1}) to 17% (240 kg ha^{-1}) while MP decrease rate rose from -34.53% (120 kg ha^{-1}) to -4.83% (240 kg ha^{-1}). The corresponding values for 2010-2011 were 22.67% to 42.92% for yield increase rate, and -11.21% (180 kg ha^{-1}) to -3.61% (120 kg ha^{-1}) for MP increase rate, whereas these values in the growth season of 2011-2012 were 8.54% to 12.43% and 4.88% to 46.87% for yield and MP increase rate, respectively. This indicates that the ranges between 120 to 180 kg ha^{-1}, which is similar to the results Zhu & Chen (2002) referred to.

Water and nitrogen coupling: Contour plots, an alternative to three-dimensional (3D) response surface plots, as shown in Fig. 3, are graphical representations of the relationship between irrigation, nitrogen and grain yield on a two-dimensional (2D) format. They are utilized to achieve better understanding of interactions between irrigation and nitrogen and to determine the optimum level of each variable for maximum grain yield. From Fig. 3, it is found that irrigation has positive synergistic impacts when being coupled with nitrogen. This pair of irrigation and N variable combination is statistically significant in terms of their p-values.

The grain yield differences in the period 2009-2012 are due to variations in climatic factors like solar radiation, average air temperature and rainfall. However, we would like to concentrate further on the interaction of irrigation and nitrogen on grain yield here rather than on the interaction with weather. Although the irrigation and N interaction has a positive term, this does not mean that increasing both values simultaneously will contribute to high grain yield. Based on Fig. 3a, for an irrigation depth of 300mm, grain yield is 6.19 t ha^{-1} for an application of 120 kg N ha^{-1},

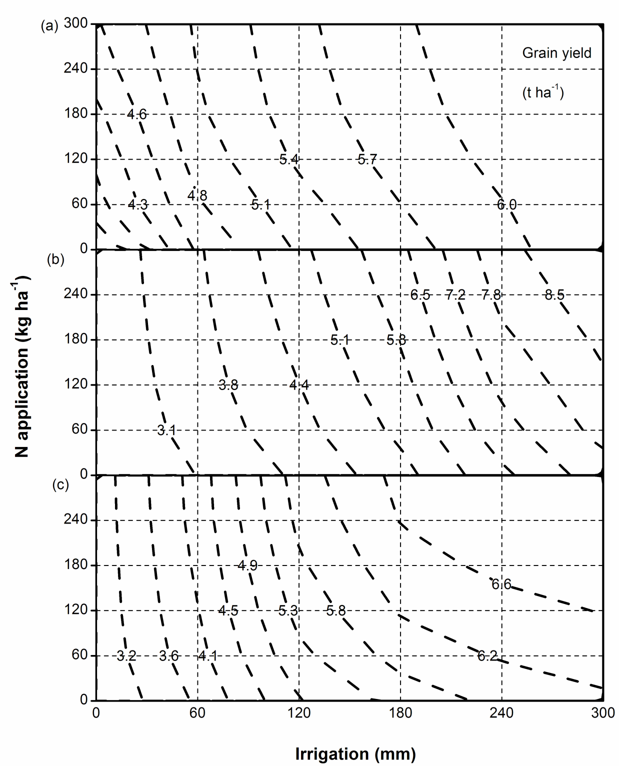

Fig. 3: Contour plots of winter wheat yield during the period of 2009-2012. Interaction between irrigation and N, (a) 2009-2010, (b) 2010-2011, (c) 2011-2012.

6.28 t ha^{-1} for 180 kg N ha^{-1}, and 6.32 t ha^{-1} for 240 kg N ha^{-1}. This indicates that a 50% (60 kg N ha^{-1}) increase of N at 120 kg ha^{-1} results in an increase in grain yield of 1.46% (0.09 t grain yield ha^{-1}), while a 100% (120 kg N ha^{-1}) increase of N at 120 kg ha^{-1} causes an increase in grain yield of 2.12% (0.13 t grain yield ha^{-1}). When N applied is 300 kg ha^{-1}, grain yields are all 6.33 t ha^{-1} for an application of 120, 180 and 300mm, respectively. From Fig. 3b and Fig. 3c, the simulated results in Fig.3c are similar to those in Fig. 3a whereas Fig. 3b shows different results.

In addition, there are the same grain yields with the combination of different irrigation and N. For example, grain yield is 6.0 t ha^{-1} for both the combination of 159 mm irrigation and 180 kg ha^{-1} and 176 mm irrigation and 120 kg ha^{-1} during the first growth season of 2009-2010. A comparison of these two combinations shows that, the negative effect on grain yield due to decrease in N by 60 kg ha^{-1} below 180 kg ha^{-1} can be compensated for by an increase in irrigation of 17 mm in order to obtain the same grain yield of 5.5 t ha^{-1}.

The slopes of the contours represent a greater impact of irrigation on grain yield than that of N. For instance, for an application of 180 kg N ha^{-1}, grain yield increased by 47.2% as irrigation rose from 0 mm to 300 mm. Whereas, N application from 0 to 300 kg ha^{-1} changed grain yield by 8.9%. This to some degree indicates that irrigation contributes to grain yield 5.3 times more than N.

The results above are quite helpful for irrigation and N management of winter wheat for Yangling and the entire Guanzhong region as a consequence of similar climate. However, irrigation and N application still requires climate information, according to which the amounts and distribution of them are determined.

Impact of water, nitrogen and climate on yield: Cumulative probability distribution of simulated wheat grain yield under the six irrigation regimes with 0, 60, 120, 180, 240 and 300 kg N ha^{-1} are shown in Fig. 4. It demonstrates that, in many years (over 80%) the grain yield is less than 4 t ha^{-1} with no irrigation I_0 under no N application and the percentage of years decreased with increase in N, but it still exceeded 70%. This indicates that irrigation is of great importance in wheat productivity. When irrigation and N both are equal or greater than 180 mm and 180 kg N ha^{-1}, there are grain yields all more than 4 t ha^{-1}. In addition, the line of I_{120} with grain yield less than 6.0 t ha^{-1} becomes increasingly long as more N is applied. This is because N is indispensable for high yield.

Fig. 4. also shows that the grain yield curve has a large spread representing year-to-year variability as a consequence of climate change, especially solar radiation and temperature for irrigated areas. Median yield (with 50% probability of exceedance) increases with increase in irrigation, I_0 (2.8 t ha^{-1}) I_{60} (4.1 t ha^{-1}), I_{120} (5.7 t ha^{-1}), I_{180} (6.1 t ha^{-1}) and I_{240} (6.4 t ha^{-1}), then decreases to 6.3 t ha^{-1} in I_{300} under N_0 regime, and the same tendency is for other N regimes. Under I_0 regime, median yield illustrates a consistent increase trend, from 2.7 to 3.0 t ha^{-1}. Furthermore, the difference of maximum and minimum grain yield between I_0 and I_{300} is increasingly large with the increment of fertilizer N.

Nevertheless, cumulative probability distribution curves are almost different when the irrigation amount is larger than 120 mm among all scenarios. The highest grain yield is always obtained using I_{240}, which indicates that the scenario of I_{240} is capable of representing the highest yields in the best growing environment. These results indicate that irrigation and fertilizer N have a synergistic effect on grain yield and there is a greater effect of irrigation than N on yield, which is due to a critical factor determining yield (LAI) more influenced by irrigation than N.

Furthermore, the degree of the impact of climate, irrigation and N is essential to be considered with multiple comparison. Under I_{180} regime, the increase rate of grain yield from N_0 to N_{300} varies from 3.6% to 91.2% during the grow-

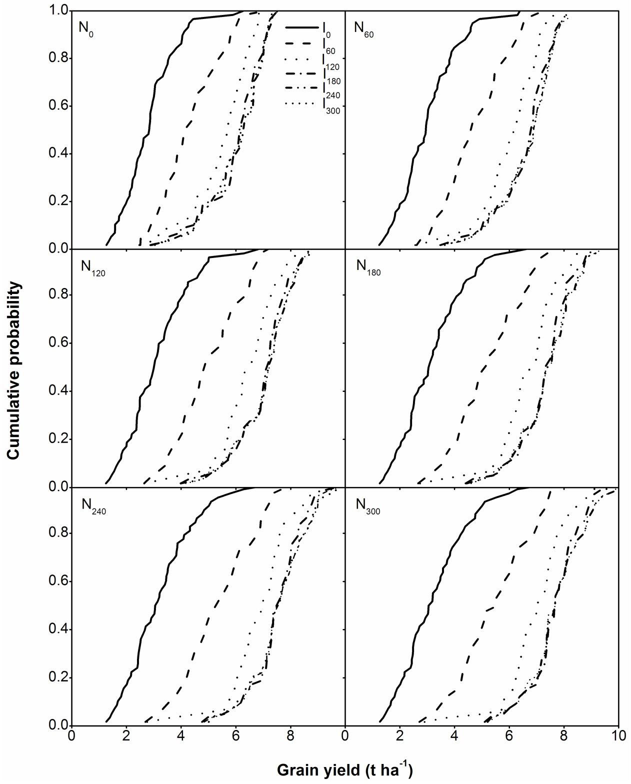

Fig. 4: Cumulative probability distribution of simulated grain yield. A long-term simulation (58 growth seasons) under variable irrigation and N regimes; irrigation and N application, e.g., I_0 (irrigation input of 0 mm), N_0 (N application of 0 kg ha^{-1}).

ing seasons of 1954-1955 to 2011-2012. Under N_{180}, its ranges are -7.7% to 499.8% from I_0 to I_{300} in the growing seasons. This shows that the interaction of irrigation and climate has greater effect on grain yield than that of N and climate, and the impact of irrigation on grain yield is affected by climate than that of N. Furthermore, the simulated results showed that weather-driven yield fluctuated, but these results had a declining trend (Liu et al. 2010, Lobell et al. 2005). The changes of irrigation and N application cannot mitigate the yield variation caused by weather, however, to reduce yield variation caused by the weather may develop new cultivars (Zhang et al. 2013). Among three factors, irrigation and nitrogen in the region contributed 46.8% and 5.5% of grain yield through linear regression analysis while climate factors were not uncertain. Therefore, climatic factors need to be chosen to determine the rough contribution to grain yield.

Relationship between grain yield and climate factors: Climate variation exerts a direct influence on inter-annual yield variability (Qian et al. 2009). Six main climatic factors (solar radiation, precipitation, maximum temperature, minimum temperature, relative humidity and wind speed) were selected to assess the impact of climate factors on grain yield under no irrigation and N conditions, as well as under the conditions with irrigation or N. The six factors contributed 2.4% of grain yield by the method of linear regression.

The correlation coefficients (R) between grain yield and the factors mentioned above are depicted in Table 5. Wind speed and minimum temperature showed non-significant correlation with grain yield under all conditions. Grain yield without irrigation and N was quite significantly correlated with precipitation, followed by maximum temperature and relative humidity. The same relationships were for I_0N_{180}. For $I_{180}N_0$, only relative humidity was highly correlated with wheat yield while maximum temperature and precipitation showed significant correlations with grain yield. The correlation between relative humidity and wheat yield was highly significant, whereas there were significant correlations between maximum temperature and grain yield, and solar radiation and grain yield also.

Apparently, the relationships between yield and sole climatic variable to a certain degree reflected its actual effect. Precipitation and relative humidity was negatively related to wheat yield while temperature and solar radiation was positively associated with wheat yield when irrigation was available, and vice versa. Relative humidity and maximum temperature were the key climate factors affecting wheat yield, especially relative humidity. High relative humidity decreases evapo-transpiration, while temperature increases evapo-transpiration. And the transpiration influences translocation of food materials and nutrients. Therefore, relative humidity has a significant effect on wheat yield (Hoffman & Jobes 1978). Precipitation was definitely the dominant factor that affected wheat production when no irrigation and N were applied, or one of them was applied; whereas solar radiation seemed to be the key climate factor that affects wheat yields under both irrigation and N availability. The former finding is due to the reason that, the water source wheat requires is only precipitation, which inevitably has a great and direct impact on the yield. The latter finding is due to the reason that, precipitation is not limited to wheat yield when irrigation exists, and that precipitation has a great impact on maximum temperature and solar radiation (Yu et al. 2013). As a result, the dominant factors are replaced by other factors, not by precipitation.

CONCLUSION

In the present study, we utilized step-by-step method to explain the contributions of irrigation, N, and climate to grain yield. As for the scenarios with a single factor (either irrigation or N), the optimum irrigation was determined by

Table 4: Grain yield and marginal production (MP) under various nitrogen (N) regimes in the period 2009-2012.

Year	N application (kg ha^{-1})	N uptake (kg ha^{-1})	Yield(t ha^{-1})	Yield increase rate (%)	MP	MP increase rate (%)
2009–2010	0	172	6.12			
	60	187	6.28	2.66	10.87	
	120	196	6.41	4.66	13.56	24.71
	180	203	6.47	5.75	9.57	-11.95
	240	209	6.49	6.00	2.50	-77.00
	300	214	6.49	6.09	1.20	-88.96
	360	218	6.50	6.18	1.25	-88.50
	420	223	6.50	6.23	0.60	-94.48
	480	227	6.51	6.29	1.00	-90.80
2010–2011	0	161	6.00			
	60	179	6.76	12.79	42.61	
	120	192	7.39	23.27	48.31	13.37
	180	204	7.98	33.11	49.17	15.39
	240	217	8.63	44.00	50.23	17.88
	300	228	8.95	49.29	28.82	-32.37
	360	239	9.06	51.13	10.00	-76.53
	420	250	9.15	52.54	7.73	-81.87
	480	261	9.18	53.06	2.82	-93.39
2011–2012	0	200	6.15			
	60	212	6.29	2.28	11.67	
	120	221	6.36	3.45	8.00	-31.44
	180	229	6.38	3.86	3.13	-73.22
	240	235	6.40	4.08	2.33	-80.01
	300	241	6.41	4.26	1.83	-84.29
	360	245	6.43	4.56	4.50	-61.44
	420	247	6.44	4.72	5.00	-57.16
	480	247	6.45	4.90		

Table 5: Correlations between grain yield (t ha^{-1}) and climate factors, i.e., precipitation (mm), wind speed (m s^{-1}), relative humidity (%), minimum temperature (°C), maximum temperature (°C) and solar radiation (MJ m^{-2}) under various irrigation and N regimes in the period 2009-2012.

	Grain yield	Precipitation	Wind speed	Relative humidity	Minimum temperature	Maximum temperature	Solar radiation
I_1N_{90}							
R		0.58**	0.09	0.42**	-0.07	-0.45**	-0.18
Slope		9.80	191.56	115.39	-92.91	-476.71	-0.70
Mean	2.867	205	1.6	69	3.4	13.8	2455
I_3N_{90}							
R		-0.29*	-0.07	-0.37**	0.12	0.33*	0.17
Slope		-5.08	-174.19	-105.09	164.72	363.18	0.66
Mean	5.993	205	1.6	69	3.4	13.8	2455
I_1N_{180}							
R		0.57**	0.07	0.47**	-0.06	-0.45**	-0.21
Slope		11.73	199.54	158.78	-96.44	-579.34	-0.97
Mean	3.206	205	1.6	69	3.4	13.8	2455
I_3N_{180}							
R		-0.19	0.07	-0.38**	0.16	0.33*	0.27*
Slope		-3.131	163.44	-101.83	202.86	341.67	1.01
Mean	7.288	205	1.6	69	3.4	13.8	2455

* indicates that the correlation is significant at the 0.05 level, and ** indicates that the correlation is significant at the 0.01 level.

climate according to grain yield and WUE, whereas the range of N was not uncertain based on grain yield and MP. The impact of irrigation and N on grain yield was analysed to illustrate that irrigation influenced grain yield greater than the influence of N, which was the same as that obtained from 2009-2012 experiments. When climate was considered, the combination of irrigation and climate contributed to grain yield larger than that of N and climate. Furthermore, climate exerted a greater influence on the response of grain yield to irrigation than to N application. The contribution rates of irrigation, nitrogen and climate were 46.8%, 5.5% and 2.4%, respectively. And climatic factors, i.e., relative humidity and maximum temperature, consistently had significant correlations with grain yield under all conditions mentioned before. Precipitation was significantly correlated with grain yield when no irrigation or N, or one of them was applied. Contrary to the precipitation, solar radiation was significantly associated with grain yield under the conditions of irrigation and N applied.

This analysis has implications for enhancing our understanding of the cooperation of climate, irrigation, and N, which provides the guidelines for irrigation and N management. The past yield-climate relationships can serve as a foundation for wheat production prediction within a year. However, wheat production was influenced not only by the three factors mentioned above, but also by other factors, such as planting density and soil conditions. In addition, only one cultivar is considered, which leads to lack of the comparisons between different cultivars. Therefore, more factors should be included in similar studies, and other different cultivars to be considered for wheat yield variability and further yield gap analysis.

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