Acta Agriculturae Scandinavica, Section B — Soil & Plant Science

ISSN: 0906-4710 (Print) 1651-1913 (Online) Journal homepage: http://www.tandfonline.com/loi/sagb20

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To cite this article: Yutong Hu, Mingde Hao, Xiaorong Wei, Xu Chen & Jing Zhao (2016) Contribution of fertilisation, precipitation, and variety to grain yield in winter wheat on the semiarid Loess Plateau of China, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 66:5, 406-416, DOI: 10.1080/09064710.2016.1149215

To link to this article: http://dx.doi.org/10.1080/09064710.2016.1149215

ACTA AGRICULTURAE SCANDINAVICA, SECTION B — SOIL & PLANT SCIENCE, 2016
VOL. 66, NO. 5, 406–416
http://dx.doi.org/10.1080/09064710.2016.1149215

Taylor & Francis
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ORIGINAL ARTICLE

Contribution of fertilisation, precipitation, and variety to grain yield in winter wheat on the semiarid Loess Plateau of China

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ABSTRACT
Wheat yield is influenced by fertilisation, precipitation and variety, among other factors. There is limited research identifying the most important factors affecting wheat yield and assessing their relative importance in the long run. In this study, we evaluated the contribution of fertilisation, precipitation and variety to wheat yield using a long-term field experiment (1984–2014) on the semiarid Loess Plateau in China. The experiment consisted of six treatments: fertilisation with nitrogen (N), phosphorus (P), manure (M), NP, NPM, and a control without fertilisation. We monitored the yield of three varieties of winter wheat over time and assessed the changes in grain yield, soil properties, fertiliser-contribution rate (FCR) and precipitation-use efficiency (PUE) with different fertilisation treatments and precipitation patterns. Stepwise multiple linear regression was used to identify the most important factors affecting wheat yield and examine their relative importance. The results showed that fallow-season precipitation and annual precipitation (AnP) positively correlated with wheat yield in the N, M, NP, and NPM treatments. The amount of fertilisation, AnP, and monthly precipitation of February and September were included in the linear regression model; however, the influence of variety on yield could be ignored. With 30 years of fertilisation, soil organic matter, total nitrogen, and available potassium levels with NPM was higher than the control by 70.6%, 70.5%, and 319.2%, respectively. Yield, FCR, and PUE with M increased annually at rates of 89 kg ha^{-1} y^{-1}, 1.47 kg kg^{-1} y^{-1}, and 0.13 kg mm^{-1} y^{-1}, respectively. The yields and FCR, but not PUE, of all fertilised treatments were higher in wet than normal and dry years. The FCR with P was negative in all the three precipitation patterns. This study has implications for maximising the long-term winter yield with various factors in the rain-fed winter wheat cropping system of the Loess Plateau.

ARTICLE HISTORY
Received 23 October 2015
Accepted 28 January 2016

KEYWORDS
Fertilisation treatments; fertiliser-contribution rate; precipitation-use efficiency; grain yield; precipitation patterns; stepwise multiple linear regression

Introduction

Wheat is a major cereal crop for global food supply, with an annual planting area of >220 million ha (Wilcox & Makowski 2014). Wheat yield (trend and variability) is influenced by fertilisation, precipitation, temperature, soil properties and crop variety, among other factors (Pirjo et al. 2010; Miranda et al. 2011; Mueller et al. 2012; Scursoni et al. 2012; Rozbicki et al. 2015). Identifying the major factors affecting wheat yield and assessing their relative importance is critical to maximise the long-term crop productivity.

The Loess Plateau is a major area of wheat production in China. The responses of crop yields to fertilisation on the Loess Plateau are quite strong but variable, mainly owing to the unbalanced use of fertilisers and the variable precipitation (Wang et al. 2011). The long-term application of combinations of organic and inorganic fertilisers can improve soil fertility and crop yields compared to the use of inorganic fertilisers alone (Bandyopadhyay et al. 2010). However, numerous studies that have focused on soil properties suggest that increasing fertilisation may not be sufficient to maintain higher wheat yield in the long run (Huang et al. 2003; Fan et al. 2005).

Precipitation is the sole source of water for dryland farming in semiarid ecosystems (Wang et al. 2005). The temporal distribution of precipitation is uneven on the semiarid Loess Plateau, with rain mostly concentrated from July to September (fallow-season precipitation, FSP) (Huang et al. 2003). Although the FSP and growing-season precipitation (GSP) are highly variable in the Loess plateau region (Basso et al. 2012; Guo et al. 2012), the annual precipitation (AnP) can be divided

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into three general patterns: normal, wet, and dry (Guo et al. 2012). Highly erratic temporal patterns of precipitation often lead to more extreme wet and dry cycles of soil-water content, which, to some extent, limit crop growth and productivity, precipitation-use efficiency (PUE), and fertiliser-contribution rate (FCR) (Basso et al. 2012; Guo et al. 2012).

Moreover, crop variety and planting year affect the yield of winter wheat (Rozbicki et al. 2015). However, there is little research identifying the most important factors affecting wheat yield and assessing their relative contribution in the long run. Subtle differences in site characteristics or management practices hamper the elucidation of the factors that control wheat yield (Krupnik et al. 2015). The problem of identifying the factors that most influence the yield of crops is how to extract information from the data. A number of possible approaches are available to address this problem, among which regression analysis is the most traditional one (Roel et al. 2007). Multiple regressions with stepwise-selection techniques are often used to examine the effects of limiting factors on plant biomass, species richness, and yield components. The main advantage of stepwise selection is its ability to select a subset of explanatory variables and then identify and rank the limiting factors (Prost et al. 2008).

In this study, we investigated the contribution of fertilisation, precipitation, and variety to grain yield of winter wheat using a long-term field experiment on the Loess Plateau. The objectives of the study were to: (1) identify the most important factors affecting grain yield by stepwise-selection, (2) assess the changes in soil properties, grain yield, FCR and PUE with fertilisation treatments, and (3) determine the changes in grain yield, FCR and PUE with precipitation patterns, over the 30 years of the experiment. The results are useful to develop a policy of optimum fertilisation for the rain-fed region of the Loess Plateau.

Materials and methods

Experimental site

The ongoing long-term field experiment was initiated in September 1984 at the State Key Agro-ecological Experimental Station in Changwu County, Shaanxi Province, China (35°12′N, 107°40′E; 1220 m a.s.l.), in the rain-fed cropping region of the Loess Plateau. This site has a semiarid and continental monsoon climate with an annual mean precipitation of 570 mm, an annual mean FSP (July–September) of 307 mm, and an annual mean temperature (1984–2014) of 9.1°C. The inter-annual and seasonal variations are the main factors influencing the temporal distribution of precipitation (Guo et al. 2012).

Records indicate that the experimental site has been cultivated with winter wheat for several centuries. The soil is classified as an aridic and loamy Cumulic Haplustoll (Heilu soil in the Chinese taxonomic system) developed from loessial deposits (Guo et al. 2012). The surface soil (0–20 cm) at the start of the long-term experiment in 1984 contained: 24.1% clay (<0.002 mm), 63.7% silt (0.002–0.05 mm), 11.5% sand (0.05–1 mm), 0.8 g kg^{-1} total nitrogen (N, TN), 37 mg kg^{-1} alkaline dissolved N, 10.5 g kg^{-1} soil organic matter (OM), 0.7 g kg^{-1} total P (TP), 3.0 mg kg^{-1} available P (AP), and 129.3 mg kg^{-1} available potassium (K, AK), with a pH of 8.3 (Li & Hao, 2013).

Experimental design

The study tested the effects of precipitation in six fertilisation treatments: CK (no fertiliser), N (120 kg N ha^{-1}), P (26.2 kg P ha^{-1}), M (75 t manure ha^{-1}), NP (120 kg N ha^{-1} and 26.2 kg P ha^{-1}), and NPM (120 kg N ha^{-1}, 26.2 kg P ha^{-1}, and 75 t manure ha^{-1}). The concentrations varied from year to year, and average values were as follows: OM, TN, AP, and AK in the manure were 106.0 g, 2.65 g, 110.0 mg, and 905 mg kg^{-1}, respectively, and the pH of the manure was 8.2. Experimental plots (10.3 × 6.5 m) were randomly arranged in a complete block design, with three replicates. The fertilisers were broadcast on the soil surface as a basal dressing and ploughed into the top 20 cm of soil in mid-September each year.

Varieties of winter wheat have changed over time. We used three major local varieties that have been historically widely used in the study area: qinmai4# in 1984 and 1985, changwu131 from 1986 to 1995, and changwu134 from 1996 to 2013 (years represent the sowing time). The plots were harrowed, and winter wheat was annually sown at 180 kg seeds ha^{-1}, with 20 cm intervals between rows, in late September and harvested by hand at the end of June in the following year; the rest of the year was the fallow season. The plots were not irrigated but ploughed to a depth of 20 cm after the harvests in July and left fallow from July to September to store water for the next sowing. Crop cultivation and field management, including pest and weed control, followed local farming practices.

Sampling and analysis

Wheat was harvested each year from the central half of each experimental plot when the aboveground biomass reached physiological maturity in July. Grains were oven dried at 60°C for 48 h, and weighed.

The soil was sampled for measuring pH and concentrations of OM, TN, AP, and AK after 30 years of experiment. Five soil cores were randomly collected from the surface (0–20 cm) of each plot using an auger (diameter, 3 cm) after harvesting in mid-September 2014. Soil cores from the same plots were mixed by hand, air-dried, and screened through 1- and 0.25-mm meshes before testing. Soil pH was measured in water at a soil:water ratio of 1:2.5. OM concentration was determined by titration (Walkley & Black, 1934). TN concentration was determined by Kjeldahl digestion (Bremner & Tabatabai, 1972). AP concentration was determined by the Olsen method of 0.5 M $NaHCO_3$ extractable P (Olsen et al. 1954). AK (NH_4OAc-K) was extracted with neutral 1 M ammonium acetate (Hanway & Heidel 1952) and estimated by a flame photometer.

Rainfall data were obtained from the Changwu Meteorological Station, approximately 3 km from the experimental site.

Data analysis

Precipitation in the region can be classified as GSP, FSP, and AnP, based on the periods of cropping of winter wheat. GSP falls during the crop season from October to the following June. FSP falls between successive crops from July to September. AnP is the sum of GSP and FSP.

The drought index (DI) for the AnP was calculated to assess the variations and statuses of precipitation among different years as follows:

$$\mathrm{DI} = (\mathrm{AnP} - M_1)/\sigma,$$

where AnP is the annual precipitation, M_1 is the average precipitation, and σ is the standard deviation for precipitation. DI was used to distinguish among the wet (DI > 0.35), normal (–0.35 ≤ DI ≤ 0.35), and dry (DI < –0.35) years (Guo et al. 2012). Similarly, the DIs for FSP and GSP were calculated to assess the variations and statuses in seasonal precipitation among different years.

The coefficient of variation (CV) was calculated as follows:

$$\mathrm{CV}(\%) = 100 \times s/\bar{X},$$

where s is the standard deviation and $\bar{X}$ is the average yield (Chloupek et al. 2004).

The yield of wheat was recorded every year (1984–2014) from the experimental treatments. A simple linear regression analysis of grain yield over years was computed to determine a time trend as follows:

$$Y = a + b_t,$$

where Y is the grain yield (kg ha^{-1}) of the wheat, a is a constant, t is the time expressed as the experimental period in years, and b is the trend, expressed as the slope of the regression line of yield with time (Manna et al. 2007). The trends for PUE and FCR were similarly calculated.

PUE (kg mm^{-1}) was estimated as the ratio of grain yield (kg ha^{-1}) to AnP (Guo et al. 2012). FCR (kg kg^{-1}) was calculated as (Wang et al. 2010) follows:

$$\mathrm{FCR} = (Y_\mathrm{T} - Y_\mathrm{CK})/Y_\mathrm{T},$$

where Y_T and Y_CK are the yields of the fertilised and control treatments at harvest, respectively.

Statistical analysis

The data were analysed using SPSS 18.0 (SPSS Inc., Chicago, IL, USA). Pearson's correlation analysis was first conducted to evaluate the relationships of wheat yield with AnP, GSP, FSP, and monthly precipitation (MnP) in various fertilisation treatments. Variety as a categorical variable was converted to a "dummy" variable before analysis. A dummy variable is a numerical variable that usually represents a binary categorical variable. For a categorical variable with multiple levels (n), (n–1) numbers of dummy variables are required to represent it (Xiong & Meullenet, 2006). In the experiment, there are three varieties present. Here, we used "1" for "qinmai4#" and "0" for "changwu131" in 1984–1985; "1" for "changwu131" and "0" for "qinmai4#" in 1986–1995; and "0" for both "qinmai4#" and "changwu131" in 1996–2013.

Stepwise multiple linear regression (SMLR) was then used to identify and quantify the relationships of wheat yield with AnP, FSP, GSP, month precipitation, fertilisation, and variety. The stepping criteria used for entry and removal were based on the level of significance of Fisher's F, which was set at 0.05. The data were standardised prior to the SMLR to eliminate their differences among various models. Zhan et al. (2013) have reported that standard partial regression coefficients are useful for examining the differences between independent variables and can represent the relative importance of different variables when the data eliminated the error from the model.

SMLR can provide an equation linking wheat yield to fertilisation, AnP, FSP, GSP, MnP, and variety. SMLR constructs a multivariate model for the dependent variable, Y, based on the explanatory variables. The best equation is selected according to the highest multiple correlation coefficient (R). The equation takes the form:

$$Y = b_0 + b_1X_1 + b_2X_2 + \cdots + b_nX_n,$$

where Y is the dependent variable (i.e. wheat yield); X_1, X_2, … , X_n are the independent variables (i.e. the amount of fertilisation, AnP, year, and variety); b_0 is a constant, where the regression line intercepts the Y-axis, representing the value of the dependent Y when all explanatory variables are 0; and b_i ($1 \leq i \leq n$) is the partial regression coefficient, which represents the amount the response variable Y changes when the explanatory variable changes by 1 unit (Zhan et al. 2013). The data in the equation were original, which were not standardized.

Analyses of variance (ANOVA) was performed using the F-test at a 0.05 level of significance to determine if significant differences existed among treatments means. When F was significant, Duncan's multiple-range test was used to compare the means among different treatments at $p < .05$. Linear regression analyses were performed to calculate the trends, expressed as the slopes of the regression lines for actual yields, PUEs, and FCRs over time at $p < .05$ and $< .01$.

Results

Relationship of wheat yield with different factors

The correlations of grain yield with FSP, GSP, AnP, and MnP in various fertilisation treatments are displayed in Table 1. FSP and AnP correlated positively with yield in various fertilisation treatments except for the P treatment. In the NPM treatment, the correlation between AnP and yield reached a significant level ($r = .60$). GSP was not correlated with yield in any of the fertilisation treatments. However, the correlation between the MnP_{Sep} and yield in the M, NP, and NPM treatment reached a significant level ($r = .54$, .41, and .48, respectively). Yield correlated positively with year in the M treatment and negatively with variety in the P treatment.

A correlation analysis conducted with a single parameter may be insufficient, because the parameters are often inter-related. SMLR was thus used to quantify the relationships of wheat yield with AnP, FSP, GSP, MnP, fertilisation, and variety. The SMLR equation optimises the model for the relationship, and the statistics calculated in this analysis were:

$$\text{Wheat yield} = -1137.977 + 22.927*\text{amount of M} + 8.579*\text{amount of N} + 21.168*\text{amountof P} + 2.359*\text{AnP} + 43.096*\text{MnP}_{\text{Feb}} + 6.481*\text{MnP}_{\text{Sep}} (R^2 = 0.576, F = 12.77, p < .05).$$

The relationship was not significant between Qinmai4# and wheat yield ($r = .32$), as well as between Changwu131 and yield ($r = .37$). The effect of variety on the yield thus could be ignored. The partial correlation coefficients of the equation were 0.62, 0.43, and 0.25 for the amounts of M, N, and P, respectively; and 0.22, 0.29, and 0.26 for the AnP, MnP_{Feb}, and MnP_{Sep}, respectively. The partial correlations were significant for the amounts of M, N, and P ($p < .01$), the MnP_{Feb} and MnP_{Sep} ($p < .01$), and the AnP ($p < .05$).

Table 1. Correlation coefficients of wheat yield with fallow-season precipitation (FSP), growing-season precipitation (GSP), annual precipitation (AnP), and monthly precipitation (MnP) in various fertilisation treatments for 1985–2014.

	CK	N	P	M	NP	NPM
MnP_{Jul}	0.26	0.36	0.05	0.30	0.47**	0.32
MnP_{Aug}	0.20	0.29	0.16	0.10	0.11	0.28
MnP_{Sep}	0.33	0.31	0.31	0.54**	0.41*	0.48**
MnP_{Oct}	−0.03	−0.06	0.13	0.09	−0.10	0.10
MnP_{Nov}	0.09	0.06	0.11	0.26	0.27	0.27
MnP_{Dec}	−0.09	−0.23	0.12	−0.26	−0.34	−0.40*
MnP_{Jan}	−0.07	0.03	−0.06	0.10	−0.02	0.03
MnP_{Feb}	0.27	0.29	0.14	0.27	0.42*	0.39*
MnP_{Mar}	0.05	0.26	0.06	−0.14	−0.02	0.04
MnP_{Apr}	0.33	0.37*	0.14	0.19	0.43*	0.26
MnP_{May}	−0.02	−0.00	−0.03	−0.06	−0.03	−0.01
MnP_{Jun}	0.00	−0.09	0.00	−0.17	−0.20	−0.10
FSP	0.40*	0.50**	0.27	0.46**	0.49**	0.55**
GSP	0.19	0.19	0.19	0.05	0.09	0.22
AnP	0.45*	0.54**	0.33	0.45*	0.49**	0.60**

Notes: CK, unfertilized control; N, nitrogen fertilisation; P, phosphorus fertilisation; and M, manure fertilisation.
** indicates significance at $p < .01$.
* indicates significance at $p < .05$.

Table 2. Soil pH and nutrient levels in the 0–20 cm surface layers after 30 years of fertilisation.

Treatment	pH	OM (g kg^{-1})	TN (g kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})
CK	8.29 ± 0.01a	11.54 ± 0.32c	0.78 ± 0.01c	4.98 ± 0.12d	126.38 ± 11.28c
N	8.27 ± 0.01b	11.77 ± 0.74c	0.86 ± 0.01c	4.85 ± 0.18d	126.96 ± 1.51c
P	8.29 ± 0.01a	12.33 ± 0.12c	0.80 ± 0.03c	40.18 ± 1.08b	123.06 ± 1.91c
M	8.29 ± 0.01ab	19.55 ± 0.14a	1.31 ± 0.03a	35.69 ± 2.22b	551.22 ± 4.39a
NP	8.25 ± 0.01c	15.09 ± 0.26b	1.01 ± 0.03b	22.17 ± 1.12c	116.94 ± 2.66c
NPM	8.28 ± 0.00ab	19.69 ± 0.86a	1.33 ± 0.04a	56.69 ± 5.16a	529.77 ± 5.85b

Notes: Values are expressed as mean ± standard error. Different letters within a column indicate significant differences between fertilisation treatments at $p < .05$.
CK, unfertilized control; N, nitrogen fertilisation; P, phosphorus fertilisation; M, manure fertilisation; OM, organic matter; TN, total nitrogen; AP, available phosphorus; and AK, available potassium.

Changes in soil properties, grain yield, FCR and PUE with fertilisation treatment

The manure had high concentrations of OM and AK, so the soil properties were significantly affected by the addition of M ($p < .05$) (Table 2). The soil pH changed little among the treatments, except in the NP treatment. The pH after 30 years had decreased little in all treatments relative to the initial soil. The OM and AP concentrations in the top soil, however, increased relative to the initial soil (1984) in all treatments. The OM concentration in CK was 11.54 g kg^{-1}, but was higher in the M, NP, and NPM treatments than in CK by 69.41%, 30.76%, and 70.62%, respectively. The AP concentrations were 7.07-, 6.17-, and 10.38-fold higher in the P, M, and NPM treatments, respectively, than in CK. The TN concentrations were higher in the M, NP, and NPM treatments than in CK by 67.95%, 29.49%, and 70.51%, respectively. The AK concentrations were lower in the CK, N, P, and NP treatments than in the initial soil by 2.26%, 1.81%, 4.83%, and 9.58%, respectively. The AK concentrations, however, were higher in the M and NPM treatments than in the initial soil by 326.31% and 309.72%, respectively.

Wheat yields were significantly affected by fertilisation treatment ($p < .05$) (Tables 3 and 7). The average yields ranged from 1320 to 4280 kg ha^{-1}. The long-term application of most fertilisers (M, NP, and NPM) increased yields relative to CK, but the application of N alone did not. The long-term application of P alone produced lower yields relative to CK after four years of planting. The average annual increases in yield in the M and NP treatments were 89.0 and 53.3 kg ha^{-1} y^{-1}, respectively, between 1985 and 2014, a significantly increasing trend. The average yield in the CK treatment remained nearly unchanged, but the yields were highly variable, with a CV of 38.4%. The yields for M, NP, and NPM had CVs of 41.1%, 34.3%, and 36.9%, respectively. Yields for the N and P treatments generally declined between 1985 and 2014, at rates of 20.8 and 23.2 kg ha^{-1} y^{-1}, respectively, and fluctuated markedly between years with CVs of 45.7% and 44.2%, respectively.

The fertilisation treatments also significantly affected FCR between 1985 and 2014 ($p < .05$) (Table 4). M and NP FCRs increased between 1985 and 2014 at rates of 1.47 and 0.83 kg kg^{-1} y^{-1}. P FCR, however, decreased at a rate of 1.22 kg kg^{-1} y^{-1} and fluctuated markedly with a CV of −148% between years. The trend of FCR changes in the N treatment was not significant. P FCR was lower than those in the other treatments over the 30 years. The P treatment generally had the lowest and the NPM treatment had the highest FCRs between 1985 and 2014.

Table 3. Means, coefficient of variation (CV), and trends of wheat yield in various fertilisation treatments for 1985–2014.

	Wheat yield		
Treatment	Mean (kg ha^{-1})	CV (%)	Trend (kg ha^{-1} y^{-1})
CK	1495 ± 105c	38.4	−5.88 ± 12.28
N	1795 ± 150c	45.7	−20.79 ± 17.17
P	1320 ± 107c	44.2	−23.17 ± 11.74
M	3310 ± 249b	41.1	88.98 ± 23.90**
NP	3692 ± 232b	34.3	53.25 ± 25.29*
NPM	4280 ± 289a	36.9	43.81 ± 32.91

Notes: Yield mean and trend are expressed as mean ± standard error. Different letters within a column indicate significant differences between treatments at $p < .05$.
CV = standard deviation/mean yield.
CK, unfertilized control; N, nitrogen fertilisation; P, phosphorus fertilisation; and M, manure fertilisation.
The trend is the slope of the linear regression line of yield against time for 1985–2014, tested for significant differences.
** indicates significance at $p < .01$.
* indicates significance at $p < .05$.

Table 4. Means, coefficients of variation (CV), and trends of fertiliser-contribution ratio (FCR) in various fertilisation treatments for 1985–2014.

	FCR (kg kg^{-1})		
Treatment	Mean (kg kg^{-1})	CV (%)	Trend (kg kg^{-1} y^{-1})
N	7.02 ± 6.89b	537.16	0.12 ± 0.81
P	−18.56 ± 5.04c	148.79	−1.22 ± 0.55*
M	51.33 ± 3.21a	34.29	1.47 ± 0.26**
NP	57.85 ± 2.54a	24.01	0.83 ± 0.25**
NPM	62.65 ± 2.46a	21.55	0.57 ± 0.27*

Notes: Values are expressed as mean ± standard error. Different letters within a column indicate significant differences between treatments at $p < .05$.
CV = standard deviation/mean yield.
N, nitrogen fertilisation; P, phosphorus fertilisation; and M, manure fertilisation.
The trend is the slope of the linear regression line of FCR against time for 1985–2014, tested for significant differences.
** indicates significance at $p < .01$.
* indicates significance at $p < .05$.

Table 5. Means, coefficients of variation (CV), and trends of precipitation-use efficiency (PUE) in various fertilisation treatments for 1985–2014.

	PUE ($kg\ mm^{-1}$)		
Treatment	Mean ($kg\ mm^{-1}$)	CV (%)	Trend ($kg^{-1}\ mm^{-1}\ y^{-1}$)
CK	2.63 ± 0.14c	29.63	−0.02 ± 0.02
N	3.10 ± 0.20c	36.16	−0.04 ± 0.02
P	2.35 ± 0.17c	39.17	−0.05 ± 0.02*
M	5.81 ± 0.36b	33.83	0.13 ± 0.03**
NP	6.48 ± 0.33b	27.95	0.08 ± 0.04*
NPM	7.43 ± 0.40a	29.72	0.05 ± 0.05

Notes: Values are expressed as mean ± standard error. Different letters within a column indicate significant differences between treatments at $p < .05$.
CV = standard deviation/mean yield.
CK, unfertilized control; N, nitrogen fertilisation; P, phosphorus fertilisation; and M, manure fertilisation.
The trend is the slope of the linear regression line of PUE against time for 1985–2014, tested for significant differences.
** indicates significance at $p < .01$.
* indicates significance at $p < .05$.

The fertilisation treatments significantly affected PUE between 1985 and 2014 ($p < .05$) (Table 5). PUE was higher in NPM than the other treatments. M PUE increased at a rate of 0.13 $kg\ mm^{-1}\ y^{-1}$, the highest increasing trend among the treatments ($p < .01$). P PUE was the lowest at 2.35 $kg\ mm^{-1}$ and decreased over time. CK and N PUEs generally declined between 1985 and 2014 at rates of 0.02 and 0.04 $kg\ mm^{-1}\ y^{-1}$ and fluctuated with CVs of 29.6% and 36.2%, respectively. NPM had the highest PUE, which was 182.5% higher than the CK PUE.

Changes in grain yield, FCR, and PUE with precipitation patterns

Pairwise correlation analyses showed that AnP was correlated with FSP ($p < .01$) and GSP ($p < .05$). However, the relationship between GSP and FSP was not significant (Table 6). AnP was highly variable over the 30 years of recorded meteorological data, with the highest total rainfall in 2004 and the lowest in 1995. GSP was lowest in 2011 and highest in 2000 at 177.2 and 367.6 mm, respectively. FSP was lowest in 1995 and highest in 2004 at 140.2 and 608.8 mm, respectively. Precipitation among the years was divided into three types based on the DIs: dry, normal, and wet. AnP was 22.8% lower in dry years (DI < −0.35) and 23.3% higher in wet (DI > 0.35) than normal (−0.35 ≤ DI ≤ 0.35) years. The frequencies of dry, normal, and wet seasons were generally similar among the GSP, FSP, and AnP data. The total annual rainfall varied between years, and there were 11, 9, and 10 dry, normal, and wet years, respectively, in the experimental period. The GSP, FSP, and AnP data sets, however,

Table 6. Fallow-season precipitation (FSP), growing-season precipitation (GSP), and annual precipitation (AnP) for 1985–2014.

	FSP	DI	Type	GSP	DI	Type	AnP	DI	Type
1986	223.4	−0.76	Dry	276.9	0.28	Normal	500.3	−0.59	Dry
1987	202.7	−0.95	Dry	277.8	0.30	Normal	480.5	−0.76	Dry
1988	233.4	−0.67	Dry	320.4	1.15	Wet	553.8	−0.14	Normal
1992	153.2	−1.41	Dry	215.2	−0.96	Dry	368.4	−1.71	Dry
1994	267	−0.37	Dry	309	0.93	Wet	576	0.05	Normal
1995	140.2	−1.52	Dry	178.2	−1.70	Dry	318.4	−2.13	Dry
1996	174.8	−1.21	Dry	273.7	0.22	Normal	448.5	−1.03	Dry
2000	200.8	−0.97	Dry	367.6	2.10	Wet	568.4	−0.01	Normal
2001	152.4	−1.41	Dry	283.4	0.41	Wet	435.8	−1.14	Dry
1998	269.3	−0.35	Dry	326.9	1.28	Wet	596.2	0.22	Normal
2003	184.6	−1.12	Dry	257.1	−0.12	Normal	441.7	−1.09	Dry
1990	285	−0.20	Normal	273.2	0.21	Normal	558.2	−0.10	Normal
1993	346	0.35	Normal	270.7	0.16	Normal	616.7	0.39	Wet
1999	327.8	0.19	Normal	246.6	−0.33	Normal	574.4	0.04	Normal
2002	313.5	0.06	Normal	361.1	1.97	Wet	674.6	0.89	Wet
2005	309.5	0.02	Normal	213.8	−0.99	Dry	523.3	−0.40	Dry
2006	299.3	−0.07	Normal	229.2	−0.68	Dry	528.5	−0.35	Normal
2007	333	0.24	Normal	194.8	−1.37	Dry	527.8	−0.36	Dry
2008	344.4	0.34	Normal	291.8	0.58	Wet	636.2	0.56	Wet
2009	315.2	0.07	Normal	177.5	−1.72	Dry	492.7	−0.66	Dry
2010	289.2	−0.16	Normal	242.8	−0.40	Dry	532	−0.32	Normal
2013	304.6	−0.02	Normal	217.9	−0.90	Dry	522.5	−0.40	Dry
1985	379.5	0.66	Wet	293.6	0.62	Wet	673.1	0.87	Wet
1989	516.2	1.91	Wet	268.1	0.10	Normal	784.3	1.81	Wet
1991	392.8	0.78	Wet	272.7	0.20	Normal	665.5	0.81	Wet
1997	371.2	0.58	Wet	223.3	−0.80	Dry	594.5	0.21	Normal
2004	608.8	2.75	Wet	281.7	0.38	Wet	890.5	2.71	Wet
2011	457.9	1.38	Wet	177.2	−1.72	Dry	635.1	0.55	Wet
2012	443.4	1.24	Wet	260.6	−0.05	Normal	704	1.13	Wet
2014	377.2	0.64	Wet	305.3	0.85	Wet	682.5	0.95	Wet

Notes: DI is defined as $(AnP - M_1)/\sigma$, where AnP is the annual precipitation (the sum of FSP and GSP), M_1 is the average precipitation, and σ is the standard deviation for precipitation during the observed years.
Dry, normal and wet years are classified by DI < −0.35, −0.35 ≤ DI ≤ −0.35 and DI > 0.35, respectively.

differed substantially. For example, three years (1988, 1994, and 1998) with wet GSPs had dry FSPs but normal AnPs (Table 6).

Yields generally increased with precipitation and were significantly higher in wet than normal and dry years ($p < .05$) (Figure 1). The yields in various fertilisation treatments had CVs of 14–50%. Yields were higher in the N, M, NP, and NPM treatments than in the CK treatment in all the three precipitation patterns. Yields in the NPM treatment were higher than those in CK by 163–212% for the three precipitation patterns. Yields in the NPM treatment were higher than those in NP by 10.6%, 12.8%, and 22.4% and those in M by 21.7%, 40.2%, and 27.8% in the dry, normal, and wet years, respectively. Yields in the M treatment were higher than those in the N treatment by 97.8%, 84.0%, and 76.1%, while yields in the P treatment were lower than those in CK by 6.5%, 15.5%, and 13.2%, in the dry, normal, and wet years, respectively.

N, NP, and NPM FCRs were higher in normal and wet than dry years, whereas the FCRs did not differ significantly in the other treatments among the three precipitation patterns (Figure 2). NPM FCRs were higher in the dry, normal, and wet years than those in P by 620.8%, 360.1%, and 392.1% and those in NP by 5.7%, 6.6%, and 13.3%, respectively. N FCR fluctuated markedly with a CV of −722.2%, 165.9%, and 152.7% in the dry, normal, and wet years, respectively.

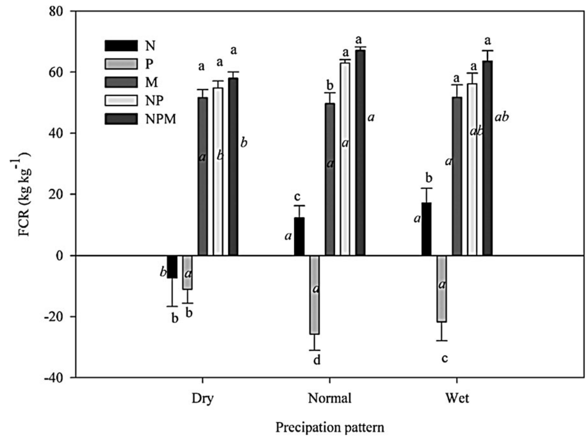

Figure 2. Response of FCR to three precipitation patterns in various fertilisation treatments. Different letters in italics denote significant differences among the precipitation patterns within the same fertilisation treatment ($p < .05$). The different letters above and below the error bars (one standard deviation) denote significant differences among the fertilisation treatments within the same precipitation pattern ($p < .05$).
Note: N, nitrogen fertilisation; P, phosphorus fertilisation; M, manure fertilisation; NP, nitrogen and phosphorus fertilisation; NPM, nitrogen, phosphorus and manure fertilisation; FCR, fertiliser-contribution rate.

P PUEs were higher in dry than wet and normal years, whereas PUEs in the other treatments did not differ significantly among the three precipitation patterns (Figure 3). N, M, NP, and NPM PUEs were higher

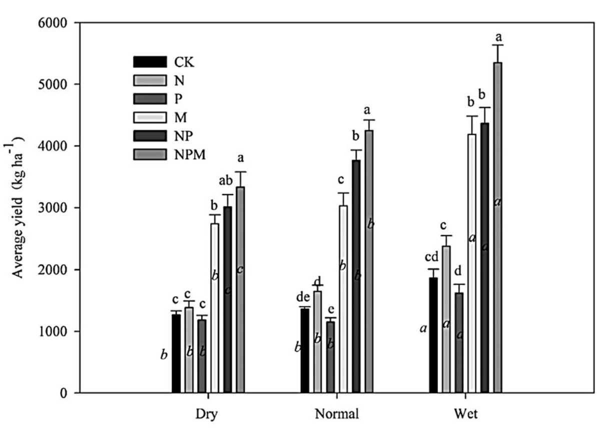

Figure 1. Response of grain yield to three precipitation patterns in various fertilisation treatments. Different letters in italics denote significant differences among the precipitation patterns within the same fertilisation treatment ($p < .05$). The different letters above the error bars (one standard deviation) denote significant differences among fertilisation treatments within the same precipitation pattern ($p < .05$).
Note: CK, unfertilized control; N, nitrogen fertilisation; P, phosphorus fertilisation; M, manure fertlisation; NP, nitrogen and phosphorus fertilisation; NPM, nitrogen, phosphorus and manure fertilisation.

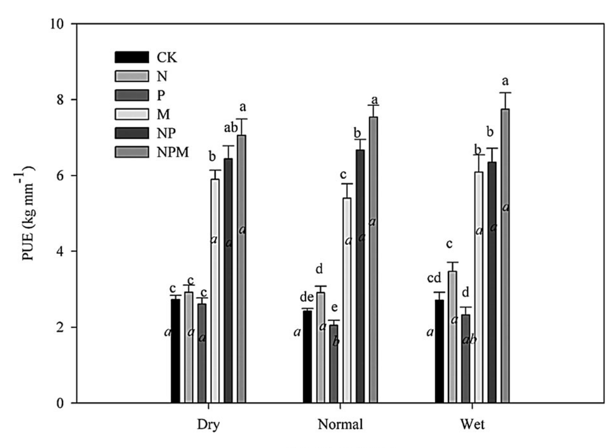

Figure 3. Response of PUE to three precipitation patterns in various fertilisation treatments. Different letters in italics denote significant differences among the precipitation patterns within the same fertilisation treatment ($p < .05$). The different lowercase letters above the error bars (one standard deviation) denote significant differences among the fertilisation treatments within the same precipitation pattern ($p < .05$).
Note: CK, unfertilized control; N, nitrogen fertilisation; P, phosphorus fertilisation; M, manure fertlisation; NP, nitrogen and phosphorus fertilisation; NPM, nitrogen, phosphorus and manure fertilisation; PUE, precipitation-use efficiency.

than those in CK for the three precipitation patterns. PUEs were higher in wet years in NPM than in CK, N, P, M, and NP by 186.0%, 123.3%, 232.6%, 27.3%, and 22.0%, respectively. PUEs in dry and normal years were 158.6% and 211.6% higher, respectively, in NPM than in CK. P PUEs, however, were 4.4%, 15.3%, and 14.0% lower than those in CK in the dry, normal, and wet years, respectively.

Discussion

Identification of the most important factors affecting yield

Many variables can affect wheat yield in the rain-fed cropping region of the Loess Plateau, such as fertilisation and precipitation (Huang et al. 2003; Guo et al. 2012). SMLR, which has a scheme for selecting variables, can quantify the relationship between a dependent variable and one or more independent variables (Prost et al. 2008). Selection and elimination steps determine the significant variables in the model (Prost et al. 2008). In this study, we used SMLR to evaluate the relationships of wheat yield with fertilisation, precipitation, and variety in a 30-year experiment on the Loess Plateau.

Prior to the SMLR, Pearson's correlation analysis indicated that wheat yield correlated with FSP and AnP in various fertilisation treatments, except for the P treatment. The exception of P treatment may be related to the poor mobility of P in the soil (Liu & Zhang 2000a, 2000b). Meanwhile, MnP showed different effects on grain yield in various fertilisation treatments. We found that the MnP_{Sep} had higher correlation with grain yield in the M, NP, and NPM treatments, while the MnP_{Feb} had higher correlation with grain yield in the NP and NPM treatments (Table 1). The precipitation in September (sowing period) provides favourable conditions for seed germination, and the precipitation in February (before turning green) is beneficial to robust growth of plant seedlings, thereby contributing to yield formation (Dang & Gao 2003; Basso et al. 2012).

Zhang et al. (2013) showed that variety, fertilisation, and weather could influence wheat yield on the North China Plain. Lobell et al. (2002) reported that precipitation and management strongly influence wheat productivity in the semiarid region of northwestern Mexico. In the present study, however, the SMLR analysis showed that wheat yield correlated with the amounts of fertilisation and precipitation, but not with variety. The influence of variety, which changed with time, was lower than the other factors for the yield, and thus could be ignored. Our result is in agreement with the finding of Zhang et al. (2008) who reported that the three varieties were associated with similar grain-filling characteristics and yields.

In the regression equation established in this study, a high standard partial regression coefficient for the amount of manure indicated that its contribution was greater than that of N application, which were both greater than the amount of P and the MnP_{Feb} and MnP_{Sep}. The significant contribution of manure can be attributed to the low levels of organic nutrients in the original Heilu soil, as has been reported by Dang and Zhang (1999).

Effects of fertilisation treatment on soil properties, grain yield, FCR, and PUE

Fertilisation and precipitation are the main factors limiting wheat production in rain-fed cropping systems in arid and semiarid regions (Huang et al. 2003; Guo et al. 2012). The contribution of the amount of manure to wheat yield was higher than that of precipitation in our study, mainly because of poor organic nutrients in the Heilu soil. Fertiliser management is used primarily to maintain soil fertility and sustain crop yield (Yang et al. 2015). Appropriate fertiliser management can improve the soil quality and crop yield, while poor management can degrade soil quality and decrease crop yield (Chen et al. 2011; Yang et al. 2015).

Our study showed that annual yields in the N and P treatments (Table 3) and FCR in the P treatment tended to decrease with time (Table 4, Figure 2). Similarly, Sharma and Subehia (2003) reported a strong decrease in the yields of corn and wheat fertilised with N treatment over 25 years in the western Himalayas of India, where the soil pH decreased, limiting the growth of plants. Our study found that the soil pH had the same decreasing trend over time. The soil pH, however, had changed little after 30 years of fertilisation relative to the initial level. The soil can become deficient in other nutrients with the long-term application of N and P fertilisers and a consequent accumulation of N and P (Yang et al. 2006; Guo et al. 2008). In our experiment, the long-term application of N and P fertilisers particularly decreased the levels of AK (Table 2) and thus might limit the yield of wheat.

The trends of yield and FCR were the highest in the M treatment over 30 years. The addition of manure with N and P improved the nutrient levels in the soil and increased wheat yield and FCR (Tables 2–4). A combination of organic and inorganic fertilisers may improve the efficiency of nutrient uptake by crops and pose a positive effect on crop yield on the Loess

Plateau compared to no fertilisation or to the addition of only inorganic N and P (Han et al. 2004; Fan et al. 2005; Yang et al. 2006). This result suggests that adding manure to the soil can be used to sustain soil fertility and improve wheat yield and FCR in the rain-fed cropping system of the Loess Plateau.

Effects of precipitation pattern on grain yield, FCR, and PUE

As the sole source of soil water, precipitation is a major factor in determining the optimum fertilisation treatment in rain-fed cropping systems (Huang et al. 2003; Guo et al. 2012). From the SMLR, we could know that precipitation was also an important factor affecting the yield of winter wheat. Precipitation patterns can strongly influence the structure and functioning of semiarid ecosystems (Miranda et al. 2011). In our study, the precipitation patterns had a strong effect on wheat yields over the 30 years: yields were higher in wet than normal and dry years (Figure 1). Similar results have been reported by a study of wheat yields with different level of N treatments in three precipitation patterns (Guo et al. 2012). The FCR was higher in the normal years than in the dry years for the N, NP, and NPM treatments (Figure 2). However, the three precipitation patterns did not affect PUE within the same fertilisation treatments, except P treatment (Figure 3). This is because grain yields changed less with precipitation in the P treatment compared with other fertilisation treatments.

Predicting AnP is difficult due to the high seasonal variations in precipitation. On the semiarid Loess Plateau of China, the temporal distribution of rainfall is uneven, especially before the growing season. This variation is important to plant communities and AnP (Miranda et al. 2011; Basso et al. 2012). FSP, however, was easily recorded before planting, which positively correlated with AnP in the study region (Table 6). These results thus identify a potential method for selecting a reasonable fertilisation treatment based on FSP before planting, because FSP has a considerable influence on wheat yield (Guo et al. 2012). For example, an M treatment is recommended when FSP before planting is <224 mm, that is, a dry year (e.g. 1992, 1995, and 2001). In contrast, fertilisation with NPM would be optimal in years with higher FSPs.

Although 35–40% of the FSP is retained in soils under conventional management on the Loess Plateau, the amount of FSP is important for yield (Guo et al. 2012). The proportion of FSP retained may be increased by reasonable conservational practices, such as reduced or no tillage during the fallow season (Moret et al. 2006; Moret et al. 2007). Recent studies on the Loess Plateau have suggested that cover crops combined with no tillage can restore the water-holding capacity and biological activity of the soil, which help to solubilise soil nutrients and thereby reduce the need for chemical inputs (Liu et al. 2013; Chen et al. 2014). These conservational practices during FSP may thus contribute to the efficient use of precipitation and the sustainable production of food in rain-fed cropping systems.

Table 7. Results of the analysis of variance for all variables and interactions of fertilisation treatments and precipitation pattern.

Factors	d.f.	*F*	*p*
N	1	166.039	.000**
P	1	47.723	.000**
M	1	166.167	.000**
N × P	1	124.892	.000**
N × P × M	1	42.973	.000**
Precipitation pattern	2	74.326	.000**
N × Precipitation pattern	2	5.492	.004*
P × Precipitation pattern	2	0.385	.681
M × Precipitation pattern	2	6.130	.002**
N × P × Precipitation pattern	2	1.104	.332
N × P × M × Precipitation pattern	2	0.098	.907

Notes: × indicates interaction.
CK, unfertilized control; N, nitrogen fertilisation; P, phosphorus fertilisation; and M, manure fertilisation.
** indicates significance at $p < .01$.
* indicates significance at $p < .05$.

We found that average grain yields and FCRs were consistently highest in the NPM and lowest in the P treatments regardless of precipitation pattern. However, wheat yields in arid and semiarid regions vary considerably from year to year, perhaps due to different precipitation patterns and fertilisation treatments (Huang et al. 2003; Guo et al. 2012). The interactions between N and M fertilisation and precipitation pattern were significant in our study (Table 7). Sandhu et al. (1996) also founded the N cycling and precipitation had a strong interaction in crop yields.

Therefore, combining conservational practices during FSP with optimised NPM levels may be the best solution to improve the efficient use of precipitation and the contribution of fertilisers for sustainable production of wheat in rain-fed cropping systems.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by a Farmland Soil and Water Conservation project of the National Science and Technology

Programme of China under Grant No. 2011BAD31B01. The research on the yield potential and technology for increasing crop yields on the Loess Plateau was supported by a National Science and Technology Programme of China support project under Grant No. 2015BAD22B01.

References

Bandyopadhyay, KK, Misra, AK, Ghosh, PK, Hati, KM. 2010. Effect of integrated use of farmyard manure and chemical fertilizers on soil physical properties and productivity of soybean. Soil Till Res. 110:115–125.

Basso B, Fiorentino C, Cammarano D, Cafiero G, Dardanelli J. 2012. Analysis of rainfall distribution on spatial and temporal patterns of wheat yield in Mediterranean environment. Eur J Agron. 41:52–65.

Bremner JM, Tabatabai MA. 1972. Use of an ammonia electrode for determination of ammonia in Kjedahl analysis of soils. Commun Soil Plan. 3:159–165.

Chen R, Hu J, Dittert K, Wang J, Zhang J, Lin X. 2011. Soil total nitrogen and natural ^{15}nitrogen in response to long-term fertilizer management of a maize–wheat cropping system in Northern China. Commun Soil Plan. 42:322–331.

Chen YX, Wen XX, Sun YL, Zhang JL, Wu W, Liao YC. 2014. Mulching practices altered soil bacterial community structure and improved orchard productivity and apple quality after five growing seasons. Sci Hortic-Amsterdam. 172: 248–257.

Chloupek O, Hrstkova P, Schweigert P. 2004. Yield and its stability, crop diversity, adaptability and response to climate change, weather and fertilisation over 75 years in the Czech Republic in comparison to some European countries. Field Crops Res. 85:167–190.

Dang TH, Gao CQ. 2003. Study on key water factors of affecting wheat yield in Weibei dry highland. Res. Soil Water Conserv. 10:9–11.

Dang TH, Zhang M. 1999. The position study of organic manure on soil nutrient content forms and transformation in Heilu soil. Agric Res Arid Areas. 17:1–4.

Fan TL, Stewart BA, Yong W, Junjie L, Guangye G. 2005. Long-term fertilization effects on grain yield, water-use efficiency and soil fertility in the dryland of Loess Plateau in China. Agric Ecosyst Environ. 106:313–329.

Guo SL, Dang TH, Hao, MD. 2008. Phosphorus changes and sorption characteristics in a calcareous soil under long-term fertilization. Pedosphere. 18:248–256.

Guo SL, Zhu HH, Dang TH, Wu JS, Liu WZ, Hao MD, Li Y, Syers JK. 2012. Winter wheat grain yield associated with precipitation distribution under long-term nitrogen fertilization in the semiarid Loess Plateau in China. Geoderma. 189–190:442–450.

Han KH, Choi WJ, Han GH, Yun SI, Yoo SH, Ro H-M. 2004. Urea–nitrogen transformation and compost-nitrogen mineralization in three different soils as affected by the interaction between both nitrogen inputs. Boil Fert Soils. 39:193–199.

Hanway JJ, Heidel H. 1952. Soil analysis methods as used in Iowa State College Soil Testing Laboratory. Iowa Agric. 57:1–31.

Huang MB, Dang TH, Gallichand J, Goulet M. 2003. Effect of increased fertilizer applications to wheat crop on soil-water depletion in the Loess Plateau, China. Agric Water Manage. 58:267–278.

Krupnik TJ, Ahmed ZU, Timsina J, Yasmin S, Hossain F, Al Mamun A, Mridha AI, McDonald AJ. 2015. Untangling crop management and environmental influences on wheat yield variability in Bangladesh: an application of non-parametric approaches. Agr Syst. 139:166–179.

Li WJ, Hao MD. 2013. Effect of long-term fertilization on wheat productivity and soil properties in the Northern Loess Plateau, China. J Food Agric Environ. 11:132–137.

Liu JL, Zhang FS. 2000a. Dynamics of soil P pool in a long-term fertilizing experiment of wheat maize rotation I. Crop yield effect of fertilizer P and dynamics of soil total P and inorganic P. Chin J Appl Ecol. 11:360–364.

Liu JL, Zhang FS. 2000b. Dynamics of soil P pool in a long-term fertilizing experiment of wheat–maize rotation Π. Dynamics of soil Olsen-P and inorganic P. Chin. J Appl Ecol. 11:365–368.

Liu Y, Gao MS, Wu W, Tanveer SK, Wen XX, Liao YC. 2013. The effects of conservation tillage practices on the soil water-holding capacity of a non-irrigated apple orchard in the Loess Plateau, China. Soil Till Res. 130:7–12.

Lobell DB, Ortiz-Monasterio JI, Addams, CL, Asner GP. 2002. Soil, climate, and management impacts on regional wheat.pdf. Agr Forest Meteorol. 114:31–43.

Manna MC, Swarup A, Wanjari RH, Mishra B, Shahi DK. 2007. Long-term fertilization, manure and liming effects on soil organic matter and crop yields. Soil Till Res. 94: 397–409.

Miranda JD, Armas C, Padilla FM, Pugnaire FI. 2011. Climatic change and rainfall patterns: effects on semi-arid plant communities of the Iberian Southeast. J Arid Environ. 75:1302–1309.

Moret D, Arrúe JL, López MV, Gracia R. 2006. Influence of fallowing practices on soil water and precipitation storage efficiency in semiarid Aragon (NE Spain). Agric Water Manage. 82:161–176.

Moret D, Braud I, Arrúe J. 2007. Water balance simulation of a dryland soil during fallow under conventional and conservation tillage in semiarid Aragon, Northeast Spain. Soil Till Res. 92:251–263.

Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA. 2012. Closing yield gaps through nutrient and water management. Nature. 490:254–257.

Olsen SR, Cole CV, Watanable FS, Dean LA. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circulars No. 939. Washington, DC: U.S. Government Printing Office.

Pirjo PS, Lauri J, Miroslav T, Jörgen EO, Pierluigi C, Henrik E, Josef E, Anne G, Kurt CK, Jerzy K, et al. 2010. Coincidence of variation in yield and climate in Europe. Agric Ecosyst Environ. 139, 483–489.

Prost L, Makowski D, Jeuffroy M-H. 2008. Comparison of stepwise selection and Bayesian model averaging for yield gap analysis. Eco Model. 219:66–76.

Roel A, Firpo H, Plant RE. 2007. Why do some farmers get higher yields? Multivariate analysis of a group of Uruguayan rice farmers. Comput Electron Agr. 58:78–92.

Rozbicki J, Ceglińska A, Gozdowski D, Jakubczak M, Cacak-Pietrzak G, Mądry W, Golba J, Piechociński M, Sobczyński G, Studnicki M, Drzazga T. 2015. Influence of the cultivar, environment and management on the grain yield and bread-making quality in winter wheat. J Cereal Sci. 61:126–132.

Sandhu KS, Benbi DK, Prihar SS. 1996. Dryland wheat yields in relation to soil organic carbon, applied nitrogen, stored water and rainfall distribution. Fert Res. 44:9–15.

Scursoni JA, Palmano M, De Notta A, Delfino D. 2012. Italian ryegrass (*Lolium multiflorum* Lam.) density and N fertilization on wheat (*Triticum aestivum* L.) yield in Argentina. Crop Prot. 32:36–40.

Sharma SP, Subehia SK. 2003. Effects of twenty-five years of fertilizer use on Maize and Wheat yields and quality of an acidic soil in the Western Himalayas. Exp Agr. 39:55–64.

Walkley A, Black IA. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37:29–38.

Wang WN, Lu JW, Li YS, Zou J, Su W, Li XK, Li YC. 2010. Study on fertilization effect and fertilizer contribution rate of different crops at present production conditions. Sci Agric Sin. 43:3997–4007.

Wang XB, Dai K, Zhang DC, Zhang XM, Wang Y, Zhao QS, Cai DX, Hoogmoed WB, Oenema O. 2011. Dryland maize yields and water use efficiency in response to tillage/crop stubble and nutrient management practices in China. Field Crops Res. 120:47–57.

Wang XP, Li X-R, Zhang J-G, Zhang Z-S, Berndtsson R. 2005. Measurement of rainfall interception by xerophytic shrubs in re-vegetated sand dunes/Mesure de l'interception de la pluie par des arbustes xérophiles sur des dunes de sable replantées. Hydrolog Sci J. 50:897–910.

Wilcox J, Makowski D. 2014. A meta-analysis of the predicted effects of climate change on wheat yields using simulation studies. Field Crops Res. 156:180–190.

Xiong R, Meullenet JF. 2006. A PLS dummy variable approach to assess the impact of jar attributes on liking. Food Qual Prefer. 17:188–198.

Yang SM, Malhi SS, Song JR, Xiong YC, Yue WY, Lu LL, Wang JG, Guo TW. 2006. Crop yield, nitrogen uptake and nitrate-nitrogen accumulation in soil as affected by 23 annual applications of fertilizer and manure in the rainfed region of Northwestern China. Nutr Cycl Agroecosyst. 76:81–94.

Yang X, Chen Y, Pacenka S, Gao W, Ma L, Wang G, Yan P, Sui P, Steenhuis TS. 2015. Effect of diversified crop rotations on groundwater levels and crop water productivity in the North China Plain. J Hydrol. 522:428–438.

Zhan X, Liang X, Xu G, Zhou L. 2013. Influence of plant root morphology and tissue composition on phenanthrene uptake: stepwise multiple linear regression analysis. Environ Pollut. 179:294–300.

Zhang X, Wang S, Sun H, Chen S, Shao L, Liu X. 2013. Contribution of cultivar, fertilizer and weather to yield variation of winter wheat over three decades: a case study in the North China Plain. Eur J Agron. 50:52–59.

Zhang Y, Hao MD, Pang YH. 2008. Study on the grain-filling characteristic of the succession of wheat cultivars in the gully areas of the Loess Plateau. J Triticeae Crops. 28(6): 1058–1062.