Quantitative analysis of irrigation water productivity in the middle reaches of Heihe River Basin, Northwest China

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Abstract: With the growing shortage of surface water resources, it is of great significance for improving the irrigation water productivity (IWP) to ensure the water and food security. The contribution of the driving factors of the IWP and the rational regulation of the input factors of agricultural production is required. In this paper, 118 and 80 sampling points were selected in Pingchuan and Liaoquan irrigation districts (PLID, the spacing of sampling point is approximately 1 km) and the middle reaches of the Heihe River basin (MHRB, the spacing of sampling point is approximately 10 km), respectively. Soil characteristics and management measures near the sampling points were obtained. Results showed that the average value of the IWP in MHRB was 1.67 kg/m^3, with a moderate heterogeneity in the space. The main driving factors of IWP were irrigation, fertilization and planting density. On the PLID, the contribution rates of soil factors and management measures to IWP were 20.6% and 35.2%, respectively, and the contribution of soil factors to IWP increased to 43.8% in the MHRB, while the contribution rate of management measures decreased to 24.8%. It shows that in a small irrigation districts, from the perspective of farmers, the improvement of IWP should be mainly controlled by management measures, while in the large area of watershed scale, the spatial differences in soil factors also need to be considered by the government management departments, when they want to increase IWP through regulating management measures.

Keywords: irrigation water productivity, driving factors, quantitative analysis, partial least squares, maize
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1 Introduction

Water is an important natural resource, and with population and industry growth, the gap between water supply and demand will also grow[1]. By 2050, the pressure on water resource will increase more than 20% over the current level[2]. In addition, with the development of human society, the world population will increase to approximately 9.15 billion by 2050, which will lead to increasing demand for food[3]. At present, agriculture is a major sector for the water use, consuming about 70% of total water use in the world[4]; however, shortages of water resource will limit the high crop yields[5]. Therefore, improving agricultural water productivity is an important measure for ensuring global water safety and food security in the future.

Increasing water productivity relieves pressure on water resources[6]. The concept of water productivity is not the same in different fields and at different research scales[7-11]. Based on “More Crop per Drop”, Molden[12] proposed the irrigation water productivity (IWP) concept and defined it as the crop yield per irrigation water amount. IWP reflects the production efficiency of unit water in agricultural production and is an important indicator for evaluating irrigation management and irrigation systems. Therefore, increasing IWP has great importance to the development and sustainability of food production and irrigated agriculture.

IWP reflects the relationship between crop yield and irrigation water use. Crop yield is closely related to the growth and development, and the transfer of water resources from source to crop involves canal water transport, soil infiltration, root absorption and so on. Therefore, the IWP is affected by factors which affect crop yield and irrigation water applied. The main factors affecting yield and irrigation amount are variety, climate, soil, and management[9,13,14]. Research has shown that IWP is influenced by genetic factors, and the difference in the eco-physiological characteristics of different varieties of crops affects the yield formation and water consumption[15]. In addition, the formation of crop yields is closely related to the air temperature, solar radiation and precipitation[16,17]. Recent evidence suggests that under rainfed conditions the potential yield of maize and potato could decline by 19% and 50%, respectively, by the middle of this century, due to the gradual increase of global average temperature[18].

Water and mineral elements essential for crop growth come from the soil. Previous studies have reported that the physical and chemical characteristics of different types of soil vary greatly, and crops have different absorption and utilization of water and nutrients in the soil[19,20]. However, among all the factors

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affecting IWP, management measures are easily controlled (e.g., the application of water, fertilizers and pesticides, the input of man-machineries). Hatfield[21] pointed out that water use efficiency (Ratio of yield to evapotranspiration, WUE=Y/ET) can be increased by 25% to 40% through soil management practices involving tillage. Compared with unfertilized treatment, applying N fertilizer can significantly increase water productivity[22]. In the Hexi Corridor region of arid northwestern China, Li[23] analyzed agricultural production statistics for the past 30 years and found that agronomic practice factors (irrigation, fertilization, agricultural film and agricultural pesticide) had greater impacts on IWP than climate factors (daily mean temperature, solar radiation and precipitation).

Factors controlling IWP need to be regulated to obtain the best crop yield and minimize water input. At present, many studies are focused on the influence of a certain factor on IWP, and there are few studies on the effects of driving factors on IWP under the multi-factor synergies. The middle of Heihe River Basin (MHRB) is an important production area of seed maize in Northwest China. In this area, the crop varieties and climatic factors have little effect on spatial differences in IWP because the variety of maize planted was relatively single and the spatial difference of climate factors was small. Therefore, our quantitative analysis of IWP was mainly focused on soil and management factors, and the main objectives of this study are to: a) understand the spatial difference of IWP, soil factors and management measures; b) analyze the key driving factors of IWP in soil factors and management measures; c) quantify the contribution of various factors to IWP.

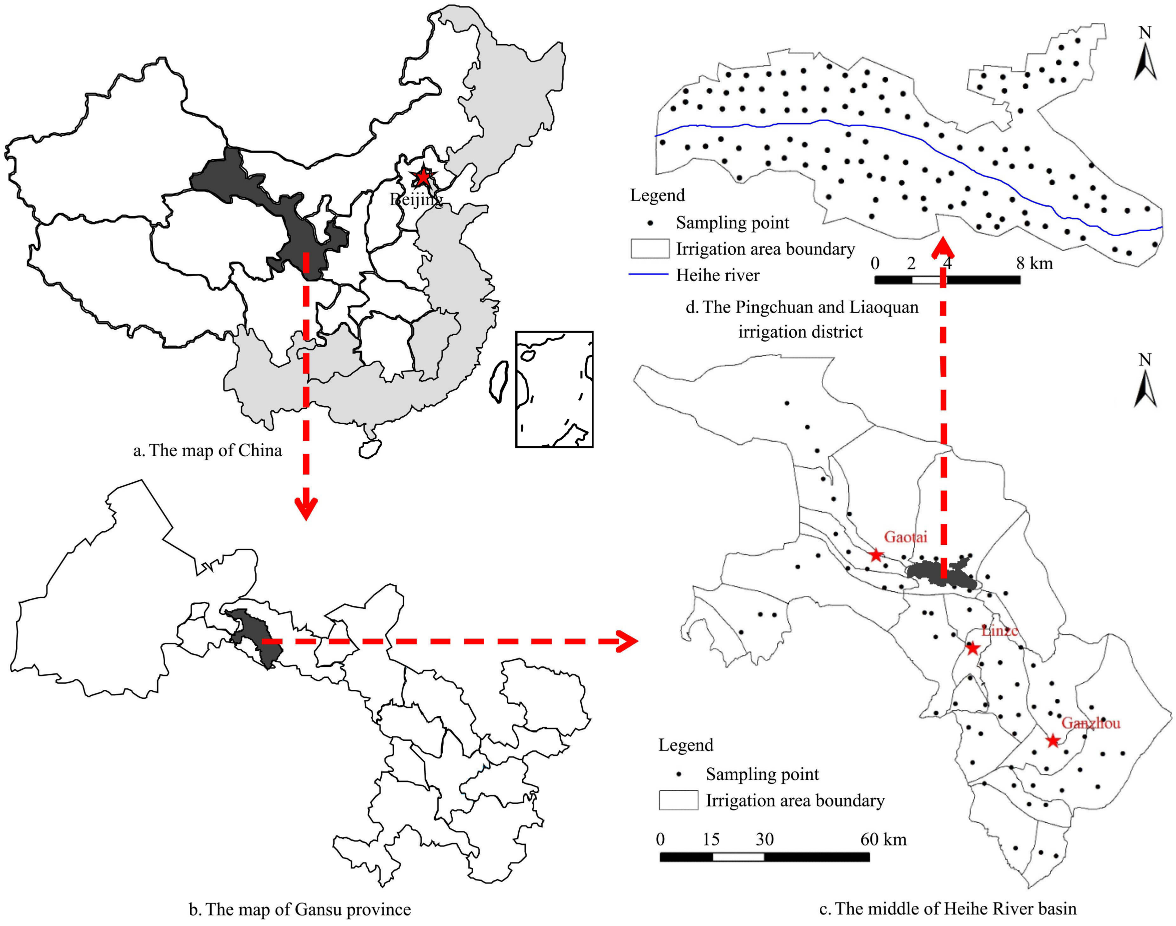
2 Materials and methods

2.1 Study area

The middle reach of Heihe river basin, located in the middle of Qilian mountains and Badain Jaran desert (38°36′-39°45′N, 99°16′-100°40′E, average altitude is 1470.5 m), includes Ganzhou district, Linze county and Gaotai county of Zhangye city, Gansu Province. The catchment area is 11 300 km^2, with average annual rainfall of 69-216 mm mainly concentrated in the June to September crop growth period, average annual evaporation of 1453-2351 mm, and continental arid climate[24]. The Pingchuan and Liaoquan irrigation district (PLID), which is located in the north of Linze county (39°17′-39°24′N, 99°56′-100°10′E), the average altitude is 1373 m and the irrigation area is 1100 km^2, with the annual average precipitation of 117 mm, and the annual potential evaporation of 2365.6 mm.

2.2 Field investigation and sampling design

In 2015, a grid of 1 km×1 km was used to design 118 sampling points (the spacing of sampling point is approximately 1 km) in PLID, and a grid of 5 km×10 km was used to design 80 sampling points (the spacing of sampling point is approximately 10 km) throughout the MHRB in 2016, and the crop planted in the sampling field was maize. GPS was used to record the latitude, longitude and elevation of the sampling points (Figure 1).



a. The map of China

b. The map of Gansu province

c. The middle of Heihe River basin

d. The Pingchuan and Liaoquan irrigation district

Figure 1 Location of study area and the sampling point distribution

2.2.1 Soil factors

Before the maize was planted (early April), composite soil samples (in a 10 m × 10 m plot) with three replications were collected from the cultivated (0-30 cm) and bottom layer (30-100 cm). Simultaneously, two soil samples were collected near the sampling points by cutting rings (with the diameter of 5 cm and volume of 100 cm^3) for measurements of soil bulk density (BD) and gravimetric soil water content (SWC). After the soil samples were air-dried in the laboratory, the air-dried soil samples were divided into two subsamples. One was sieved through a 2 mm mesh for particle-size analysis by laser diffraction using a laser particle size analyzer (Mastersizer 2000 analyzer, UK); the other was passed through a 0.25 mm mesh for soil chemical properties measurements. The soil organic matter (SOM) was measured by the potassium dichromate oxidation method[25]. The soil total nitrogen (TN) was digested by H_2SO_4 and cupric sulfate-potassium sulfate ($CuSO_4$-K_2SO_4) as the catalyst agent and measured by the Kjeldahl method with an automatic Kjeldahl apparatus (FOSS 2300 Kjeltec Analyzer Unit, Sweden)[26]. The available nitrogen (AN) was measured using a continuous flow analyzer (Auto Analyzer 3, Bran+Luebbe, SEAL Analytical GmbH, Germany)[27]. Available phosphorus (AP) was determined by the Olsen extraction method using alkaline sodium bicarbonate as the extractant in a 20:1 ratio[28]. The soil samples were calcined in a muffle furnace at 450°C for 3 h and then hydrochloric acid (3.5 mol/L) was added, after that shaken for 16 hours to convert the soil organic phosphorus into inorganic phosphorus, and total phosphorus (TP) was measured by Olsen extraction method[29].

2.2.2 Management factors

In August of each year, the irrigation water amount was obtained from Water Conservancy Bureau of Zhangye City (automatic monitoring by triangular weir flowmeter) and the fertilizer application was carried out in our study area through a survey. At the maturity stage of maize, the planting row and spacing were measured to obtain planting density, and at the same time, the grain yield was measured in 100 m^2 area at each sampling location. A 100-seed sample was selected randomly, weighed, and further dried for 72 h at 80°C to determine the seed moisture. Finally, every sampling crop yields have been converted into the grain weight (Y) with 13% moisture content[30] using the seed moisture data. In this paper, the IWP is defined as the yield per unit of irrigation water use, which was calculated as follows:

$$IWP=Y/IW \tag{1}$$

where, IWP is irrigation water productivity, kg/m^3; Y is grain yield, kg/hm^2; I is the amount of irrigation water, m^3/hm^2. Therefore, the experimental data in our study includes one dependent variable factor (IWP) and 18 independent variables. The 18 independent variables and their abbreviations are shown in Table 1.

Table 1 Independent variable factors and their abbreviation

Full name	Abbreviation
Initial soil organic matter	SOM
Initial total nitrogen	TN
Initial available nitrogen	AN
Initial total phosphorus	TP
Initial available phosphorus	AP
Soil bulk density	BD
Soil water content	SWC
Soil clay content of 0-30 cm	Clay0
Soil silt content of 0-30 cm	Silt0
Soil sand content of 0-30 cm	Sand0
Soil clay content of 30-100 cm	Clay1
Soil silt content of 30-100 cm	Silt1
Soil sand content of 30-100 cm	Sand1
Irrigation water	IW
Amount of nitrogen fertilizer applied	NF
Amount of phosphorus fertilizer applied	PF
The total amount of fertilizer applied	TF
Planting density	PD

2.2.3 Contribution rate analysis of independent variables

There is a significant correlation between soil characteristics and related factors[31], so there may be a problem of collinearity between the independent variables when analyzing the influence of independent variables such as, soil factors and management measures on IWP. And to solve this problem, partial least-squares (PLS) regression can be used to quantitatively analyze the dependent variable of IWP[32-34]. The variable projection importance (VIP) means the importance of the independent variable X_j in explaining partial variable Y in PLS regression analysis[35], and which was defined as follows:

$$VIP_j=\sqrt{\frac{p}{Rd(Y;t_1,\cdots,t_m)}\sum_{h=1}^{m}Rd(Y;t_h)w_{hj}^2} \tag{2}$$

where, W_{hj} is the j-th component of axis W_h; and X_j interprets Y by passing t_h.

When all the VIP values are 1, it implies that the independent variable X_j has the same effect (importance and influence) on the dependent variable. When VIP > 1, it means that the independent variable has more important. When VIP < 0.8, it means that the independent variable contributes less to the dependent variable[35-37]. Therefore, we can calculate the contribution of each independent variable to the dependent variable by the complex correlation coefficient between the VIP value of the independent variable and the PLS regression model[38] as follows:

$$W_i=\frac{VIP_i}{\sum_{i=1}^{n}VIP_i}R\times 100\% \tag{3}$$

where, W_i is the contribution of the i-th factor to the dependent variable; VIP_i is the VIP value of the i-th factor; R is the complex correlation coefficient of the PLS regression model, and n is the number of independent variables in the PLS model.

In this paper, the correlation of IWP and its driving factors were analyzed by SPSS 21.0 software. Partial least squares regression was analyzed by XLSTAT 2010 software. We also used EXCEL 2010 for the descriptive statistics and drawing the figure.

3 Results and discussion

3.1 Descriptive statistical analysis

The Kolmogorov–Smirnov (K-S) test is widely used in applied statistical studies[39,40]. From the descriptive statistics of IWP and its driving factors (Table 2), the results of K-S test showed that the data of IWP and most of the driving factors were consistent with a normal distribution. On the scale of PLID, the average value of IWP was 1.48 kg/cm^3 and the coefficient of variation (CV) was 40%, showed a moderate heterogeneity in space[41]. However, the average value of IWP in MHRB was 1.67 kg/cm^3, and it also exhibits moderate heterogeneity (CV=39%) in space. Wu[42] showed that per cubic water can produce 2.0 kg of grain in developed areas of water-saving agriculture. The mean of IWP between oasis region of northwest China and some developed countries or regions is still having a gap. Therefore, there is a potential for increasing the IWP in the Oasis region of northwest China.

It can be found from Table 2, the CV value of the independent variables except BD varies between 12% and 71%, and showing moderate degree of spatial heterogeneity at different scales. The CV values of BD were 6% and 7% on the PLID and MHRB, respectively, showing a weak heterogeneity in space. Thus, there were spatial differences in soil environmental factors and management measures. In addition, with the increase of sampling distance, the CV values of soil factors also increased in addition to SOM and Sand1 (soil sand content of 30-100 cm). Di Virgilio et al. studied spatial variability of switchgrass in 4.8 hm^2 fields (the sampling was about 90m), and reported that the CV values of SOM, TN, AP, Clay, Silt, Sand, SWC were 15%, 11%, 27%, 10.4%, 13.7%, 19.1%, 16%, respectively[43]. Therefore, we were found that the spatial differences in soil properties will increase with the increase of sampling distance. There is no clear trend between the spatial difference of management measures and the sampling distance. From the data of fertilization (Table 2), it can be seen that the amount of nitrogen fertilizer applied in the MHRB was far beyond the level of the annual nitrogen application of 46-200 kg/hm^2 in the cultivated land[44]. However, the content of TN was 0.85 g/kg in MHRB, indicating that the local soil nitrogen was at a medium level[45], and the aforementioned results indicate that there may be severe nitrogen leaching in the oasis region of northwest China.

Table 2 Descriptive statistics of irrigation water productivity and its driving factors

Variable	PLID scale				MHRB scale			
	Mean	Std.	CV	K-S	Mean	Std.	CV	K-S
IWP/kg·m^{-3}	1.48	0.60	40	0.25	1.67	0.64	39	0.59
SOM/g·kg^{-1}	13.58	4.08	30	0.83	14.83	3.21	22	0.82
TN/g·kg^{-1}	0.85	0.27	32	0.40	0.85	0.31	37	0.99
AN/mg·kg^{-1}	52.34	21.74	42	0.00	37.55	26.61	71	0.00
TP/g·kg^{-1}	0.72	0.11	15	0.79	0.52	0.11	22	0.99
AP/mg·kg^{-1}	27.77	15.82	57	0.85	15.25	7.78	51	0.43
BD/g·cm^{-3}	1.58	0.10	6	0.61	1.57	0.11	7	0.98
SWC/%	15.5	4.28	28	0.12	14.7	4.63	31	0.71
Clay0/%	12.4	2.15	17	0.03	10.3	2.29	22	0.83
Silt0/%	48.7	8.94	18	0.44	49.7	12.92	26	0.69
Sand0/%	38.9	10.85	28	0.28	40.0	14.82	37	0.47
Clay1/%	15.2	4.82	32	0.16	9.9	3.40	34	0.95
Silt1/%	53.6	14.22	27	0.00	48.9	15.36	31	0.26
Sand1/%	31.2	18.46	59	0.01	41.2	18.37	45	0.32
IW/10^3 m^3·hm^{-2}	7.25	1.00	14	0.39	7.33	1.30	18	0.01
NF/kg·hm^{-2}	601	263.51	44	0.48	470	63.17	13	0.12
PF/kg·hm^{-2}	86	38.63	45	0.09	108	28.36	26	0.09
TF/kg·hm^{-2}	724	253.97	35	0.54	612	74.31	12	0.04
PD/plant· m^{-1}	8.75	1.38	16	0.02	9.62	1.71	18	0.32

Note: PLID: The typical irrigation district, MHRB: Middle reaches of the Heihe River basin, Mean: The mean value, Std: Standard deviation, CV: Coefficient of variation, K-S: Asymp. Sig. (2-tailed), IWP: irrigation water productivity, SOM: Initial soil organic matter, TN: Initial total nitrogen, AN: Initial available nitrogen, TP: Initial total phosphorus, AP: Initial available phosphorus, BD: bulk density, SWC: soil water content, Clay0: Soil clay content of 0-30 cm, Silt0: soil silt content of 0-30 cm, Sand0: soil sand content of 0-30 cm, Clay1: Soil clay content of 30-100cm, Silt1: Soil silt content of 30-100 cm, Sand1: Soil sand content of 30-100 cm, IW: Irrigation water, NF: Amount of nitrogen fertilizer applied, PF: Amount of phosphorus fertilizer applied, TF: The total amount of fertilizer applied, PD: Planting density.

3.2 Reasonable sampling number analysis

In the analysis of soil spatial characteristics on a large scale, it is of great significance to determine the reasonable number of samples for improving work efficiency and reducing costs[46,47]. The analysis of reasonable sampling numbers was mainly based on the Cochran formula[48]. After more than 40 years of application and improvement, the calculation formula for the reasonable sampling number of random variables in the region was defined as follows[49,50]:

$$RSN = t^2 \cdot Cv^2 / \Delta^2 \tag{4}$$

where, RSN is the reasonable number of samples; t is the T-test threshold for a random variable at a certain level; Cv is the coefficient of variation (the ratio of the standard deviation to the mean); and Δ is the relative error allowed.

When the level of confidence is 95%, the reasonable sampling of the factors affecting the productivity of irrigation water in oasis farmland is shown in Table 3. The results show that the sampling number of all factors meets the requirements when the allowable error is 10%, so the sampling data in this paper can represent the actual situation of the oasis farmland.

Table 3 Reasonable sampling number of IWP and its influencing factors in Heihe Oasis farmland

Variable	PLID Scale (N=118)			MHRB Scale (N=80)		
	Δ=5%	Δ=10%	Δ=15%	Δ=5%	Δ=10%	Δ=15%
IWP	254	64	29	243	61	27
SOM	143	36	16	95	24	11
TN	163	41	19	241	61	27
AN	272	68	31	627	77	70
TP	37	10	5	82	21	10
AP	516	109	58	406	72	46
BD	6	2	1	7	2	1
SWC	122	31	14	162	41	18
Clay0	48	12	6	80	20	9
Silt0	54	14	6	103	26	14
Sand0	123	31	14	201	51	23
Clay1	161	41	19	213	54	24
Silt1	112	28	13	148	37	17
Sand1	349	108	61	335	74	38
IW	30	8	4	47	12	6
NF	305	77	34	35	9	4
PF	333	84	37	98	25	11
TF	196	49	22	27	7	3
PD	39	10	5	49	13	6

Note: PLID: The typical irrigation district, MHRB: Middle reaches of the Heihe River basin, Δ: the relative errors, IWP: irrigation water productivity, SOM: Initial soil organic matter, TN: Initial total nitrogen, AN: Initial available nitrogen, TP: Initial total phosphorus, AP: Initial available phosphorus, BD: bulk density, SWC: soil water content, Clay0: Soil clay content of 0-30 cm, Silt0: soil silt content of 0-30 cm, Sand0: soil sand content of 0-30 cm, Clay1: Soil clay content of 30-100 cm, Silt1: Soil silt content of 30-100 cm, Sand1: Soil sand content of 30-100 cm, IW: Irrigation water, NF: Amount of nitrogen fertilizer applied, PF: Amount of phosphorus fertilizer applied, TF: The total amount of fertilizer applied, PD: Planting density.

3.3 Colinearity analysis of driving factors of IWP

Although the selection of more independent variables can make the analysis more comprehensive, it also brings multiple collinearity problems. The 18 independent variables in this study can be classified into three categories: soil chemical properties, soil physical properties and crop management measures. There is a significant correlation between SOM and TN[51], clay and silt[52]. The common collinearity diagnostic criteria include conditional index (CI), tolerance (TOL) and variance inflation factor (VIF), in which TOL and VIF are reciprocal[53-55]. We used VIF to diagnose collinearity between independent variables. The small VIF values indicate low R^2, indicating that the collinearity between the independent variables is weak. In general, when the VIF value is less than 10, it is shown that the collinearity problem between the independent variables does not exist or can be neglected[56].

The collinearity diagnostic using VIF values of the factors affecting IWP are shown in Table 4. The VIF value of Sand0 (soil sand content of 0-30 cm) and Sand1 were far more than 10, and the VIF value of Clay1 (soil clay content of 30-100 cm) and Silt1 (soil silt content of 30-100 cm) in the MHRB were 10.8 and 11.9 respectively. On the scale of the MHRB, the VIF values of irrigation water (IW), amount of nitrogen fertilizer applied (NF), amount of phosphorus fertilizer applied (PF) and total amount of fertilizer applied (TF) were all more than 10, which were 14.3, 46.7, 25.4, 51.3, respectively. The results indicate that there was collinearity between the physical properties of the soil (sand, silt and clay), irrigation and fertilization (NF, PF and TF). Belsley[57] pointed out that when quantifying the dependent variable, the collinearity problem would mask the true relationship between variables, and making it difficult to distinguish the individual effects of each independent variable. Therefore, in the quantitative analysis of IWP, we adopted the PLS regression analysis method, which can solve the collinearity problem.

Table 4 Collinearity diagnosis independent variables (VIF)

Variable	PLID scale	MHRB scale
SOM/g·kg^{-1}	6.4	3.9
TN/g·kg^{-1}	6.6	4.1
AN/mg·kg^{-1}	1.4	1.5
TP/g·kg^{-1}	1.6	5.2
AP/mg·kg^{-1}	2.0	3.8
BD/g·cm^{-3}	1.7	2.2
SWC/%	1.8	2.0
Clay0/%	5.2	5.8
Silt0/%	6.6	7.6
Sand0/%	∞	∞
Clay1/%	3.9	10.8
Silt1/%	4.1	11.9
Sand1/%	∞	∞
IW/10^3 m^3·hm^{-2}	1.5	14.3
NF/kg·hm^{-2}	14.8	46.7
PF/kg·hm^{-2}	2.1	25.4
TF/kg·hm^{-2}	15.7	51.3
PD/plant·m^{-1}	1.2	1.8

Note: PLID: The typical irrigation district, MHRB: Middle reaches of the Heihe River basin, ∞: The value of VIF>10^6, IWP: irrigation water productivity, SOM: Initial soil organic matter, TN: Initial total nitrogen, AN: Initial available nitrogen, TP: Initial total phosphorus, AP: Initial available phosphorus, BD: bulk density, SWC: soil water content, Clay0: Soil clay content of 0-30 cm, Silt0: soil silt content of 0-30 cm, Sand0: soil sand content of 0-30 cm, Clay1: Soil clay content of 30-100 cm, Silt1: Soil silt content of 30-100 cm, Sand1: Soil sand content of 30-100 cm, IW: Irrigation water, NF: Amount of nitrogen fertilizer applied, PF: Amount of phosphorus fertilizer applied, TF: The total amount of fertilizer applied, PD: Planting density.

3.4 Analysis of driving factors of IWP

In this study, 18 independent variables were analyzed by PLS regression, and the importance of variable projection importance index (VIP value) was used to quantitatively analyze the influence factors of IWP (Figure 2). The main driving factors of IWP (VIP>0.8) in PLID are IW, NF, PD (planting density), TF and AN. At the scale of MHRB, the main driving factors of IWP are IW, PF, PD, Silt0 (soil silt content of 0-30 cm), Sand0 (soil sand content of 0-30 cm), AP, TN, SOM, Clay0 (soil clay content of 0-30 cm), NF and TP. The results showed that the IWP was mainly influenced by the management measures at PLID scale, and the IWP on the scale of MHRB was mainly influenced by management measures and soil factors, and the main reason was that the difference in spatial distribution of soil factors increases with the increase of sampling distance (Table 2)[43]. In addition, Li et al.[23] also pointed out that in irrigated agriculture, management measures were the main factors restricting the increase of IWP.

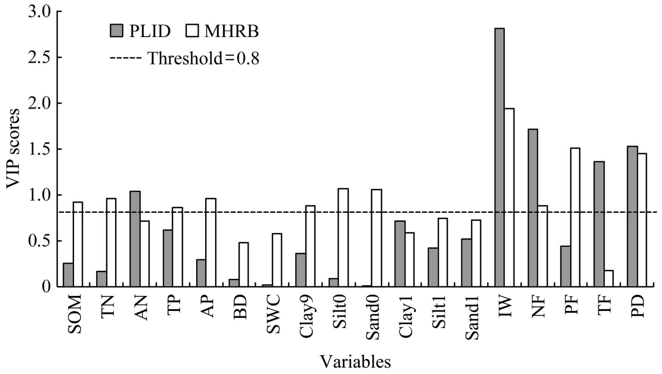


Figure 2 Variable projection importance of driving factors for irrigation water productivity

In most arid areas, water has replaced arable farmland as a key factor in restricting agricultural production[58]. It can be found from the VIP score chart of the driving factors of IWP (Figure 2) that the VIP score of IW was greater than other factors under different regions, which indicated that the contribution of IW to the IWP was much more than other factors in the arid oasis region of northwest China. In addition, the PD of maize also has a large VIP score at different scales, mainly because the PD has a significant positive correlation with the yield of maize, and the appropriate increase in PD has a significant effect on the increase of crop yield[59,60].

3.5 Contribution rate of driving factors of IWP

Under different sampling distance, the influence of the driving factors on IWP changed (Figure 2). Quantifying the contribution rate of each driving factor to IWP, analyzing its characteristics with the change of the sampling distance, and adjusting the input of soil and agronomic measures in agricultural production, can effectively improve the IWP and could ensure the food security in arid oasis region.

In China, irrigated farmland accounts for 49% of the total arable land, and produces 75% of the country's grain yield and more than 90% of the economic crop yield[61]. This study found that the contribution of IW to IWP was the largest in PLID and MHRB scales, 12.6% and 8.1% respectively (Figure 3), mainly because irrigation was the main factor to ensure grain production[4]. According to the results, the second largest contributor to IWP in PLID scale was NF (7.7%), while in the MHRB scale, the second largest contributor to IWP was PF (6.3%). The main reason was that the application of nitrogen and phosphate fertilizer can indirectly affect water use efficiency through the physiological regulation of crops[21]. In addition, the differences in the contribution rates of N and P fertilizers to IWP were mainly due to: 1) there were differences in the mean value of soil nitrogen and phosphorus content; and 2) the average amount of N on the scale of PLID was much higher than that of the MHRB, while the application of P was just the opposite. A study has shown that suitable PD can effectively improve the water productivity of maize[62,63]. As can be seen from Figure 3, the PD has the third-highest contribution to IWP at different sampling distance, and the contribution rate was 6.8% and 6% respectively. In summary, the main driving factors of IWP are irrigation, fertilization and planting density.

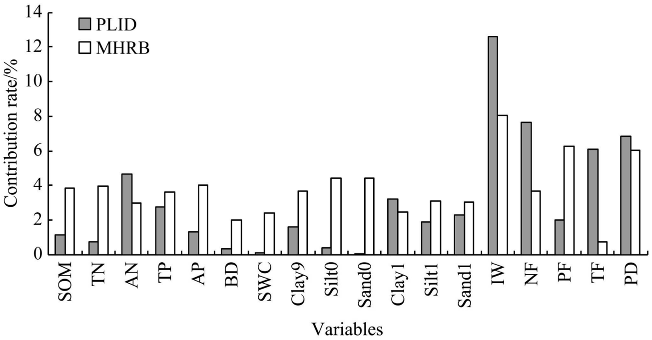


Figure 3 Contribution rate of driving factors of irrigation water productivity

Analysis of the contribution rate of soil factors and management measures to IWP, improving the growth environment of crops have a significant effect on promoting IWP[9,13,14]. In this study, the soil factors mainly include soil physics (soil texture, SWC, BD) and soil chemistry (SOM, soil nitrogen, and phosphorus content), and the management measures were IW, fertilization and PD. The contribution of different types of driving factors to IWP is shown in Figure 4. Other factors mainly refer to crop varieties, climatic conditions, and soil factors (soil heavy metal and trace element content, PH, conductivity, etc.) not covered in this paper, and agronomic practices (farming methods, cover conditions, pesticide application, etc.). The contribution rates of soil factors and management measures to IWP were 20.6% and 35.2%, respectively on the PLID scale, and the contribution of soil factors to IWP increased to 43.8% in the MHRB, while the contribution rate of management measures decreased to 24.8%. It shows that in a small irrigation districts, from the perspective of farmers, the improvement of IWP should be mainly controlled by management measures, while in the large area of watershed scale, the spatial differences in soil factors also need to be considered by the government management departments, when they want to increase IWP through regulating management measures.

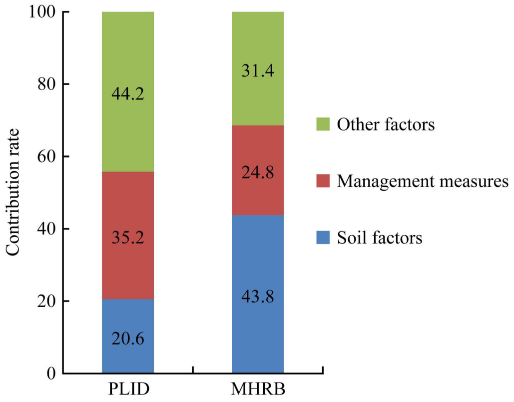


Figure 4 Contribution of different types of driving factors to irrigation water productivity

4 Conclusions

The average value of the IWP of maize in the middle reaches of Heihe River in northwestern China was 1.67 kg/m^3. The IWP has a moderate degree of heterogeneity (CV=40%) in the space, and has a larger space for improvement in the study areas. The amount of nitrogen fertilizer used in the study area was large. The collinearity diagnosis of the influencing factors of IWP showed that the soil factors and management measures will interact with each other and showed strong collinearity. The quantitative analysis of IWP through the PLS-VIP method showed that the contribution rates of soil factors and management measures to IWP were 20.6% and 35.2%, respectively on the PLID scale, and the contribution of soil factors to IWP increased to 43.8% in the MHRB scale, while the contribution rate of management measures decreased to 24.8%. Based on the results of PLID and MHRB scales, the main driving factors of IWP were irrigation, fertilization and planting density.

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