Improving grain yield and water use efficiency of winter wheat through a combination of manure and chemical nitrogen fertilizer on the Loess plateau, China

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Abstract

Developing an effective fertilization management practice is crucial for ensuring food security in dryland. A 3-year field experiment was conducted on the Loess plateau dryland, China, to investigate the effects of manure and nitrogen (N) fertilization on soil water regime, grain yield, and water use efficiency (WUE) of winter wheat (*Triticum aestivum*). The results showed that soil water content at winter wheat sowing was 13.4 mm (3.7%) higher with manure than without after 2 years of fertilization. Additional manure increased soil water recharge, grain yield, and WUE by a mean of 20.7%, 11.6% and 12.6%, respectively, relative to those without manure. Compared with applying manure alone, N fertilization improved soil water recharge, grain yield and WUE by a mean of 56.3%, 11.5%, and 7.0%, respectively. However, no further increases were observed when the N rate exceeded 75 or 150 kg N ha⁻¹, and combining 78 kg N ha⁻¹ fertilizer with manure is sufficient to get 95% of the theoretical highest yield. Therefore, combining manure (30 t ha⁻¹ poultry or pig manure) with 78–150 kg N ha⁻¹ chemical N fertilizer (manure-N : chemical-N = 1:0.47-0.91) is recommended for achieving the sustainable winter wheat farming system on the Loess plateau.

Keywords: Soil water regime, high-yield and water-efficient fertilization, dryland farming

1. Introduction

Wheat (*Triticum aestivum*) is a globally major food crop, whose production covers an area of 2.18×10^8 ha, accounting for more than 20% of the world's arable land. China is one of the largest wheat producing countries, with a total planting area of 2.43×10^7 ha, of which approximately 27%–29% is located in the Loess plateau dryland (Gao *et al.*, 2009). However, wheat production in this region are facing great challenge of a scant water supply and nutrient deficit. Due to the sparse and deep groundwater resources, rainfall is the sole water source for wheat production in the Loess Plateau, which is limited (200–600 mm) and unevenly distributed. Only 30%–40% of annual rainfall occurs during winter wheat growing season, whereas most of the rain falls between July and September, which is concurrent with the summer fallow between two growing seasons of winter wheat (Li *et al.*, 2015). Meanwhile, unreasonable cultivation practices, including excessive chemical fertilizer input and intensive soil cultivation result in soil with a fragile structure, low nutrients availability and water holding capacity (Wu *et al.*, 2004).

Within this context, organic materials input is gaining increasingly attention to sustain soil fertility and promote crop production in the Loess plateau. In 2011, China produced animal manure yielding up to 3 trillion tons, and it will be a huge waste if they are untreated or non-recycled (He *et al.*, 2016). Unlike the long-term application of chemical fertilizer which results in further soil degradation and a series of environmental problems (Ju *et al.*, 2009), animal manure amendment supplies both major and micro nutrients necessary for plant growth. And provides a better environment for root development by improving soil physical, chemical, and biological properties (Pan *et al.*, 2015; Schoebitz and Vidal, 2016), which, in turn, improves nutrient and water uptake by winter

wheat. (Foster *et al.*, 2016; Guo *et al.*, 2016; Ibrahim *et al.*, 2015; Shah *et al.*, 2016). More importantly, the ability of manure to improve mean weight diameter of the aggregates, total porosity, water field-saturated hydraulic conductivity, infiltration rate, and water holding capacity of soil conserves more rainfall in the soil profile, reduces evaporation through the soil surface, and improves use of the water available for crop growth (Bandyopadhyay, *et al.*, 2010; Yang *et al.*, 2015). However, using manure alone is insufficient to maintain the present production levels of high yielding varieties of winter wheat (Efthimiadu *et al.*, 2010), as most of the N in manure is in an organic form, and a long time is needed for mineralization before it is available for plant uptake (Li and Li, 2014). Therefore, an integrated nutrient management, in which both manure and chemical N fertilizer are used simultaneously, may be a more compatible approach in dryland.

Although emerging evidence indicates that integrated use of manure and chemical N fertilizer is a feasible approach to improve winter wheat production and water use efficiency (WUE) in the Loess Plateau (Fan *et al.*, 2005a; Fan *et al.*, 2005b; Liu *et al.*, 2013), the problem of blind fertilization still remains in most areas of the Loess Plateau. As there is a lack of systematic and comprehensive observations of the optimal fertilization ratio for manure-N and chemical-N to achieve a high-yielding, water use efficiency and sustainable winter wheat cropping system. In the present study, we used a three-year long spilt-plot design, stationary field experiment in the Loess plateau, to determine; (1) the responses of soil water content, grain yield and WUE of winter wheat to the combination of manure and different N application rates. And (2) determine the recommended combined ratio of manure-N and chemical-N for sustainable winter wheat production systems under dryland condition.

2. Materials and Methods

2.1. Site description

A 3-year stationary winter wheat monoculture experiment was conducted from October 2011 to June 2014 in Bai Shui (109°58'N 35°18'E, 850 m asl) Shaanxi Province, China. Bai Shui county is located in the

north of the Loess plateau and has a temperate continental monsoon climate, with mean annual temperature of 11.4 °C and annual precipitation of 577.8 mm. Agricultural production in this area is completely dependent on natural precipitation. Data of monthly rainfall during the experimental years was obtained from the Bai Shui county Meteorological Station (Figure 1).

Figure 1. Monthly and yearly precipitation at the experimental site over the 3 year experiment

The experimental field had been used for winter wheat production for a long time prior to this experiment. The soil at the experimental site is classified as Calcic Cambisols (FAO taxonomy), with mean bulk density of $\sim 1.30 \text{ g cm}^{-3}$ in 0–200 cm soil layer. The background soil sample collected from 0–20 cm layer at the experimental site had 12.4 g kg^{-1} organic matter, 0.8 g kg^{-1} total N, 9.2 mg kg^{-1} Olsen-P, 177.2 mg kg^{-1} available K, 76.55% sand concentration, 19.60% silt concentration, and 3.85% clay concentration. All the basic soil properties were measured with the methods described by Bao (2000).

2.2. Experimental design

The experiment was carried out with two treatment factors: (1) with and without manure, and (2) five N

application rates of 0, 75, 150, 225, and 300 kg N ha^{-1} . The 10 treatments were arranged in a split-plot design with four replications each; the five N fertilizer application rates were in the main plot, and manure treatments (with and without manure) were subplots. Plot size was 6-m wide and 10-m long, and all treatments were arranged randomly.

A widely used local winter wheat cultivar called ‘Jinmai-47’ was used as the test crop, and was sown on 12, 15 and 17 October in 2011, 2012, and 2013, respectively by a seeding machine, at a rate of 150 kg ha^{-1} , with 20 cm wide rows and a sowing depth of 5 cm. On the same day right before winter wheat seeding, fertilizer was applied to the field. The manure areas were fertilized with a combination of manure and the five different application rates of N fertilizer.

The areas without manure were only fertilized with chemical N fertilizer, at the application rate of 0, 75, 150, 225 and 300 kg N ha⁻¹ in each plot, respectively. In addition, 90 kg P₂O₅ ha⁻¹ and 60 kg K₂O ha⁻¹ were applied to all plots. The manure was applied as pig manure. Well-composted pig manure were collected from hogger, and spread by a shovel at 30 Mg ha⁻¹ on fresh weight basis (the water and nutrient contents of the manures applied in the study are shown in Table 1).

The N fertilizer was applied as urea (N: 46%), 70% of which was applied at sowing, and 30% was applied at the elongation stage of winter wheat (early April). The phosphorus (P) fertilizer was superphosphate (P₂O₅: 16%), and the potassium (K) fertilizer was a sulfate of potash (K₂O: 50%). All fertilizers were applied evenly and incorporated into the top 0–20 cm soil layer before seeding.

Table 1. Water and nutrients contents of manures applied during the experimental years.

Year	Water content (%)	pH	Organic C (g kg ⁻¹)	N content (g kg ⁻¹)	P content (g kg ⁻¹)	K content (g kg ⁻¹)	C:N ratio
2011-2012	22.6	7.6	107.9	7.0	10.5	12.6	15:1
2012-2013	23.1	7.6	103.8	7.5	11.1	11.8	13:1
2013-2014	23.3	7.5	104.4	6.9	10.2	12.9	14:1

The wheat was harvested in early June of the following year. All plots were tilled twice, one week after harvest and two weeks before sowing. No supplemental irrigation was provided. Herbicide was used in the blooming stage (early May) of winter wheat every year to control weeds.

2.3. Sampling and sample analysis

2.3.1. Soil sampling

Before the experiment, soil from 7 random cores at a depth of 0–200 cm layer was collected using an auger (inner diameter, 4.0 cm) at an interval of 20 cm, and the soil from the same layer was mixed as a soil sample for background soil moisture determination. Besides, soil collected from 0–20 cm soil was used for determining the background soil properties. During the experiment, every year at the sowing and harvest time of winter wheat, three soil core samples

at depths of 0–200 cm in each plot were also collected randomly to determine the soil water content. The soil in each 20 cm layer over the 0–200 cm depth was separated, and soil from the same layer was mixed and sealed immediately in plastic bags. The fresh soil samples were brought to the laboratory and dried in an oven at 105 °C for 12 hours. The soil bulk density at the depth of 0–200 cm was measured every year before seeding using the cutting ring method (Bao, 2000).

2.3.2. Plant sampling

The winter wheat was harvested manually at maturity from each plot in early June of all study years. An area of 12 m² gathered from three randomly collected quadrats was harvested from every single plot. These wheat samples were dried at 95 °C for 0.5 h and at 65 °C for 24 h until a constant weight

was achieved. Grain yield was determined by weighing the dried grain after manual threshing.

2.4. Calculation methods and data analysis

Soil water storage (mm) was calculated as:

$$W = \sum_i^n \rho_i \times w_i \times h_i \times 10/100$$

Where ρ_i (g cm^{-3}) is soil bulk density; w_i (%) is soil gravimetric water content; h_i (cm) is soil layer depth; i is the number of soil layer; $i=20, 40, 60, 80 \dots 200$ cm.

Soil water depletion (SWD , mm) during the growing season was calculated as the difference in soil water storage in the 0–200 cm layer from winter wheat sowing to harvest. Soil water recharge (SWR , mm) during the fallow season was calculated as the difference in soil water storage from the beginning to the end of the fallow period at depth of 0–200 cm.

Evapotranspiration (ET , mm) during growing season of winter wheat was determined by:

$$ET = SWD + PG - I - D - Wg - R$$

Where SWD (mm) is the soil water depletion, PG (mm) the amount of precipitation (mm) during growing season of winter wheat, I the amount of irrigation (mm), D the soil water drainage (mm), Wg the water use by crop through capillary rise from underground water (mm), and R the surface

runoff. The I and R should be ignored since there is no irrigation and runoff in the flat study field. Besides, the D and Wg are considered negligible because the extreme high rainfall is infrequent in the region, and the underground water in the Loess Plateau is usually too low to use by the crop. Therefore, the I , D , Wg and R are not considered in the present study.

The water use efficiency (WUE , $\text{kg ha}^{-1}\text{mm}^{-1}$) was calculated as:

$$WUE = Y/ET$$

Where Y (kg ha^{-1}) is the grain yield, and ET (mm) is the evapotranspiration of winter wheat.

Analysis of variance (ANOVA) was conducted to detect differences using SPSS 19.0 for Windows (SPSS Inc., Chicago, IL, USA). A two-way ANOVA was performed to test the manure, the N application rates, and their interactive effects on all data for each experimental year (Table 2). In addition, a one-way ANOVA was used to test for differences between N application rates in the groups with and without manure. Comparisons of means between the groups with and without manure, and the different N application rates were performed using Duncan's test. Parabolic regression was used to fit the data between N rate and grain yield of winter wheat. A correlation coefficient, r , analysis was also performed. All p -values < 0.05 were considered significant.

Table 2. Analysis of variance of the effects of nitrogen (N) fertilizer rate, manure and their interactions with soil water storage (SWS) at winter wheat sowing and harvest, soil water depletion (SWD) during growing season, soil water recharge (SWR) during fallow season, evapotranspiration (ET), grain yield, and water use efficiency (WUE) of winter wheat (P-values).

Year	Sources	SWS (sowing)	SWS (harvest)	SWD	SWR	ET	Grain yield	WUE
2011-2012	N rate (N)	-	0.002	0.002	-	0.002	<0.001	0.006
	Manure (M)	-	0.047	0.047	-	0.047	<0.001	ns
	N×M	-	ns	ns	-	ns	ns	ns
2012-2013	N rate (N)	ns	0.024	0.034	0.042	0.034	0.042	0.023
	Manure (M)	ns	ns	ns	0.036	ns	<0.001	<0.001
	N×M	ns	ns	ns	ns	ns	ns	ns
2013-2014	N rate (N)	ns	ns	0.006	0.033	0.006	<0.001	0.025
	Manure (M)	0.005	ns	ns	0.018	ns	<0.001	<0.001
	N×M	ns	ns	ns	ns	ns	ns	ns

ns, no significant difference at the 5% level. SWD, difference in soil water storage in the 0–200 cm layer from winter wheat sowing to harvest; SWR, difference between soil water storage in the 0–200 cm layer from the beginning to the end of summer fallow season.

3. Results

3.1. Soil water storage in the 0–200 cm soil layer

Adding manure increased soil water storage by 3.7% compared with the treatment without manure at the sowing time during the 2013-2014 season ($P<0.05$, Table 3). No differences were noted in soil water storage between N application rates at winter wheat sowing throughout the experimental years. After winter wheat harvest, manure amendment decreased ($P<0.05$) soil water by a mean of 8.4% compared with no manure during 2011–2012, but this decrease did not continue during the next two years. Relative to applying manure alone, additional chemical N input of 75, 150, and 225 kg N ha⁻¹ decreased ($P<0.05$) soil water storage by 15.6%, 16.7%, and 18.2%, respectively in 2011–2012, and the input of 225 kg N ha⁻¹ chemical N decreased soil water storage by 6.7% in 2012–2013 after winter wheat harvest. Manure and N

rate had no significant effect on soil water storage after harvest in 2013–2014, probably due to the higher rainfall during the growing season of that year.

3.2. Soil water depletion and recharge

According to Table 4, although the average soil water depletion was greater (6.3%) for manure treatments than that for no manure treatments during the winter wheat growing season in 2011–2012 ($P<0.05$), no differences were observed between the manure and no-manure groups in the next two years. Compared with applying manure alone, chemical N input levels from 75 to 225 kg N ha⁻¹, 150 to 225 kg N ha⁻¹, and 150 to 300 kg N ha⁻¹ increased soil water depletion by 12.6%–14.7%, 55.9%–56.2% and 10.1%–18.2% during the winter wheat growing season in 2011-2012, 2012-2013 and 2013-2014, respectively ($P<0.05$).

Table 3. Soil water storage (mm) in the 0–200 cm layer at sowing and harvest during the 3-year experiment.

N rate (kg N ha ⁻¹)		Sowing									Harvest					
		2012-2013			2013-2014			2011-2012			2012-2013			2013-2014		
		-M	+M	Average	-M	+M	Average	-M	+M	Average	-M	+M	Average	-M	+M	Average
0	553.9	331.0a	312.8a	321.9A	356.2a	364.1a	360.2A	271.0a	247.9a	259.5A	275.5a	254.1a	264.8A	264.9a	262.7a	263.8A
75	553.9	331.7a	319.6a	325.7A	362.2a	375.7a	344.0A	236.0ab	209.2b	222.6AB	265.9ab	244.1a	255.0AB	250.7a	266.4a	258.6A
150	553.9	326.8a	333.4a	330.1A	368.4a	374.5a	376.5A	224.7ab	206.4b	215.6B	258.2b	241.9a	250.1AB	265.2a	262.9a	264.1A
225	553.9	328.7a	328.8a	328.8A	372.1a	385.8a	389.0A	207.5b	202.9b	205.2B	250.7b	237.1b	243.9B	263.1a	265.9a	264.5A
300	553.9	322.7a	325.8a	324.3A	356.5a	382.3a	365.9A	240.0ab	213.1ab	226.6AB	240.4c	253.2a	246.8B	252.8a	265.7a	259.3A
Average	553.9	328.2A	324.1A		363.1B	376.5A		235.8A	215.9B		258.1A	246.1A		259.3A	264.7A	

Different lowercase (one-way ANOVA) and uppercase (two-way ANOVA) letters denote significant differences between treatments at the 5% level. -M, treatments without manure; +M, treatments with manure.

Table 4. Soil water depletion (mm) in the 0–200 cm layer during the winter wheat growing season.

N rate (kg N ha ⁻¹)	2011-2012			2012-2013			2013-2014		
	-M	+M	Average	-M	+M	Average	-M	+M	Average
0	282.9b	306.0b	294.5B	55.5b	58.7b	57.1B	91.3b	101.4b	96.4B
75	317.9ab	344.7a	331.3AB	65.8ab	75.5ab	70.7AB	111.5a	109.3ab	110.4AB
150	329.2ab	347.5a	338.4A	68.6ab	91.5a	80.1A	103.2ab	111.6a	107.4AB
225	346.4a	351.0a	348.7A	78.0ab	91.7a	84.9A	109.0ab	119.9a	114.5A
300	313.9ab	340.8ab	327.4B	82.3a	72.6ab	77.5AB	103.7ab	116.6a	110.2AB
Average	318.1B	338.0A		70.0A	78.0A		103.7A	111.8A	

Different lowercase (one-way ANOVA) and uppercase (two-way ANOVA) letters denote significant differences between treatments at the 5% level. -M, treatments without manure; +M, treatments with manure. Soil water depletion was calculated as the difference in soil water storage in the 0–200 cm layer from winter wheat sowing to harvest.

Since the field experiment was initiated in October 2011, values of rainfall harvest during summer fallow were only observed in the 2012-2013 and 2013-2014 season (Table 5). Mean soil water recharge in the manure group increased by 17.2% during the summer fallow period in 2012–2013 and by 24.2% in 2013–2014 compared to that in the no-manure

treatment ($P < 0.05$). Chemical N fertilization tended to improve soil water storage during the fallow season as well. Compared with applying manure alone, soil water recharge increased with N rate from 150 to 225 kg N ha⁻¹ by 94.0%–95.7% in 2012–2013 and from 150 to 300 kg N ha⁻¹ by 19.6%–35.2% in 2013–2014 ($P < 0.05$).

Table 5. Soil water recharge (mm) in the 0–200 cm layer during the fallow periods in 2012–2013 and 2013–2014.

N rate (kg N ha ⁻¹)	2012-2013			2013-2014		
	-M	+M	Average	-M	+M	Average
0	60.0c	64.9b	62.5B	80.7b	110.0b	95.4B
75	95.7b	110.4a b	103.1AB	96.3ab	131.6a	114.0AB
150	102.1a b	127.0a	114.6A	110.2a	132.6a	121.4A
225	121.2a	125.9a	123.6A	121.4a	148.7a	135.1A
300	82.7bc	112.7a b	97.7AB	116.1a	129.1ab	122.6A
Average	92.3B	108.2A		105.0B	130.4A	

Different lowercase (one-way ANOVA) and uppercase (two-way ANOVA) letters denote significant differences between treatments at the 5% level. -M, treatments without manure; +M, treatments with manure. Soil water recharge was calculated as the difference between soil water storage at the previous year's winter wheat harvest and soil water storage at wheat sowing in the 0–200 cm layer.

3.3. ET, grain yield, and WUE of winter wheat

In comparison with the no-manure group, manure group only improved ET significantly during 2011–

2012, whereas chemical N fertilization, at the input level of 150 or/and 225 kg N ha⁻¹ improved ET significantly throughout the experimental years (P<0.05, Table 6)

Table 6. Evapotranspiration (ET), grain yield, and water use efficiency (WUE) of winter wheat during the 3-year experiment.

Year	N rate (kg N ha ⁻¹)	ET (mm)			Grain yield (kg ha ⁻¹)			WUE (kg ha ⁻¹ mm ⁻¹)		
		-M	+M	Average	-M	+M	Average	-M	+M	Average
2011-2012	0	497.9b	521.0b	509.5B	5156c	5456c	5306C	10.4b	10.5b	10.4B
	75	532.9ab	559.7a	546.3AB	5722b	6004b	5863B	10.7b	10.7b	10.7B
	150	544.2ab	562.5a	553.4A	6300a	6525a	6413A	11.6a	11.6a	11.6A
	225	561.4a	566.0a	563.7A	6267a	6445a	6356A	11.2a	11.4a	11.3A
	300	528.9ab	555.8a	542.4AB	5656b	5750b	5703B	10.7b	10.3b	10.5B
Average		533.1B	553.0A		5820B	6016A		10.9A	10.9A	
2012-2013	0	217.5b	220.7b	219.1B	1906b	2414a	2160B	8.8b	10.0b	9.9B
	75	227.8ab	237.5ab	232.7AB	2147a	2684a	2416A	9.4b	11.3a	10.4AB
	150	230.6ab	253.5a	242.1A	2204a	2760a	2482A	9.6a	10.9ab	10.2AB
	225	240.0a	253.7a	246.9A	2432a	2854a	2643A	10.1a	11.2a	10.7A
	300	244.3a	234.6ab	239.5AB	2389a	2595a	2492A	9.8a	11.1ab	10.4AB
Average		232.0A	240.0A		2216B	2661A		9.5B	11.1A	
2013-2014	0	371.3b	381.4b	376.4B	3705c	4345b	4025B	10.0b	11.4b	10.7B
	75	391.5a	389.3ab	390.4AB	4064bc	4510ab	4287AB	10.4b	11.6b	11.1B
	150	383.2ab	391.6a	387.4AB	4359ab	4895a	4677A	11.4a	12.5a	12.1A
	225	389.0ab	399.9a	394.5A	4520a	4979a	4750A	11.6a	12.5a	12.0A
	300	383.7ab	396.6a	390.2AB	4192bc	4464ab	4328AB	10.9ab	11.3b	11.0B
Average		383.7A	391.8A		4168B	4639A		10.9B	11.8A	

Different lowercase (one-way ANOVA) and uppercase (two-way ANOVA) letters denote significant differences between treatments at the 5% level. -M, treatments without manure; +M, treatments with manure.

The grain yield of winter wheat improved by 3.3%, 20.1% and 3.3% by manure addition relative to no-manure treatments (Table 6). Compared with applying manure alone, additional chemical N fertilizer input improved grain yield by 10%, 19.6%, 18.1%, 5.4% at the rate of 75, 150, 225, and 300 kg N ha⁻¹, respectively in 2011-2012, and by 12.7% and 18.0% at the N rate of 150 and 225 kg N ha⁻¹, respectively in 2013-2014 ($P < 0.05$). But it should be noticed that once N rate was > 150 kg N ha⁻¹, increasing the N fertilizer rate did not further increase grain yield in most cases. No differences were observed between N application rates of 75–300 kg N ha⁻¹ because of severe water deficit during the growing season in 2012–2013. Manure amendment had no significant effect on WUE in 2011–2012, but improved WUE by means of 16.8% and 8.3% compared to that in the no-manure group in 2012–2013 and 2013–2014, respectively ($P < 0.05$). The highest WUE was observed when manure was combined with 150 kg N ha⁻¹ N fertilizer, which was 11.5% and 25.0% higher than that in no-fertilized

treatment, respectively in 2011-2012 and 2013-2014. In 2012-2013, the combination of manure with 75 kg N ha⁻¹ N fertilizer produced the highest WUE, which was 28.4% higher than that in no-fertilized treatment.

3.4. The correlation between N rate and grain yield of winter wheat

The grain yield of winter wheat varied as a polynomial function with N rate under manure conditions (Table 7). To determine the optimal combined ratio of chemical-N and manure-N, we calculated the N rates corresponding to 95% of the maximum yield values under manure condition, from the perspective of producing more crop yield with less fertilizer input. The 95% highest grain yield was 4534 kg ha⁻¹, corresponding to N rate of 78 kg N ha⁻¹ on average throughout the experimental years, indicating the combination of manure with 78 kg N ha⁻¹ (manure-N : fertilizer-N = 1: 0.47) was the most efficient way to achieve high yields in dryland winter wheat cropping system.

Table 7. Optimal N rates and corresponding highest grain yields.

Year	Correlation between N rates and grain yield			The 95% highest grain yield (kg ha ⁻¹)	The corresponding N rate (kg N ha ⁻¹)
	Regression equation	R ²	P value (n=20)		
2011-2012	$y = -0.039x^2 + 13.13x + 5389$	0.77	<0.001	6169	78
2012-2013	$y = -0.022x^2 + 8.01x + 2206$	0.60	0.004	2788	91
2013-2014	$y = -0.021x^2 + 7.27x + 4260$	0.78	<0.001	4644	66
average	-	-	-	4534	78

-M, treatments without manure; +M, treatments with manure.

4. Discussion

4.1. Manure effect on soil water variations, grain yield and WUE of winter wheat

A previous study showed that a wheat crop requires about 480 mm of water for maximum yield in the Loess Plateau (Wang *et al.*, 1994), but mean precipitation during the winter wheat growing season is only about 205 mm (Jin *et al.*, 2007). This water deficit is supplied from stored soil water before winter wheat sowing. In the present study, manure amendment promoted soil water content significantly at the sowing time during 2013–2014 after two years of consecutive cultivation (Table 3). Similar results were also reported in a pea-spring wheat-potato cropping system conducted in southeastern part of the Loess Plateau (Liu *et al.*, 2013). Increasing soil water recharge during fallow season is a crucial approach to increase soil water storage at sowing. In the present study, manure amendment improved soil water recharge by a mean of 20.7% during the fallow season throughout the experimental years, indicating more rainfall was harvested and captured in manured soil, relative to fertilized soil (Table 5). The increased rainfall harvest in manured soil was mainly due to three reasons. Firstly, the root branching and deeper rooting stimulated by manure addition left more soil to store rainfall. Secondly, manure addition enhances soil properties and then soil water transmission by improving water infiltration, saturated hydraulic conductivity, and soil water sorptivity (Khan *et al.*, 2010). Thirdly, manured soil has higher resistance to water and winter erosion, thus reducing the water loss from soil erosion during rainy seasons. However, some studies reported a significant decrease of soil water content before winter wheat planting due to manure addition, since adding manure results in more soil water consumption during growing season of winter wheat, such that replenishment during

the fallow period is insufficient to bring the soil water content back to its initial level (Huang *et al.*, 2003; Wang *et al.*, 2011). This phenomenon primarily due to the limited rainfall under dryland condition could not meet the water requirement of high-yielding varieties they used in the experiment.

As a result, treatments with manure produced significantly higher grain yield, and WUE than those that were not fertilized during the study. Interestingly, the increase in ET in the manure group was small (mean, 2.8%) during 2012–2013 and 2013–2014, whereas the increase in grain yield was large (mean, 16%), compared with that in the no-manure group (Table 6), indicating the water consumption through transpiration (T) was promoted whereas the water loss through soil evaporation (E) was inhibited after manure application. This is consistent with the prior studies by Wang *et al.* (2011) and Qi *et al.* (2009) in a winter wheat monoculture system on the Loess plateau. Manure amendment increases crop leaf area and dry matter accumulation, then effectively promotes transpiration (Rehman *et al.*, 2010), whereas the enlarged leaf area and canopies are effective barriers to prevent the direct effects of radiation and strong wind; thus, reducing water loss through evaporation.

4.2. N fertilization effect on soil water variations, grain yield and WUE of winter wheat

Manure tends to recouple C and N cycles and tip soil N mineralization-immobilization turnover (Zhou *et al.*, 2016), and chemical N fertilizer also affects decomposition rate of manure by regulating soil C/N ratio when combined with manure (Duan *et al.*, 2014), which alters the nutrients supply, then affects soil water uptake pattern and production of crop. In the present study, N fertilization caused significant decrease in soil water content after winter wheat harvest, especially at the N rate of 225 kg N ha⁻¹ under manure

condition (Table 3). Similarly, water deficit due to increased fertilization was also reported in semi-arid regions of the central U.S. Great Plain and the Loess Plateau (Nielsen and Halvorson, 1991; Huang *et al.*, 2003). This probably due to the larger aboveground biomass and transpirational leaf area stimulated by increased fertilizer, results in more water consumption from crop canopy during growing season (Angus and Van Herwaarden, 2001). However, Soil water recharge was improved significantly during summer fallow due to N fertilization, which was consistent with the results reported by Wang *et al.* (2012). N fertilization improved soil water recharge, either by absorbing more water during the growing season and leaving more soil reservoir to harvest rainfall during the summer fallow or by increasing the soil water holding capacity, since N fertilization increased root growth and biomass, thereby improving the soil organic matter content, which promotes soil water holding capacity (Deeb *et al.*, 2016).

No significant differences in soil water recharge were noted between 75 or 150 to 300 kg N ha⁻¹, indicating that 75 or 150 kg N ha⁻¹ was effective as 300 kg N ha⁻¹ in enhancing soil water recharge. Similarly, additional N fertilization also improved grain yield and WUE of winter wheat significantly compared with adding manure alone, but there was no further increase in grain yield or WUE when chemical N input > 150 kg N ha⁻¹ in most cases under manure condition.

Probably because the combined application of manure with 150 kg N ha⁻¹ results in a most efficient C:N for the release of soil bio-immobilized N, and enhances the synchrony between N supply with crop demand for N during the growing season, while too much N content in soil solution reduces root activity thus limiting nutrient uptake by crop.

5. Conclusion

With the population continuously increasing, the major challenge for dryland crop production is to increase crop yields with less water. The results from this 3-year study suggests manure should be involved in the fertilizer management practices, particularly under dryland condition, as a similar amount of water was consumed during winter wheat growing season, but more water was recharged during fallow season, which resulted in an improved grain yield and WUE. Comparing with applying manure alone, additional chemical N fertilizer input increased soil water recharge, ET, grain yield and WUE as well, but no further increases were observed when N rate exceeded 75 or 150 kg N ha⁻¹ in most cases. The grain yield of winter wheat varied as a polynomial function with N rate under manure conditions, according to the regression equation, a mean of 78 kg N ha⁻¹ is needed to achieve the 95% of highest grain yield with the presence of manure. Overall, we recommend that 78–150 kg N ha⁻¹ chemical fertilizer should be combined with 30 t ha⁻¹ pig manure (manure-N : fertilizer-N = 1:0.47–0.91) to achieve a sustainable winter wheat monoculture system in the Loess Plateau.

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