Soil water cycle and crop water use efficiency after long-term nitrogen fertilization in Loess Plateau

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ABSTRACT

The objective of this study was to investigate the effect of nitrogen (N) management on soil water recharge, available soil water at sowing (ASWS), soil water depletion, and wheat (*Triticum aestivum* L.) yield and water use efficiency (WUE) after long-term fertilization. We collected data from 2 experiments in 2 growing seasons. Treatments varied from no fertilization (CK), single N or phosphorus (P), N and P (NP), to NP plus manure (NPM). Comparing to CK and single N or P treatments, NP and NPM reduced rainfall infiltration depth by 20–60 cm, increased water recharge by 16–21 mm, and decreased ASWS by 89–133 mm in 0–300 cm profile. However, crop yield and WUE continuously increased in NP and NPM treatments after 22 years of fertilization. Yield ranged from 3458 to 3782 kg/ha in NP or NPM but was 1246–1531 kg/ha in CK and single N or P. WUE in CK and single N or P treatments was < 6 kg/ha/mm but increased to 12.1 kg/ha/mm in a NP treatment. The NP and NPM fertilization provided benefits for increased yield and WUE but resulted in lower ASWS. Increasing ASWS may be important for sustainable yield after long-term fertilization.

Keywords: available soil water; soil water depletion; soil water recharge; wheat; *Triticum aestivum* L.

Crop production in semi-arid areas is determined by soil water storage and growing season rainfall (Li 2001, Xue et al. 2003). The Loess Plateau of China is a large semi-arid area with annual rainfall ranging from 300 to 600 mm. The rainfall distributes unevenly and mainly occurs from July to September (up to 60% of total) (Kang et al. 2002). In the south part of the area, wheat is a major crop and normally grown under dryland conditions. A common cropping system in the area is continuous wheat, in which wheat is harvested in June and planted in late September or early October after a short fallow period. Since rainfall during growing season varies from year to year, the soil water storage at sowing is important and can account for 35.4% of crop water use (Li 2001, Wang et al. 2011). Due to the historic low soil fertility in Loess Plateau, fertilization has played an important role to increase wheat yield in last 2–3 decades. Wheat yield increased from 1696 kg/ha in the middle of 1980s to 2876 kg/ha in the middle of 1990s because of fertilizer ap-

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plications (Huang et al. 2003). However, years of increasing fertilization have caused depletion of soil water in 200–300 cm profiles in cropland (Li 2001). The soil water cycle in croplands not only affects crop growth and production but also is a key step in the regional terrain water cycle (Huang et al. 2003). There is an increasing concern about the effect of current fertilization practices on sustainable wheat production and water use efficiency (WUE) in the area (Li 2001, Huang et al. 2003, Liu et al. 2010). Currently, there are only few reports on soil water cycle and its effect on crop yield and WUE in wheat after long-term fertilization. Wang et al. (2011) analyzed soil water cycle in 0–200 cm profile and crop water use based on 4-year field data. Liu et al. (2010) showed that the depth of soil water infiltration was deeper than 200 cm in a year with higher rainfall. The objective of this study was to investigate the effect of nitrogen (N) management on soil water recharge, available soil water at sowing (ASWS), soil water depletion, and crop yield and water use efficiency (WUE) after long-term fertilization. In particular, we analyzed soil water dynamics in 0–600 cm profile and crop water use in 0–300 cm among N treatments.

MATERIAL AND METHODS

Field study was conducted in a long-term fertilization experimental site at the Changwu Agro-ecological Station from 2005 to 2007. The site (107°44.703'E, 35°12.787'N, 1220 m a.s.l.) was established in September 1984. The climate is semi-arid with annual mean temperature of 9.1°C and total rainfall of 584 mm. The average rainfall (1985–1999) in wheat growing season and fallow period was 283.0 and 246.2 mm, respectively. The growing season rainfall in 2005–2006 and 2006–2007 was 188.5 and 162.6 mm, respectively. During fallow season (Jun–Sep), rainfall was 400.7 mm in 2005 and 312.4 mm in 2006. Soils belong to the loess series (silt clay loam). The mean values of wilting point, field capacity, and soil bulk density in the 0–300 cm profile were 9% by weight, 22.4% by weight, and 1.3 kg/m^3, respectively. The soil chemical and physical properties have been shown in previous studies (Kang et al. 2002, Huang et al. 2003).

There were 2 experiments in this study. In experiment I, there were 4 treatments: (1) no any fertilization (CK); (2) N-only (120 kg N/ha, SN); (3) N and phosphorus (P) (120 kg N/ha and 26.2 kg P/ha, NP); (4) N, P and organic manure (120 kg N/ha N, 26.2 kg P/ha and 75 t/ha of manure, NPM). In experiment II, there were 3 N rates (0, 90 and 180 kg/ha) with the same level of P (39.3 kg P/ha). Experiments were designed as a randomized completely block design with 3 replications. The plot size was 66.7 m^2 in experiment I and 22 m^2 in experiment II. All fertilizer applications were made before sowing. Wheat (cv. Changwu 134) was grown under conventional tillage system, and was sowed in later September and harvested in late June of next year.

Soil water content (SWC, either in g/g or in %) was measured by a neutron moisture probe at 10 cm interval for the 0–100 cm and 20 cm interval for 100–600 cm before sowing and after harvesting. The amount of soil water (SW, mm) in 0–300 cm profile was calculated as:

$$SW = 10 \times h \times a \times \theta \quad (1)$$

Where: h – soil depth (cm); a – soil bulk density (g/cm^3); and θ – gravimetric SWC (g/g).

Available soil water at sowing (ASWS, mm), soil water depletion (ΔS, mm), and soil water recharge (ΔSW, mm) in the 0–300 cm profile were calculated as:

$$ASWS = SW(s) - SW(w) \quad (2)$$

$$\Delta S = SW(s) - SW(h) \quad (3)$$

$$\Delta SW = SW(s) - SW(h_0) \quad (4)$$

Where: SW – soil water (mm); s, h, h_0 and w – SW at sowing, harvesting, previous harvesting, and wilting point, respectively.

Crop water use (WU, mm) in the 0–300 cm profile was calculated as:

$$WU = \Delta S + P + S_g - D - R_f \quad (5)$$

Where: ΔS – soil water depletion from sowing to harvesting; P – precipitation during growing season; S_g – capillary rise from the lower soil layer to the root zone; D – drainage; R_f – surface runoff. Since the groundwater table was about 60 m deep from soil surface, upward flow into root zone (S_g) and drainage out of root zone (D) were negligible (Wang et al. 2011). Surface runoff (R_f) was zero because the field plots were flat and runoff was prevented by border dikes.

Crop yield (Y, kg/ha) was determined by harvesting 8 rows of samples, and water use efficiency (WUE, kg/ha/mm) was calculated as:

$$WUE = Y/WU \quad (6)$$

Significance among treatments was determined by the ANOVA and means were separated by *LSD* using the SPSS software (version 13.0, Chicago, USA).

RESULTS AND DISCUSSION

In experiment I, SWC in NP and NPM reduced as compared to CK or SN in 0–600 cm profile. The SWC in NPM was lower than that in NP in the 0–200 cm profile, indicating that manure increased water depletion (Figures 1a,b). In experiment II, SWC in N90P and N180P was lower than that in N0P in 0–380 cm (Figures 2a,b). During the rainy season, NP and NPM had shallower

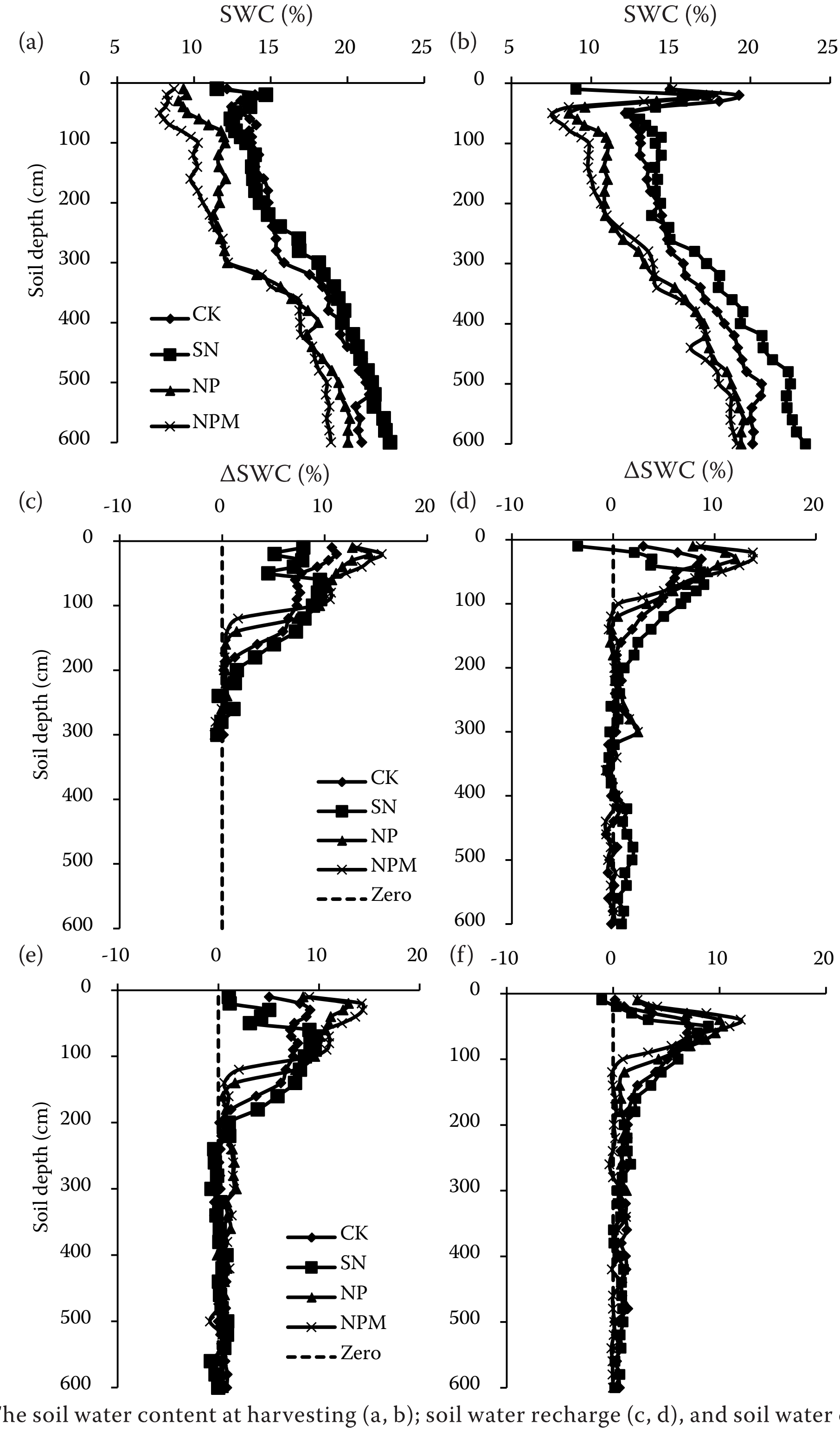

Figure1. The soil water content at harvesting (a, b); soil water recharge (c, d), and soil water depletion (e, f) along 0–600 cm profile in 2 years in experiment I (a, c, e: 2005–2006; b, d, f: 2006–2007). CK – no any fertilization; SN – N-only; NP – nitrogen and phosphorus; NPM – nitrogen, phosphorus and organic manure

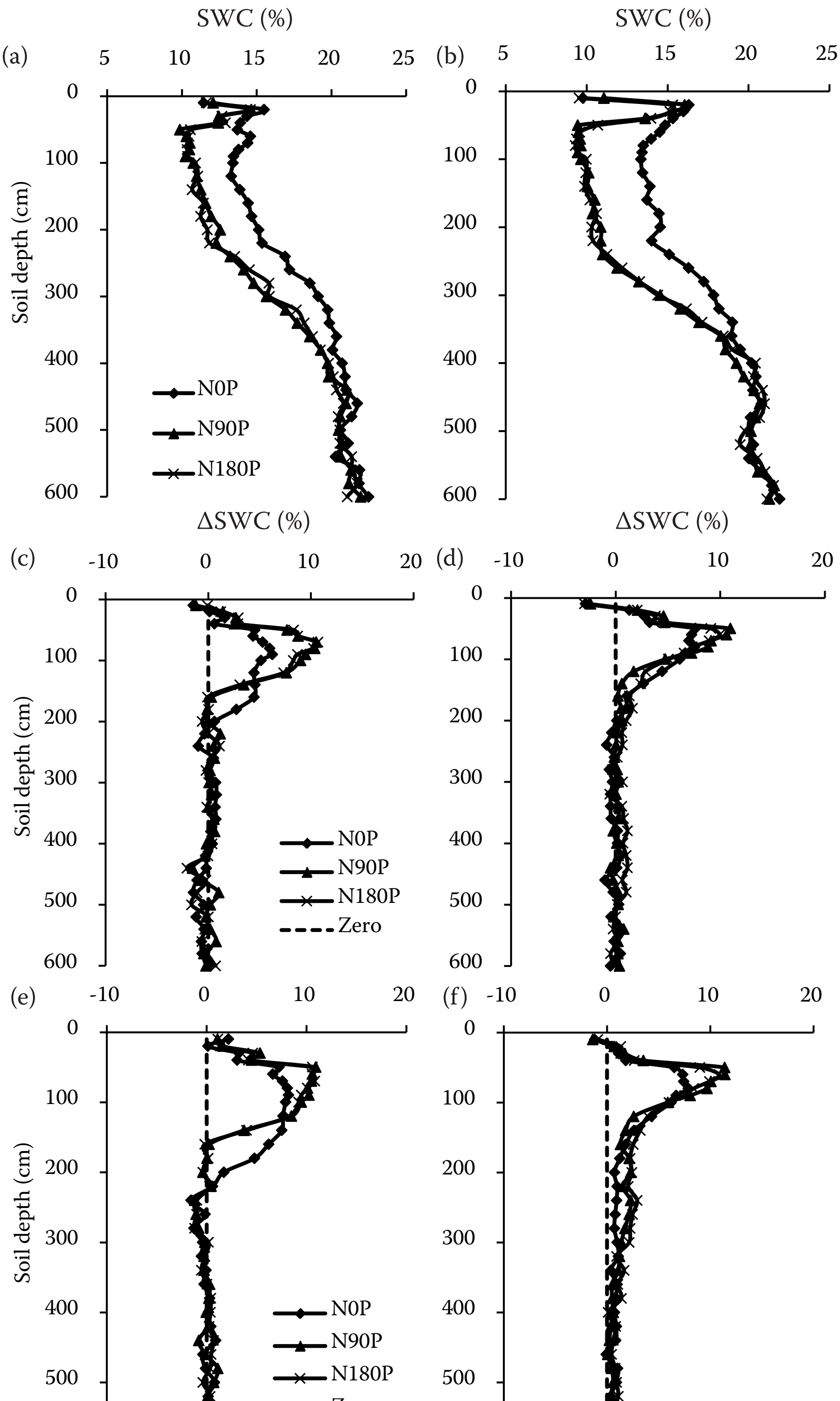

Figure 2. The soil water content at harvesting (a, b), soil water recharge (c, d), and soil water depletion (e, f) along 0–600 cm profile in 2 years in experiment II (a, c, e: 2005–2006; b, d, f: 2006–2007). N0P – 0 kg N/ha; N90P –90 kg N/ha; N180P – 180 kg N/ha

rainfall infiltration depth (120–140 cm) than the CK and SN (160–200 cm) in experiment I. The main reason for the differences in infiltration depth among these treatments was the difference in initial SWC. The SWC at harvesting in NP and NPM was reduced along the profile (Figures 1a,b). Similarly, N90P and N180P had shallower rainfall infiltration depths (140–160 cm)

Table 1. Available soil water at sowing (ASWS), soil water recharge (ΔSW), and soil water depletion (ΔS) in 0–300 cm profile in fertilization treatments in 2 experiments

Treatments	ASWS (mm)			ΔSW (mm)			ΔS (mm)		
	2005	2006	mean	2005	2006	mean	2005–2006	2006–2007	mean
Experiment I									
CK	358.1^{a}	315.9^{a}	337.0^{a}	159.3^{a}	105.9^{b}	132.6^{b}	148.1^{b}	109.9^{ab}	129.0^{bc}
SN	361.0^{a}	324.0^{a}	342.5^{a}	172.3^{a}	109.9^{ab}	141.1^{ab}	147.0^{b}	112.2^{ab}	129.6^{bc}
NP	273.9^{b}	222.8^{b}	248.4^{b}	172.5^{a}	134.1^{a}	153.3^{a}	185.2^{a}	124.1^{a}	154.6^{a}
NPM	227.2^{b}	181.6^{c}	204.4^{b}	160.9^{a}	136.1^{a}	148.5^{a}	181.7^{a}	99.7^{b}	140.7^{ab}
Experiment II									
N0P	377.1^{a}	320.5^{a}	348.8^{a}	85.7^{b}	79.2^{a}	82.4^{b}	135.8^{a}	96.6^{a}	116.2^{a}
N90P	252.2^{b}	220.4^{b}	236.3^{b}	115.5^{a}	89.4^{a}	102.5^{a}	121.1^{a}	129.1^{a}	125.1^{a}
N180P	247.7^{b}	228.3^{b}	238.0^{b}	109.0^{a}	98.0^{a}	103.5^{a}	117.3^{a}	141.0^{a}	129.2^{a}

In each column and each experiment, means with different letters are significantly different at P = 0.05 based on the *LSD* test. CK – no any fertilization; SN – N-only; NP – nitrogen and phosphorus; NPM – nitrogen, phosphorus and organic manure; N0P – 0 kg N/ha; N90P – 90 kg N/ha; N180P – 180 kg N/ha

than N0P (160–200 cm) (Figures 2c,d). For both experiments, ΔS depth in NP, NPM, N90P and N180P was also shallower as compared to CK, SN and N0P. In general, ΔS depth reduced 20–60 cm in NP, NPM, N90P and N180P, depending on year (Figures 1e,f, 2e,f).

The ASWS in 0–300 cm was reduced by long-term N and P or plus manure fertilization. In experiment I, mean ASWS values in NP and NPM were 88.6 mm and 132.6 mm lower than CK. In experiment II, mean ASWS for N90P and N180P was 110.8–112.5 mm less than N0P. The ΔSW in 0–300 cm in NP, NPM, N90P and N180P was higher than those in CK, SN and N0P in both experiments. In experiment I, the amount of ΔS was higher in NP and NPM than in SN and CK. However, manure addition did not affect the amount of ΔS compared to NP in 2005–2006. In both seasons, there were no treatment differences in ΔS in experiment II.

The results of ASWS, ΔSW and ΔS from experiment I in this study were consistent with those from Wang et al. (2011) on the same field. However, the values were generally higher than in Wang et al. (2011) because we calculated these values in 0–300 cm, instead of 0–200 cm. The differences in ASWS, ΔSW and ΔS between this study and Wang et al. (2011) reflected the water availability and WU in deep soil profile (200–300 cm). The CK and SN treatments had more ASWS (47–61 mm) than NP and NPM treatments (12–16 mm) in 200–300 cm profile. However, NP and NPM treatments had more water depletion (17–18 mm) than CK and SN (0–2 mm) in 2005–2006. These results indicated that application of fertilizers promoted more water use from deep soil profile (Li 2001). The results of this study also indicated that both N and P were required for effective use of soil water because neither single application of N (SN) nor P (N0P) increased ΔSW and ΔS as compared to CK (Table 1).

In this study, CK, SN and N0P had higher SWC at harvesting but lower rainfall infiltration depth as compared to NP, NPM, N90P and N180P. The fallow period for continuous wheat is short and soil water in 0–300 cm only can be fully recharged once in 10 years (Liu et al. 2010). Nevertheless, the amount and depth of soil water recharge and depletion were generally greater in NP, NPM, N90P and N180P than those in CK, SN and N0P. These results indicated that long-term fertilization not only increased precipitation storage efficiency (PSE) but also enhanced the use of soil water storage, particularly from the deeper profile. Another study on the same field location showed that mean PSE over 4 years was 33–34% in NP and NPM but only 28% in CK (Wang et al. 2011). The increased use of soil water storage by fertilization has been reported in Loess Plateau. Li (2001) showed that dryland crop with high yields as a result of increased fertilization considerably used more water in the 0–300 cm profile, particularly below 200 cm as compared to crop with low yields. The expla-

Table 2. Wheat yield, water use (WU) and water use efficiency (WUE) in fertilization treatments in 2 experiments

Treatments	Yield (kg/ha)			WU (mm)			WUE (kg/ha/mm)		
	2005–2006	2006–2007	mean	2005–2006	2006–2007	mean	2005–2006	2006–2007	mean
Experiment I									
CK	1462.5^{c}	1316.3^{d}	1389.4^{d}	336.6^{b}	272.5^{ab}	304.6^{bc}	4.35^{c}	4.83^{d}	4.59^{d}
SN	1324.3^{c}	1738.8^{c}	1531.5^{c}	336.6^{b}	274.8^{ab}	305.7^{c}	3.96^{c}	6.33^{c}	5.14^{c}
NP	4290.0^{b}	2786.8^{a}	3538.4^{b}	373.7^{a}	286.7^{a}	330.2^{a}	11.48^{b}	9.72^{b}	10.60^{b}
NPM	5248.8^{a}	2315.5^{b}	3782.1^{a}	370.2^{a}	262.3^{b}	316.2^{ab}	14.18^{a}	8.80^{a}	11.51^{a}
Experiment II									
N0P	1484.8^{c}	1008.0^{c}	1246.4^{c}	324.3^{a}	259.2^{a}	291.7^{a}	4.58^{c}	3.90^{c}	4.24^{c}
N90P	3408.8^{b}	3507.3^{b}	3458.0^{b}	309.6^{a}	291.7^{a}	300.7^{a}	11.01^{b}	12.02^{b}	11.52^{b}
N180P	3658.5^{a}	3663.3^{a}	3660.9^{a}	305.8^{a}	303.6^{a}	304.7^{a}	11.99^{a}	12.19^{a}	12.09^{a}

In each column and each experiment, means with different letters are significantly different at $P = 0.05$ based on the *LSD* test. CK – no any fertilization; SN – N-only; NP – nitrogen and phosphorus; NPM – nitrogen, phost phorus and organic manure; N0P – 0 kg N/ha; N90P –90 kg N/ha; N180P – 180 kg N/ha

nation for increased PSE and more efficient use of water storage may be due to the improvement of soil properties and hydraulic characteristics as a result of long-term NP and NPM fertilization. Fan et al. (2005a) showed that long-term balanced fertilization increased soil organic carbon, and total N and P. Fertilization generally increased aboveground and root biomass, which resulted in more residues on soil surface and belowground biomass accumulation. The long-term accumulation of organic materials could significantly improve soil water-holding capacity and hydraulic conductivity (Fan et al. 2005a, Zhang et al. 2006). However, long-term fertilization had little effect on soil bulk density (Zhang et al. 2006). Nevertheless, ASWS in NP, NPM, N90P and N180P were lower than CK, which could be a limiting factor in long-term fertilization for wheat. Although rainfall during fallow period determines soil water recharge level, further improving PSE may increase soil water recharge because the current PSE is about 28–35% in Loess Plateau (Wang et al. 2011). Combining fertilization with water conservation practices (e.g., residue management, conservation tillage, etc.) may be important for increasing water recharge and PSE.

For both seasons, fertilizer application increased yield (Table 2). Depending on year and treatment, yield in NP and NPM increased by 76–259% over CK. In experiment I, yields in 2006–2007 were lower than those in 2005–2006, particularly the NP and NPM treatments. Yield increase in NP and NPM was lower in 2006–2007 than in 2005–2006. In experiment II, however, yield in N180P and N90P treatments did not differ in 2 years (Table 2). Consistent to previous study (Huang et al. 2003), NP and NPM applications continuously increased crop yield after over 20 years of fertilization.

In experiment I, NP and NPM treatments had more WU than SN and CK in 2005–2006. However, the NPM treatment had less WU than other treatments in 2006–2007. In general, application of N and P increased crop WU in this experiment. In experiment II, there were no differences ($P > 0.05$) in WU among treatments (Table 2). Fertilization can reduce soil evaporation and increase the proportion of transpiration in total WU. No differences in WU among fertilization treatments may indicate that treatments without N had more soil evaporation (Caviglia and Sadras 2001). On average for experiment I, the WU values among treatments were about 14 mm higher than those from Wang et al. (2011). Therefore, the WU may be calculated based on 0–300 cm, not 0–200 cm profile.

In both seasons, WUE in CK, SN and N0P treatments was < 6 kg/ha/mm. However, the WUE in NP, NPM, N90P and N180P treatments ranged from 8.8 to 14.2 kg/ha/mm. Therefore, long-term fertilization practice considerably improved wheat WUE. The WUE values in these fertilized treatments were in the higher range for dryland wheat and in the range of irrigated wheat (7.3–14.6 kg/ha/mm) (Kang et al. 2002, Fan et al. 2005b). Thus, fertilization is a successful practice for continuous dryland wheat in the area of this study.

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