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Potato performance as influenced by the proportion of wetted soil volume and nitrogen under drip irrigation with plastic mulch

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ABSTRACT

Scarce water resources and substantial food demands require efficient water use in arid Northwestern China. Field experiments were conducted to investigate the effects of the proportion of wetted soil (P) and nitrogen fertilizer (N) on potato yield, crop evapotranspiration (ET_c), water use efficiency (WUE), and quality under drip irrigation with plastic mulch. In 2012, a factorial trial was conducted with two soil wetting proportions (40% and 70%) and five N rates (90, 135, 180, 225 and 270 kg N ha^{-1}). In 2013, a factorial trial tested two soil wetting proportions (50% and 75%) and four N rates (90, 150, 210 and 270 kg N ha^{-1}). Results showed that seasonal ET_c was greater with higher P, but the difference in ET_c was not significant among different N rates. Although tuber yields of different P levels were not statistically different, yields with lower P were numerically larger than with higher P. The water was used more efficiently with lower proportions of wetted soil. Potato yield, WUE, and tuber starch and vitamin C content responded quadratically to the rate of applied N. Tuber protein was positively and linearly correlated with the N rate. The results suggest that potato could be cultivated with a moderate P (40–50%) and an intermediate rate of applied N (135–150 kg N ha^{-1}) under drip irrigation with mulch, achieving acceptable yields and quality while saving irrigation water and conserving N fertilizer.

1. Introduction

Potato (*Solanum tuberosum* L.) ranks as the fourth largest global food crop, following rice, wheat, and maize (FAO, 2014). Between 1995 and 2014, annual production of potato in China rose from 50.0 million ton to 96.1 million ton while the average yield increased from 13.4 t ha^{-1} to 17.0 t ha^{-1}, making China the world's largest potato producer (FAO, 2014). In Northwest China, potato is generally planted on hills and is furrow-irrigated. The irrigation and nitrogen (N) application are managed by the farmers' experience to ensure against the loss of yield, which can lead to high water application, water loss, deep drainage, and N leaching. In contrast, the shortage of water resources and the development of irrigated agriculture in the region have resulted in a falling groundwater table, serious loss of vegetation, and gradual soil salinization and desertification (Kang et al., 2004a). Therefore, improving the efficiency of water and N use is necessary for potato production in Northwest China.

In order to produce potato with high yield and good quality while efficiently using water and N resources, a better understanding about the influences of water and N on potato grown using drip irrigation and plastic mulch should be achieved. Field researches on N and water use of potato have been conducted (Millard, 1986; Martin et al., 1992; Huang et al., 1996; Yuan et al., 2003; Ferreira and Gonçalves, 2007; Badr et al., 2012; Song et al., 2014; El Mokh et al., 2015; Gao et al., 2015). It is well known that potato is very sensitive to soil water status: both water stress and over-irrigation lead to reduction in tuber yield and quality (Shock et al., 2007; Wang et al., 2011; Steduto et al., 2012). Phene et al. (1989) and Wang et al. (2006, 2007b) emphasize the importance of maintaining a relatively constant soil matric potential (SMP) as high as −25 kPa with high frequency drip irrigation scheduling. Zhou et al. (2004) shows a quadratic relationship between the amount of applied N and the potato tuber yield, starch content. Gao et al. (2015) reported that N fertilization significantly enhanced the vitamin C, soluble protein and starch content. However, excessive N leads to a decrease of starch content of potato tubers, and the tubers are less resis-

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tant to decomposition in storage (Huang et al., 1996). Besides the separate effects of water and N, research information is also available on interaction effects of irrigation and N fertilizer on potato (Nimah et al., 2000; Ferreira and Gonçalves, 2007; Ierna et al., 2011; El Mokh et al., 2015) and empirical analyses for enhancing water and N use efficiency (Ferreira and Gonçalves, 2007; Ierna et al., 2011). Though such analyses are helpful in decision making, they cannot be extrapolated beyond experimental conditions in consideration of the inherent differences in soil basic fertility, agronomic practices, rain patterns, and irrigation regimes. Few of these results are directly applicable to drip-irrigated potato grown under plastic mulch.

Drip irrigation in combination with plastic film mulch are integrated water-saving measures being adopted by more and more Chinese farmers in potato production in areas with limited water resources. Drip irrigation is generally considered not only an efficient method for irrigation, but also highly suitable for fertigation (Sammis, 1980; Papadopoulos, 1985), as it can supply water and nutrients directly to the crops at the root level and provide desirable conditions for water movement in soil and for nutrient uptake by roots (Batchelor et al., 1996; Segal et al., 2000; Wang et al., 2006). Previous studies show that the simultaneous application of water and N through fertigation can save 35% of the water and improve N use efficiency in potato production (Papadopoulos, 1988; Mohammad et al., 1999; Darwish et al., 2006). However, little research has paid much attention to the unique characteristics of drip irrigation of potato to make full use of its advantages in water saving and enhancing N use efficiency. Firstly, under drip irrigation the soil is partially wet and partially dry. Boundaries of the wetted soil under a point source are well defined and surrounded by drier soil (Zur, 1996), which could help provide soil aeration for root respiration. The distribution of root system under drip irrigation is limited by the wetted soil volume perpendicular to the emitters on the drip tape, especially in an arid or semi-arid region. If the wetted soil volume is too small, the root system is limited to a small range, restricting the uptake of nutrients and water (Plaut et al., 1988; Clothier and Green, 1994; Coelho and Or, 1996; Pivonia et al., 2004). If the wetted soil volume is too large, the large wetted soil volume could lead to great water evaporation loss, possible drainage of water and nutrients, and possible temporary lack of soil oxygen (Ben-Asher et al., 2003; Li et al., 2006). Secondly, irrigation frequency can be relatively high under drip irrigation, which has been proven to be conducive to increasing both crop yield and water use efficiency (Kang and Zhang, 2004; Kang et al., 2004b; Wang et al., 2006; Sezen et al., 2006, 2008; El-Hendawy et al., 2008). Many researchers report notable effects of frequent drying/wetting cycles on nitrogen transformation and transport in soil (Sun et al., 2013; Choudhary et al., 2002; Huang et al., 2007). Therefore, the soil wetting pattern and its temporal variation should be deliberately controlled in order to improve both water and N use efficiency for sustainable potato production.

Soil wetting proportion (P), which can be described as the ratio of wetted soil volume to the total soil volume within a designed soil layer (Keller and Karmeli, 1974), can basically determine not only the irrigation amount per time but also soil wetting pattern. Keller and Karmeli (1974) determined that the value of P should be at least one-third (33%), and that lower P values may be acceptable if there is considerable supplemental rainfall. The optimal P values for a specific crop under different climate conditions and soil types have not been defined. The soil wetting proportion has been used by irrigation engineers, especially in China (Lei, 1994; Li et al., 2004; Sezen et al., 2006; Singh et al., 2006; Dabral et al., 2012; Robinson et al., 2012; Zhang et al., 2015). However, few studies have been carried out in field production, especially the interaction effects of the soil wetting proportion and N on a specific crop such as potato.

In this study, two field experiments were conducted to investigate the influence of different soil wetting proportions and N rates on potato yield, quality, ET_c and WUE. We sought to help provide a scientific basis for irrigation and N fertilization management for drip-irrigated potato production in Northwest China.

2. Materials and methods

2.1. Experimental site

The field experiments were conducted from April to August in 2012 and 2013 at the Shiyanghe Experimental Station of China Agricultural University at Wuwei, Gansu Province of Northwest China. The research was situated in an arid region with an altitude of 1581 m, at latitude 37°52′N and longitude 102°50′E. The site has a typical continental temperate climate with mean sunshine duration of 3000 h, mean annual precipitation of 164 mm, pan evaporation of 2000 mm, frost-free period of 150 d and mean annual temperature of 8.8 °C. The groundwater table is consistently below 25 m. The experiment site has a sandy loam soil with average field capacity of 0.28 $cm^3 cm^{-3}$ and soil bulk density of 1.50 $g cm^{-3}$ in the upper 0.9 m of the soil profile. The soil fertility levels were determined in the upper 0.50 m of the soil profile prior to fertilization (Table 1).

2.2. Experimental design and treatments

Both experiments included combinations of two soil wetting proportions and different nitrogen fertilizer rates through a drip irrigation system. According to Steduto et al. (2012), the recommended N fertilization rates for potato range from 100 to 250 $kg N ha^{-1}$, for soils ranging from highly fertile to highly deficient in N, so the choice of lower limit of applied N was 90 $kg N ha^{-1}$ and the upper limit was 270 $kg N ha^{-1}$. In 2012, the irrigation treatments included two soil wetting proportions (40% and 70%) and five N fertilizer rates (90, 135, 180, 225 and 270 $kg N ha^{-1}$), resulting a 2 × 5 factorial design with 10 treatments. In 2013, the two soil wetting proportions were 50% and 75% with four applied N fertilizer rates (90, 150, 210 and 270 $kg N ha^{-1}$) in a 2 × 4 factorial design with 8 treatments. In each experiment, the treatments were replicated three times arranged in a completely randomized block design.

2.3. Irrigation scheduling

Drip tape (Beijing Lvyuan Plastic Co., Ltd., Beijing, China) with wall thickness of 0.4 mm, emitter spacing of 0.2 m, and emitter flow rate of 1.38 $L h^{-1}$ at the operating pressure of 0.1 MPa was placed on the center of each bed. Each plot had a valve, a flow meter to measure the amount of irrigation, and a pressure gauge to control the operating pressure.

Because the soil was dry at the onset of the experiments both years, all the experimental plots were irrigated once with 30 mm after the mulch was laid, in order to assure uniform, rapid seed piece germination. Then, irrigation was applied to each treatment only when its soil matric potential (SMP) reached the target value (−25 kPa) (Wang et al., 2007b). The SMP was measured by dial vacuum tensiometers (Model WST-2B, Beijing Waterstar Tech. Co., Ltd., Beijing, China) installed at 0.2 m depth, between two plants and immediately under a drip emitter in the middle bed of each plot in two replications.

The irrigation amount at each time was estimated using the following equation:

$$I = 1000H\left(\theta_{max} - \theta_{min}\right)P \qquad (1)$$

Table 1
The nitrogen, phosphorus and potassium soil fertility of the experimental field prior to fertilization at Wuwei, Gansu Province, China, 2012 and 2013.

Season	Soil depth(m)	Available nitrogen(mg kg^{-1})	Readily available phosphorus(mg kg^{-1})	Readily available potassium(mg kg^{-1})
2012	0–0.1	23.3	29.9	192
	0.1–0.2	21.9	25.8	174
	0.2–0.3	26.2	24.7	187
	0.3–0.5	32.8	7.6	109
2013	0–0.1	35.8	28.0	141
	0.1–0.2	27.9	31.1	148
	0.2–0.3	27. 6	23.6	252
	0.3–0.5	35.1	20.1	169

where I is the irrigation amount at each time (mm); H is designed depth of wetted soil layer, H = 0.4 m; θ_{max} is upper limit of average soil water content within the designed wetted layer (the value is the field capacity, 0.28 cm^3 cm^{-3}); θ_{min} is lower limit of average soil water content within the designed wetted layer when the SMP reached −25 kPa, which is about seventy percent of field capacity according to soil water characteristic curve, $\theta_{min} = 70\%\ \theta_{max}$; P is soil wetting proportion.

2.4. Maintaining of the designed P

In drip irrigation, P is equal to the quotient obtained by the wetted soil volume (V_{ws}) divided by total soil volume (V_t), where both V_{ws} and V_t refer to volume served by the drip emitters. V_t is the volume of a rectangular column, where the base surface area is S ($S = a \times b$), a is the emitter spacing, and b is the plant row spacing. They were 20 cm and 80 cm respectively, in these experiments. The height (H) is the planned depth of wetted soil layer (H = 40 cm, in these experiments). Hence, $V_t = a \times b \times H$. V_{ws} can be estimated by product of P and V_t, where P is the designed soil wetting proportion. Supposing it is a point source infiltration and the geometry of wetted soil volume under the emitter is a truncated ellipsoid, then the vertical depth of wetting Z, and lateral diameter of the wetted volume D_L can be estimated by a semi-empirical model of Schwartzman and Zur (1986) by the following:

$$Z = 2.54(V_w)^{0.63}\left(\frac{K_s}{q}\right)^{0.45} \tag{2}$$

$$D_L = 1.82(V_w)^{0.22}\left(\frac{K_s}{q}\right)^{-0.17} \tag{3}$$

where q is emitter discharge (l/h), K_s is saturated hydraulic conductivity of the soil (m/s), and V_w is total water in the wetted volume (l). According to Zur (1996), V_w can be calculated by multiplying V_{ws} with FC (Field water capacity) and MAD (Management Allowed Deficiency as a decimal fraction, is 0.3 in these experiments).

Since the emitter discharge rate was the same for all the four treatments, the maximum of Z should occur in the treatment with P = 0.75, considering that it had the largest V_w. Therefore, if the maximum Z happens to be equal to H, then no deep percolation should occur in all treatments, regardless the geometry of soil wetting pattern. Then, q can be calculated by Eq. (2) in an inverse approach suggested by Zur (1996).

The exact shape of the wetted volume and moisture distribution will depend on many factors, including soil hydraulic characteristics, initial conditions, emitter discharge rate, application frequency, root characteristics, evaporation, and transpiration (Subbaiah, 2013). The emitter discharge rate was measured by field tests. Such field tests were carried out in similar ridges without potato plant when the soil matric potential reached −25 kPa. The type of emitter with a large flow rate was chosen to enable the adjustment of the emitter discharge rate by changing the operating pressure. A series of emitter discharge rates were then used while keeping the same irrigation amount (Equal to the value in treatment with P = 0.75). Longitudinal sections were then dug and measured for geometry analysis of soil wetting patterns to avoid deep percolation ($Z \le H$) 12 h after irrigation. Such calibration were made several times before experiments were conducted using an appropriate value for q. Then the emitter type and emitter spacing were chosen accordingly.

The operating pressure was maintained the same for all the treatments, so the emitter discharge rates were the same. The only difference lay in value of V_w, which was estimated by:

$$V_w = P \times V_t \times MAD = P \times a \times b \times H \times MAD \tag{4}$$

In such a case, both D_L and Z were determined by P, which became the only variable in Eqs. (2) and (3). For the treatments having smaller P, the Z values should be smaller than H. This means that the wetting front could not approach to such a depth, avoiding deep percolation. This also suggests that all the P levels should have been well maintained, although the geometry could be quite different.

2.5. Agronomic practices

Before planting, all of the phosphorus fertilizer (150 kg P_2O_5 ha^{-1} in 2012 and 200 kg P_2O_5 ha^{-1} in 2013), 40% of the total potash fertilizer (180 kg K_2O ha^{-1} both seasons) and 40% of the total N fertilizer according to the designed N rates were broadcast. Then the soil was rototilled and the beds were formed. The remaining potash fertilizer and N fertilizer were applied through the drip irrigation system every 20 days from June 7 to July 17 both years.

Black waterproof polyethylene film 0.008 mm thick and 1.4 m wide (in 2012) and 1.2 m wide (in 2013) was laid over the beds after the drip irrigation system was installed. The polyethylene film was used to reduce water evaporation from the soil and increase soil temperature.

In 2012, potato seed pieces (cv. *Longshu*-3) were planted on April 17 and potatoes were harvested on August 29. In 2013, potato seed pieces (cv. *Russet Burbank*) were planted on April 17 and potatoes were harvested on August 20. In 2012, the size of each experimental plot was 6.5 m × 6.0 m, including five beds. The length, width and height of the beds were 6.5 m, 1.2 m and 0.3 m, respectively. Potato seed pieces (30 g) were planted at a depth of 0.15 m in double rows on each bed with row spacing of 0.4 m and plant spacing of 0.3 m. In 2013, the size of each experimental plot was 6.0 m × 5.6 m and consisted of seven beds. The length, width and height of the beds were 6.0 m, 0.8 m and 0.3 m, respectively. Potato seed pieces (30 g) were planted at a depth of 0.15 m in single row in each bed with plant spacing of 0.3 m.

The agronomic practices other than irrigation and N rate, such as the prevention and control of weeds, plant diseases and insect pests, were the same for all treatments during both seasons.

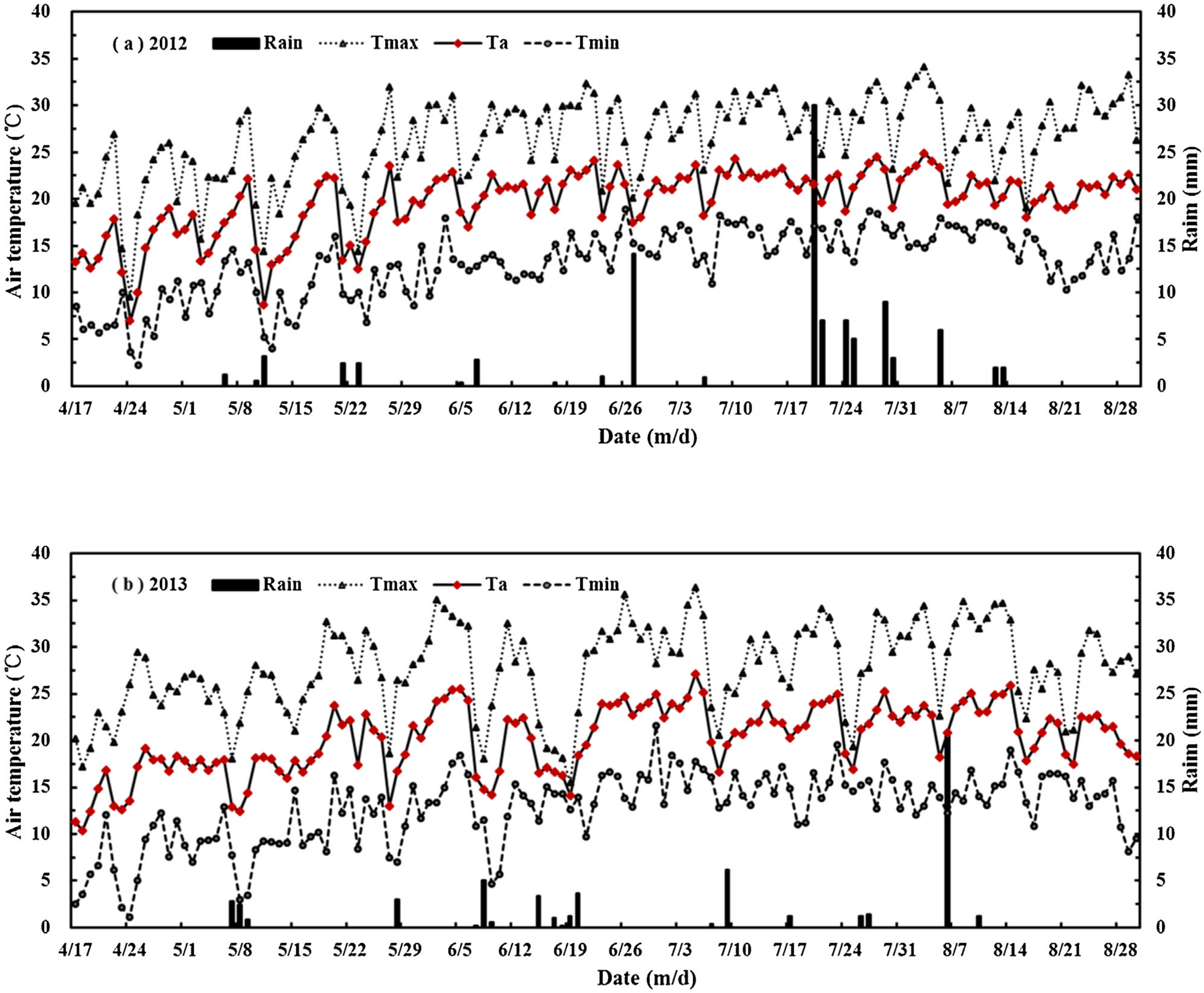

Fig. 1. Daily rainfall and air temperature (T_{max} = maximum air temperature, T_{min} = minimum air temperature, T_a = average air temperature) at 2.0 m height during the 2012 (a) and 2013 (b) potato growing seasons at Wuwei, Gansu Province, China.

2.6. Measurements

2.6.1. Estimation of crop evapotranspiration

Crop evapotranspiration (ET_c) was estimated using the soil water balance method by monitoring the change in soil water content over a period time (Allen et al., 2011):

$$ET_c = R + I + \Delta S - R_o - D \quad (5)$$

where R is rainfall (mm); I is the irrigation amount (mm); R_o is the surface runoff (mm); D is deep drainage below crop root zone (mm); and ΔS is the change of soil water storage (mm). ΔS can be calculated as:

$$\Delta S = S_{t1} - S_{t2} \quad (6)$$

where S_{t1} and S_{t2} are the water storage (mm) in the root zone at time t_1 and t_2, respectively. To estimate ΔS, soil water content in the soil profile (0–90 cm) was determined by gravimetric measurements just before planting and at the end of every growth stage. Soil samples were collected at the top of ridge under the drip tape and the side of ridge 0.4 m (in 2012) and 0.2 m (in 2013) perpendicular to the drip line in every treatment plot. The sampled depths were 0.1, 0.2, 0.3, 0.5, 0.7, and 0.9 m.

Precipitation events and the amounts of drip irrigation water applied during the growing season were relatively small, so surface runoff was negligible, therefore $R_o = 0$. Since the drip irrigation management was consistent with previous similar potato drip irrigation research (Wang et al., 2006, 2007b; Hou et al., 2010), the deep drainage below crop root zone was assumed to be negligible, D = 0. The water contribution from groundwater was negligible as the groundwater table was below 25 m. Based on the assumptions above, Eq. (5) can be simplified as follows:

$$ET_c = R + I + \Delta S \quad (7)$$

2.6.2. Yield and water use efficiency

All the plants in the middle three beds of each plot were harvested and were evaluated for fresh tuber yield, tuber number, and individual tuber weight both years.

Water use efficiency was calculated by the following equation:

$$WUE = Y/ET_c \times 10^{-1} \quad (8)$$

where WUE is water use efficiency ($kg\,m^{-3}$); Y is total fresh tuber yield ($kg\,ha^{-1}$); and ET_c is crop evapotranspiration (mm).

2.6.3. Tuber quality parameters

Five kilograms of potato tubers from each plot was used to measure the starch content, and twenty tubers were cut and homogenized in a blender to measure the vitamin C (VC) and pro-

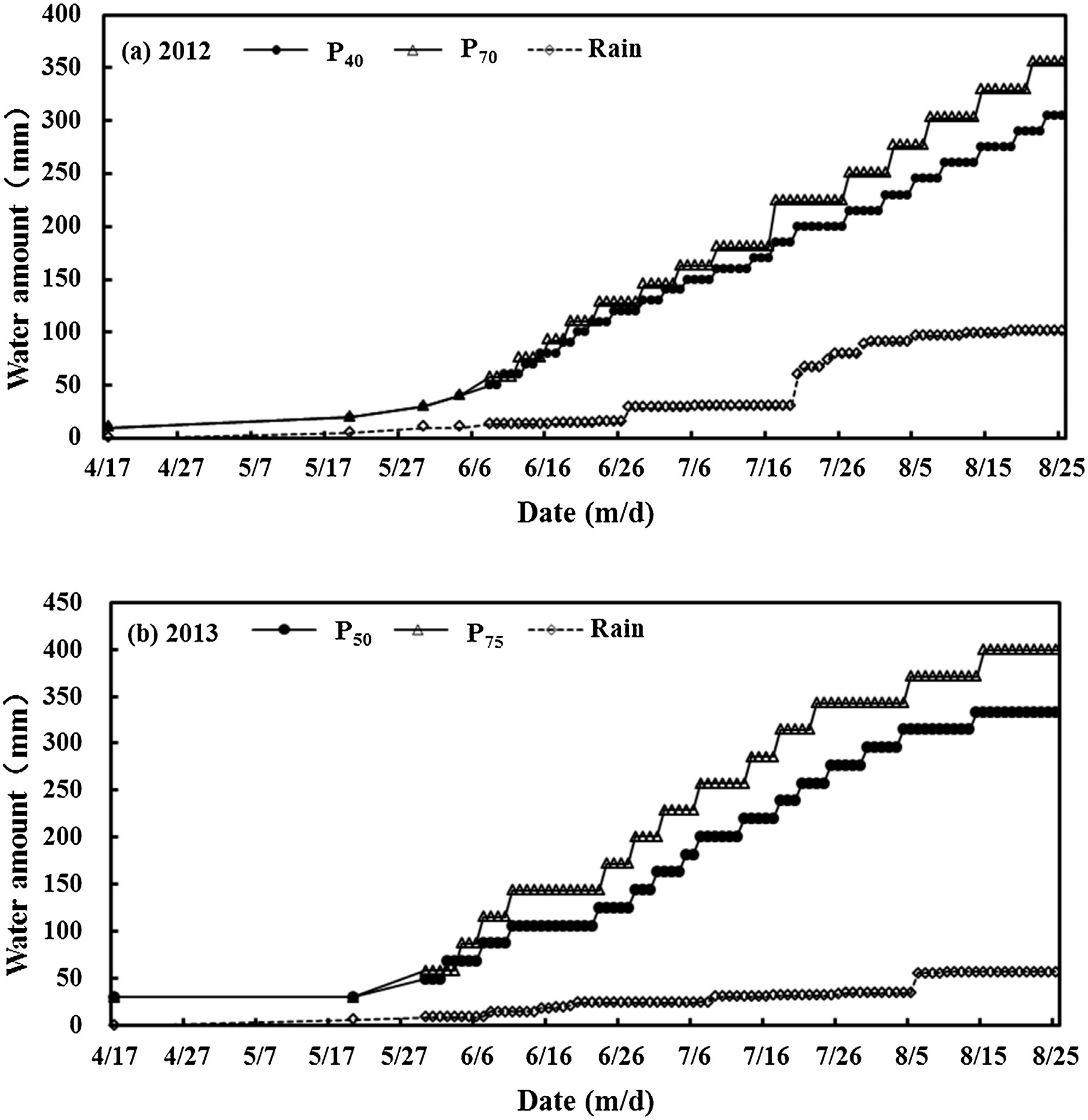

Fig. 2. Cumulative precipitation and irrigation water amount under different soil wetting proportion (P) treatments during the 2012 (a) and 2013 (b) potato growing seasons at Wuwei, Gansu Province, China.

tein content. The starch content was measured by a water specific gravity method (Huang et al., 2000). VC content was measured by the 2,6-dichloroindophenol titrimetric method (AOAC, 1984). Total protein content of potato was determined by the method of Coomassie Brilliant Blue G-250 (Bradford, 1976), using bovine serum albumin standard. The averages of the six measurements from each experimental plot were used for tuber quality parameters both years.

2.6.4. *Meteorological data*

Meteorological data were collected with an automatic weather station (Hobo, Onset Computer Corp., USA) located in the center of the experimental field. Measurements of air temperature, precipitation, solar radiation, and relative humidity were calculated every fifteen minutes and stored in a data logger.

2.7. *Statistical analysis*

Data of tuber yield, tuber quality, ET_c, and WUE were analyzed statistically by two-way analysis of variance (ANOVA) using SPSS 20.0 version software (SPSS Inc., USA) to evaluate the effect of the soil wetting proportions and nitrogen fertilizer rates. If the difference among treatments was significant ($P < 0.05$), then the least significant difference (LSD) test at 0.05 probability level was used to evaluate the difference between means for significance. The relationships between fresh potato tuber yield, WUE and tuber quality

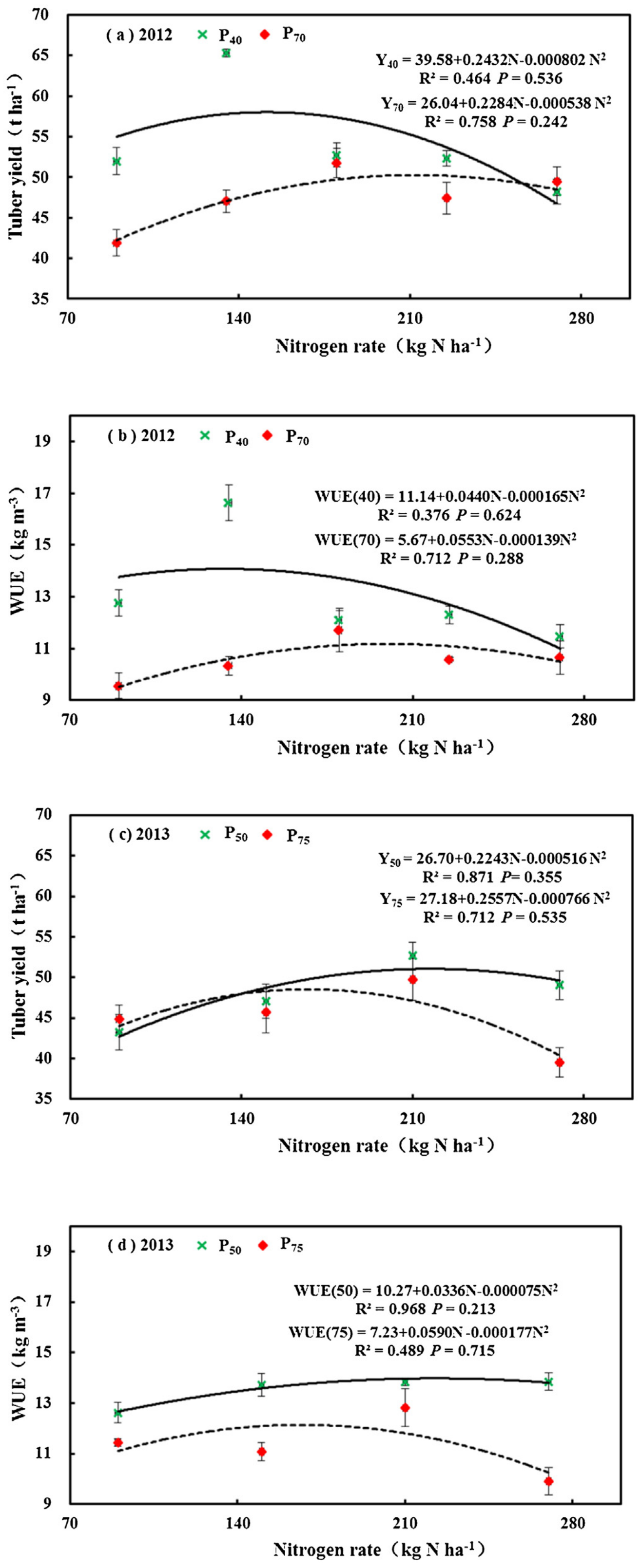

Fig. 3. Relationship between potato tuber yield, WUE and applied nitrogen (N) rates under different soil wetting proportion (P) levels in 2012 (a) and 2013 (b) at Wuwei, Gansu Province, China.

parameters with the total amount of applied N were analyzed by nonlinear regression.

3. Results and discussion

3.1. Weather conditions

Daily rainfall and air temperature during 2012 and 2013 potato growing seasons were showed in Fig. 1(a) and (b), respectively. Precipitation occurred 20 times totaling 100.4 mm in the 2012 potato growing season and occurred 19 times totaling 56.6 mm in the 2013 potato growing season. Most of the rainfall events were less than 5 mm, which might not affect soil water content under the plastic mulch (Wang et al., 2007a). Hence, rainfall was far from meeting the needs for potato growth. Air temperature fluctuation trends were similar both seasons. Average temperature from April to May was lower than the other months in the potato growing seasons, and the lowest daily temperature was about 2 °C, which was not favorable for potato emergence. There were some days in June-August with maximum temperature higher than 30 °C, which could have negative effect on potato growth (Kar and Kumar, 2007; Hou et al., 2010).

3.2. Total water received

The cumulative irrigation amounts varied with the soil wetting proportions (Fig. 2). In 2012, the number of irrigation events wetting 40 and 70 percent of the soil volume were 24 and 17 with 305 mm and 355 mm of water applied, respectively. In 2013, the number of irrigation events wetting 50 and 75 percent of the soil volume were 17 and 14 with 333 mm and 400 mm of water applied, respectively. The lower irrigated soil volume saved irrigation water each year. The irrigation amount in 2012 was less than that in 2013 due to more abundant and more effective rainfall in 2012 and also due to the larger soil wetting proportions used in 2013. In both seasons, the irrigation frequency was increased and irrigation amount was reduced with the decrease of P, and the duration of each irrigation interval was different among treatments, consistent with previous reports (Kang and Zhang, 2004; Wang et al., 2003, 2007b, 2011).

3.3. Potato evapotranspiration

The analysis of total crop evapotranspiration (ET_c) and daily mean evapotranspiration (ET_{Daily}) at different growth stages showed that water consumption varied in a similar way both seasons (Table 2). The effect of wetted soil volumes on ET_c was significant according to ANOVA ($P < 0.05$) in both seasons, and ET_c of the treatments with higher P levels (70 and 75%) were 34 mm (8.2%) and 43 mm (12.1%) greater than the lower ones (40 and 50%) in 2012 and 2013, respectively. But the differences of ET_c among different N rates were not significant, suggesting that the influence of P on ET_c is greater than the influence of N. It is well known that ET_c is mostly determined by the irrigation water in the arid regions (Xie et al., 2005; Li et al., 2007; Chakraborty et al., 2008; Hou et al., 2010; Chen et al., 2013). The treatments with higher P received more irrigation water (Fig. 2), so it is easily understood that they had greater ET_c. Additionally, the P × N interaction for ET_c was significant in 2012, indicating that both factors did not act separately. The greatest ET_c (465 mm) was found in treatment with larger wetted soil volume (70%) and largest N rate (270 kg N ha^{-1}), 72 mm (18.3%) greater than the smallest one in treatment with 40% wetted soil volume and N application of 135 kg N ha^{-1}. The maximum plant water use occurred during tuber initiation and tuber bulking, accounting for 57–72% of total ET_c both seasons. Like the influence on total ET_c, the P × N significant interaction for ET_c at tuber bulking was found in

Table 2

Effects of soil wetting proportion (P) and nitrogen (N) on total crop evapotranspiration (ET_c) and daily mean evapotranspiration (ET_{Daily}) of potatoes at different growth stages during the 2012 and 2013 cropping seasons at Wuwei, Gansu Province, China.

Season	P (%)	N (kg N ha^{-1})	Stage I		Stage II		Stage III		Stage IV		Total season	
			ET_c(mm)	ET_{Daily}(mm d^{-1})	ET_c(mm)	ET_{Daily}(mm d^{-1})	ET_c(mm)	ET_{Daily}(mm d^{-1})	ET_c(mm)	ET_{Daily}(mm d^{-1})	ET_c(mm)	ET_{Daily}(mm d^{-1})
2012	40	90	25	0.5	134	4.1	127cd	4.4	119	5.0	407ef	3.1
		135	36	0.8	139	4.2	122cd	4.2	95	4.0	393f	3.0
		180	39	0.8	170	5.1	110d	3.8	117	4.9	436cd	3.3
		225	26	0.6	181	5.5	127cd	4.4	92	3.8	425cde	3.2
		270	32	0.7	146	4.4	134bc	4.6	109	4.5	420de	3.2
		mean	32	0.7	154	4.7	124	4.3	106	4.4	416	3.2
	70	90	23	0.5	164	5.0	109d	3.8	142	5.9	438c	3.3
		135	34	0.7	136	4.1	166a	5.7	119	5.0	455ab	3.4
		180	29	0.6	155	4.7	150ab	5.2	108	4.5	442bc	3.3
		225	22	0.5	147	4.5	154a	5.3	125	5.2	448ab	3.4
		270	23	0.5	171	5.2	125cd	4.3	146	6.1	465a	3.5
		mean	26	0.6	155	4.7	141	4.9	128	5.3	450	3.4
ANOVA												
P			NS		NS		*		*		*	
N			NS		NS		*		NS		NS	
P × N			NS		NS		*		NS		*	
2013	50	90	60	1.2	70	3.3	140	4.5	72	3.1	342	2.7
		150	61	1.2	68	3.2	127	4.1	88	3.8	343	2.7
		210	80	1.6	73	3.5	137	4.4	91	4.0	380	3.0
		270	80	1.6	54	2.6	159	5.1	61	2.7	354	2.8
		mean	70	1.4	66	3.1	141	4.5	78	3.4	355	2.8
	75	90	63	1.3	92	4.4	179	5.8	58	2.5	392	3.1
		150	94	1.9	75	3.6	182	5.9	62	2.7	412	3.3
		210	61	1.2	76	3.6	171	5.5	80	3.5	388	3.1
		270	48	1.0	98	4.7	180	5.8	72	3.1	399	3.2
		mean	66	1.3	72	4.1	178	5.7	152	3.0	398	3.2
ANOVA												
P			NS		*		*		NS		*	
N			NS		NS		NS		NS		NS	
P × N			NS		NS		NS		NS		NS	

Notes: Stage I: Early vegetative growth, Stage II: Tuber initiation, Stage III: Tuber bulking, Stage IV: Tuber maturation and starch accumulation; NS: difference among different treatments in each cropping season is not significant by *F*-test ($P > 0.05$); * means significant at the 0.05 probability level ($P < 0.05$); small letters following the values of the indexes of each season within columns are the significant difference according to the least significant differences (LSD) test at 0.05 probability level ($P < 0.05$).

Table 3
Potato tuber yield and water use efficiency (WUE) in response to applied nitrogen (N) rates and soil wetting proportions (P) levels during the 2012 and 2013 cropping seasons at Wuwei, Gansu Province, China.

Season	P (%)	N (kg N ha^{-1})	Tuber yield (t ha^{-1})	ET (mm)	WUE (kg m^{-3})
2012	40	90	52.0	407ef	12.8b
		135	65.3	393f	16.6a
		180	52.7	436cd	12.1bcd
		225	52.3	425cde	12.3bc
		270	48.2	420de	11.5bcd
		mean	54.1	416	13.1
	70	90	41.9	438c	9.6e
		135	47.0	455ab	10.3de
		180	51.8	442bc	11.7bcd
		225	47.4	448ab	10.6cde
		270	49.5	465a	10.7cde
		mean	47.5	450	10.6
ANOVA					
P			NS	*	*
N			NS	NS	NS
P × N			NS	*	*
2013	50	90	43.2	342	12.6ab
		150	47.1	343	13.7a
		210	52.7	380	13.8a
		270	49.1	354	13.9a
		mean	48.0	355	13.5
	75	90	44.9	392	11.4bc
		150	45.7	412	11.1bc
		210	49.7	388	12.8ab
		270	39.5	399	9.9c
		mean	45.0	398	11.3
ANOVA					
P			NS	*	*
N			NS	NS	NS
P × N			NS	NS	*

Notes: NS: difference among different treatments in each cropping season is not significant by *F*-test ($P > 0.05$); * means significant at the 0.05 probability level ($P < 0.05$); small letters following the values of the indexes of each season within columns are the significant differences according to the least significant differences (LSD) test at 0.05 probability level.

2012. The greatest ET_c (166 mm) was found in treatment wetting 70 percent of the soil volume and applied 135 kg N ha^{-1}, significantly greater than other treatments except for treatments applied with 180 and 225 kg N ha^{-1} and wetting 70 percent of the soil volume. In 2013, although the greatest ET_c (182 mm) was found in treatment wetting 75 percent of the soil volume and applied 150 kg N ha^{-1} which was close to the result of 2012, the difference among treatments was not significant (ANOVA, $P > 0.05$). In both seasons, the effects of wetted soil volume on ET_c at tuber bulking stage were significant, ET_c of the treatments wetting 40 and 50 percent of the soil volume were decreased by 12.1% and 20.8% compared to the treatments wetting 70 and 75 percent of the soil volume in 2012 and 2013, respectively. Steduto et al. (2012) reports that water deficit during these stages following tuber initiation might result in tuber cracking or tuber with black heart and it could also reduce the yield of marketable tubers from 90% to 70% or even 50%. In contrast, the cumulative ET_c during the early vegetative stage was the lowest, as well as ET_{Daily}. No significant influence was found on ET_c at the early vegetative growth stage between different P levels, suggesting that the supply of water can be restricted during the early vegetative growth before flowering, but canopy growth would be slowed, so the restriction must be within bounds (Shock et al., 1992; Steduto et al., 2012).

3.4. Tuber yield and water use efficiency (WUE)

There was no significant difference of potato tuber yield among different P and N treatments (ANOVA, $P > 0.05$) in either potato growing season (Table 3). However, yields with lower P levels were numerically larger than those with higher P levels. This phenomenon could be explained by the fact that lower P levels lead to higher frequency irrigation, and the frequent dry-wet cycling of soil would not only maintain constant and high soil moisture in the root zone (Wang et al., 2006, 2011; Sezen et al., 2006, 2008; El-Hendawy et al., 2008), but also avoid poor aeration and help provide enough oxygen for root respiration. On the contrary, too large wetted soil volume could lead to shortdated lack of soil oxygen in the root zone (Ben-Asher et al., 2003; Li et al., 2006), which could be detrimental to tuber growth. In other words, the lower P levels (40–50%), compared to the higher ones, were more conducive to build the optimal rhizosphere environment for tuberization and tuber enlargement and then resulted in increases in yield. Under a given designed P, tuber yield increased as the N rate increased then it decreased when the dosage of N application beyond a certain range (Table 3 and Fig. 3(a) 2012 and (c) 2013), the result was consistent with some early reports (Zhou et al., 2004; Darwish et al., 2006; El Mokh et al., 2015; Rens et al., 2015). The increase in tuber yields may be attributed to improved growth and yield components due to moderate N application, while the reduction in tuber yields may be caused by the harm to potato growth induced by the excessive N. The results above indicated that both limited or excessive N would lead to yield reduction, so the lower P levels (40–50%) with an intermediate rate of applied N (135–150 kg N ha^{-1}) were enough to obtain high tuber yield in this arid region.

In both seasons, WUE varied significantly under different P levels (ANOVA, $P < 0.05$), water was used more efficiently in the lower designed P. Improved WUE can be obtained either by achieving the same yield with reduced water or by increasing yield with the same applied water (Kashyap and Panda, 2003; Badr et al., 2012). The treatments with lower P received less amount of irri-

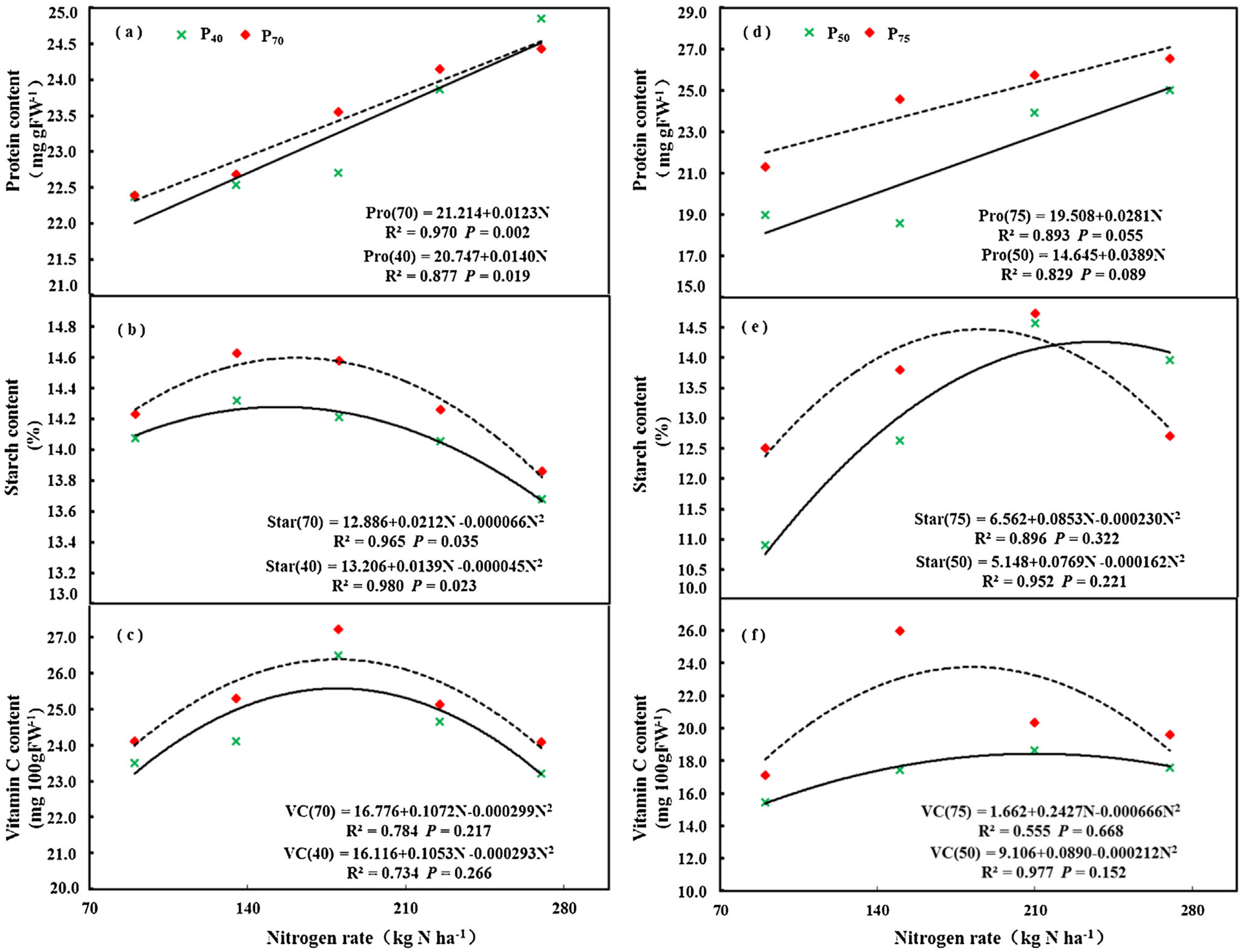

Fig. 4. Relationship between potato protein (Pro), starch (Sta), and vitamin C (VC) and applied nitrogen (N) rates under different soil wetting proportions (P) in 2012 (a–c) and 2013 (d–f) at Wuwei, Gansu Province, China.

gation water (Fig. 2) and achieved higher yield (Table 3), so WUE was greatly improved. The P × N significant interaction for WUE (ANOVA, $P < 0.05$) was found in both seasons. In 2012, the greatest WUE (16.6 kg m^{-3}) was obtained in treatment with 40% wetted soil volume and 135 kg N ha^{-1}, significantly higher than other treatments. In 2013, the greater WUE (13.7–13.9 kg m^{-3}) was also found in treatment under lower P level (50%), similar to the result of 2012, but there's no significant difference between different N rates with the same P level.

3.5. *Potato tuber quality*

Although the content of protein, starch and vitamin C with lower P were numerically smaller than with higher P, the differences were not statistically significant (Fig. 4).

A positive effect of the increasing N on the protein content was clear at all wetted soil volumes, similar to the results of some early researches (Millard, 1986; Leszczynski and Lisinska, 1988; Gao et al., 2015). In 2012, the interactive effects of P and N on the protein content was statistically significant (Fig. 4a), and the highest content (24.8 mg gFW^{-1}) was found in the treatment with 40 percent of the wetted soil volume and 270 kg N ha^{-1}. Although protein content increased with the increase of N application in 2013, no significant difference was found among different N rates at both P levels (Fig. 4d).

There was a quadratic response of starch content to the total amount of applied N both cropping seasons, similar to the N effect on tuber yield (Fig. 4b and e). Gao et al. (2015) reported that the application of N fertilizers increased the starch concentration to some extent, while Leszczynski and Lisinska (1988) reported that intensified nitrogen fertilization decreased the content of dry matter and starch in potato tubers. Under a given designed wetted soil volume, the difference of starch content was significant among different N rates (ANOVA, $P < 0.05$). According to the quadratic equations ($P < 0.05$) in 2012, the highest values (14.3 and 14.6%) were found at the N rate of 154 and 161 kg N ha^{-1} under 40 and 70 percent of wetted soil volume, respectively. In 2013, the highest values (14.6 and 14.7%) were obtained at the N rate of 210 kg N ha^{-1} under 50 and 75 percent of wetted soil volume, respectively.

The separate effect of P and N on VC content was significant, but the P × N interaction for VC was not significant according to two-way ANOVA. VC content under the higher P levels was 13% and 20% higher than that under the lower ones in 2012 and 2013, respectively. Similar to the result of starch content in potato tubers, there were quadratic responses of VC to N rates (Fig. 4c and f). An increase in N rate from 90 to 180 kg N ha^{-1} in 2012 and from 90 to 150 kg N ha^{-1} in 2013 resulted in the increase of VC content. Gao et al. (2015) reported that increased nitrogen supply enhanced the VC content of potato tubers. However, the VC content in the present study was reduced with excessive N fertilization (larger than 180 kg N ha^{-1} in 2012 and larger than 210 kg N ha^{-1} in 2013), this phenomenon might be due to the fact that the excessive N applications resulted in increased vegetative growth and larger tubers which could provoke biological dilution effect on VC (Lee and Kader, 2000; Stefanelli et al., 2010).Results of the two years suggested that under well irrigated condition, the intermediate rate of N (135–150 kg N ha^{-1}) was sufficient for high quality potato tubers.

4. Summary and conclusions

When the irrigation threshold was the same, total irrigation amount was reduced by 50 and 67 mm with the decrease in P, respectively in 2012 and 2013 growing seasons. Seasonal ET_c of the larger wetted soil volumes (70 and 75%) were significantly greater than those of the smaller ones (40 and 50%), but the differences in ET_c were not significant among different N rates. Tuber yield of different P levels were not statistically different. The applied water was used more efficiently in the lower designed soil wetting proportion levels. The highest WUEs (16.6 and 13.9 kg m^{-3}) would be obtained with the N application of 135 and 210 kg N ha^{-1} for wetting 40 and 50 percent of the soil volume, respectively. The interactive influence of P and N on WUE was significantly different.

Tuber quality parameters like protein content, starch content and vitamin C content were significantly influenced by the total amount of applied N. Quadratic curves can fit well the relationship of tuber starch content and vitamin C content with the amount of applied N. Tuber protein was positively and linearly correlated with the amount of applied N.

Based on the above results from different soil wetting proportion levels and N rates, considering the yield, ET_c, WUE and quality, it is recommended that the potatoes be irrigated timely (irrigation was applied when the soil matric potential (SMP) at 0.2 m depth immediately under the drip emitters reached −25 kPa), the proportion of wetted soil volume remained moderate (40–50%), and applied N also be moderate (135–150 kg N ha^{-1}). For the arid regions of Northwest China moderate irrigation and N fertilization are adequate to realize yields triple of the national average, simultaneously harvesting higher quality potatoes, and conserving irrigation water.

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