Yield, Nutrient Quality and Water and Phosphorus Recovery Efficiencies of Alfalfa under Different Drip Irrigation and Phosphorus Levels in Northern Xinjiang, China

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Research Article

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Abstract

Rational water and fertilizer management have an important impact on alfalfa production. This research aimed to explore the effects of water and phosphorus (P) fertilizer on hay yield, nutrient quality, water-use efficiency (WUE) and phosphorus-recovery efficiency (PRE) of each cut of alfalfa under drip irrigation and to determine the best water and P interaction model for high quality and yield of alfalfa. In this study, different irrigation levels, i.e., 5.25, 6.0, and 6.75 ML ha^{-1} (referred to as W_1, W_2, W_3, respectively), and P fertilizer levels (0, 50, 100, and 150 kg P_2O_5 ha^{-1} referred to as P_0, P_1, P_2, P_3, respectively) were set to determine the hay yield and nutrient quality of each cut of alfalfa under drip irrigation and to calculate WUE and PRE. The hay yield of each cut of alfalfa increased first and then decreased with increased P fertilizer under the same irrigation amount, and there was no significant difference among different irrigation treatments with respect to the hay yield of alfalfa. The crude protein (CP) reached a maximum under the W_2P_2 treatment. WUE decreased gradually with an increasing irrigation amount under the same P application. The WUE of alfalfa increased first and then decreased with the increase of P application under the same irrigation amount, and WUE was 0.20%–4.75% (2016) and 1.31%–6.22% (2017) higher in the P treatments than in the non-phosphorus treatments. PRE decreased gradually with increasing P application under the same irrigation amount. Therefore, we conclude that moderate irrigation (6.0 ML ha^{-1}) and P fertilizer (100 kg P_2O_5 ha^{-1}) combined with application, the alfalfa has higher WUE and PRE, and can significantly promote the alfalfa hay yield and nutrient quality of each cut.

Background

Alfalfa (*Medicago sativa* L.) is a perennial leguminous forage with high yield, good nutritive value and wide adaptability[1]; it is known as the "king of forage". Alfalfa is a important ecological functions, and is widely grown in semiarid areas[2], has the effect of improving soil fertility and is widely grown in northwest China (the planting area of alfalfa is about 2.62×10^5 ha), where precipitation is scarce and evaporation is high. Water resources are the key that restricts alfalfa production and directly or indirectly affect hay yield and quality of alfalfa[3]. Some studies demonstrated that sufficient irrigation could significantly increase the hay yield of alfalfa[4], mainly because water supply significantly affects the growth and development of alfalfa plants, hay yield, nutrient quality and water-use efficiency (WUE)[5], while a water shortage could significantly reduce the hay yield of alfalfa[6]. In addition to water, phosphorus (P) is an indispensable nutrient element for alfalfa and is one of the main factors for increasing crop yield[7]. Alfalfa is a crop with a high P demand, and long-term planting reduces the available phosphorus (AP) in the soil[8]. A lack of P in soil will affect the growth and development of alfalfa, so P application can improve the hay yield of alfalfa[9], and P concentrations of alfalfa increase with increased P fertilizer[10]. P application also plays a significant role in regulating water, and proper P application can improve WUE[6].

Crude protein (CP), neutral detergent fibre (NDF) and acid detergent fibre (ADF) are three important nutrient quality indicators for forage. An earlier study suggested that the nutritive value of alfalfa was positively correlated with CP and negatively correlated with NDF and ADF[11]. P application can affect nutrient quality by increasing the CP and adjusting the NDF and ADF in plants[12]. Alfalfa hay yield decreased gradually, and CP also decreased with an increase in planting years. P application is a good way to solve the problem, but phosphorus-recovery efficiency (PRE) remains low[13]. Most of the phosphate fertilizer applied to the soil cannot be fully utilized in the current season in actual production. Usually, 80% of P fertilizer is adsorbed by metal ions in soil or converted to insoluble forms in the soil [14-15], which enriches soil P and causes environmental pollution while restricting the growth and development of alfalfa. Water and fertilizer are two main factors affecting the growth of alfalfa, and there are synergistic effects[16]. At the same time, P concentration and hay quality parameters (CP and ADF) are closely related to plant growth capacity and plant mass; then, any water effect on v and mass would also promote changes in P concentration and hay quality[17]. However, the mechanism underlying the interaction between water and P and plant growth leading to changes in plant phosphorus concentration, CP and ADF concentration are still unclear. It is of interest to distinguish the effects of water-P interaction on P concentration and hay quality between (i) the indirect effect through plant growth and (ii) direct effect through water deficit and P nutrition.

Since the 21st century, drip irrigation technology has been rapidly and extensively promoted in the oasis district of Xinjiang, which has brought about major changes in the production technology of Xinjiang's agriculture due to the high efficiency of water-saving and increasing production. For the first time, drip irrigation technology has been successfully applied to alfalfa cultivation at the 148th Regiment in the Xinjiang Production and Construction Corps, China, in 2008, and has been widely promoted. However, researches on the effect of water-P interaction on hay yield, nutrient quality and WUE and PRE of drip-irrigated alfalfa between different cuts are scarce, and how much irrigation and P application can make alfalfa hay yield and nutritional quality achieve the best, it is still unclear in the actual production of alfalfa. Therefore, it is of great practical significance to determine the optimal water and phosphorus interaction mode for improving alfalfa hay yield and nutritional quality of each cut. The objectives of this study were to clarify the relationship between the production performance, nutrient quality, WUE and PRE rate of drip-irrigated alfalfa between different cuts, and to provide a theoretical basis for the formulation of high-quality and high-yield management measures of drip irrigation alfalfa in the world with the same longitude and latitude.

Materials And Methods

Site Description

The field experiment was conducted during 2016 and 2017 at Tianye group agricultural demonstration park (44°26' N, 85°95' E), Shihezi City, Xinjiang, China. The experimental site was located in an arid temperate continental climate zone with large diurnal temperature variations. Mean annual temperature was 11.2 (2016) and 14.0°C (2017), and annual precipitation was 395 (2016) and 203 mm (2017). The previous crop was cotton (*Gossypium* spp.). The physical and chemical properties of the 0-20 cm plough layer soil are shown in Table 1.

Experimental Design

The experimental treatments were the factorial combinations of three irrigation rates (5.25 ML ha^{-1} (W_1), 6.0 ML ha^{-1} (W_2, the actual irrigation amount of local alfalfa high yield field) and 6.75 ML ha^{-1} (W_3)) and four P fertilizer rates (as P_2O_5 equivalent; 0 kg ha^{-1} (P_0), 50 kg ha^{-1} (P_1), 100 kg ha^{-1} (P_2) and 150 kg ha^{-1} (P_3)), with three replicates in a randomized complete block design. The P was monoammonium phosphate (P_2O_5 52 %). Each block was 40 m^2 (5 × 8 m).

There were 8 irrigation times in each growing season, the specific irrigation time was 8–10 days before harvest and 3–5 days after harvest, and the P fertilizer was evenly divided into four times and applied to the soil with irrigation under drip irrigation, beginning at the branching stage of spring growth following winter dormancy and subsequently 3–5 d after the each cuts. The specific cutting time was May 25, June 26, August 1 and September 25, 2016. The cutting time was May22, June26, July 30 and September 23, 2017.

The alfalfa cultivar WL354HQ (Fall dormancy class, FDC 3.9) was sown on April 19, 2015. The crop was sown with artificial drilling (seed drill) using a seed rate of 18.0 kg·ha^{-1} with a row-spacing of 20 cm, and the sowing depth was 2.0 cm. Drip irrigation belts were buried at a depth of 8–10 cm with a distance between drip irrigation belts of 60 cm. Inlaid drip irrigation belts (produced by Green Source Co., Ltd. in Beijing) were used, and the distance between the drip heads was 20 cm. Monthly rainfall and average temperature during the growing seasons in 2016 and 2017 are presented in Fig. 1.

Soil sample collection

Soil samples of 0–20 cm were taken from soil drills in each plot by the "S" sampling method in October of each year. Five soil samples from the same soil layer were mixed to make composite soil samples. After removing impurities such as alfalfa roots and stones, the soils were brought back to the laboratory and dried to constant weight in an oven at 65°C. The fine soil was sifted through a 100 mesh sieve for reserve[18].

Sampling and Measurements

The hay yield of each cut of alfalfa was measured by cutting three 1 m × 1 m quadrats in each plot at the early flowering stage (10 % blooming) and cut four times a year. The specific harvesting dates were May 25, June 26, August 1, and September 25, 2016 and May 22, June 26, July 30 and September 23, 2017. The alfalfa plants in the sample plot (cut height 5 cm) were cut with scissors and weighed, and the yield of fresh alfalfa forage was recorded. A sample of 300 g per plot fresh alfalfa was taken back to the laboratory. The samples were first oven-dried at 105°C for 30 min and then at 65°C to a constant mass.

Crude protein (CP) was determined by the semimicro Kjeldahl method. The neutral detergent fibre (NDF) and acid detergent fibre (ADF) were determined according to procedures of Van Soest[19]. The relative feeding value (RFV) was calculated by NDF and ADF using the following equation[20]:

$$RFV = (88.9 - 0.779 \times ADF) \times (120 / NDF) / 1.29 \qquad (1)$$

In the process of measuring alfalfa hay yield, three fresh alfalfa samples were dried and crushed. Forage P concentration was determined using the molybdenum-antimony spectrophotometric method[21].

The P concentration of the alfalfa was multiplied by the respective yields to calculate the shoot P uptake based on the hay yield. The P uptake based on the hay yield was added together to determine the total P uptake and was converted to kg P uptake ha^{-1}. Phosphorus recovery efficiency (PRE) was calculated as the following equation[21]:

$$PRE = (U_p - U_0) / F_p \qquad (2)$$

where U_p and U_0 are the P taken up by alfalfa from soils with (U_p) and without (U_0) added P and F_p is the amount of P applied, and the result expressed as a percentage.

The WUE of alfalfa was calculated using the following equation[23]:

$$WUE = HY / ET \qquad (3)$$

where HY is the alfalfa hay yield, and ET (evapotranspiration) is the crop water consumptio[16]. Then:

$$ET = P + U + I - F - R - \Delta W \qquad (4)$$

where P is precipitation, U is the groundwater recharge, I is the amount of irrigation, F is the deep drainage, R is the runoff, and ΔW is the change in soil moisture from the beginning to the end of the trial[24], soil moisture content was determined by drying method. According to the conditions during the experiments (no slope, deep water table), the contributions of groundwater recharge, runoff and deep drainage were negligible.

Total phosphorus (TP) was determined by the sulfuric acid-perchloric acid decoction molybdenum antimony colorimetric method, and AP was determined by the $NaHCO_3$ extraction molybdenum antimony colorimetric method[25].

Economic benefits

Economic benefit analysis refers to the assessment and evaluation of the size or level of economic benefits, and the analysis and Research on the causes of its formation[26].

$$EB=YB-TC \quad (5)$$

$$YB=Y-P \quad (6)$$

$$TC=LRC+SC+WC+PC+WEC+LC+HC \quad (7)$$

where EB is the Economic benefit, YB is the yield benefit, TC is the total cost, Y is the yield of alfalfa, P is the price of alfalfa, LRC is the land rent cost, SC is the seed cost, PC is the phosphorus cost, WE is the water and electricity cost, LC is the labor cost, and HC is the harvesting cost.

Statistical Analysis

The effects of water and P on the hay yield, CP, RFV, WUE, PRE and P concentration of alfalfa were examined using two-way (W, P, W×P) ANOVA for each of the 8 harvest dates separately. The means were compared using Duncan tests at $P < 0.05$. The statistical analyses were determined with 7.05 (Data Processing System, China).

The subordinate function evaluation method was used to comprehensively evaluate the optimal treatment using the following formulas:

$$UX(+) = (Xij - Ximin) / (Ximax - Ximin) \quad (4)$$

$$UX(-) = 1 - UX(+) \quad (5)$$

where X is the measured value of each index of the sample; UX(+) is the positive correlation low function value of each index; and UX(-) is the negative correlation low function value of each index[18].

Results

Water × Phosphorus Interaction

The water and P interaction of each index was analysed in 2016 and 2017. The irrigation amount and P application had significant effects on each index for same cut moments (Table 2). The irrigation amount and P application had a significant effect on alfalfa hay yield ($P < 0.01$), but the interaction W×P was not significant ($P > 0.05$) for alfalfa hay yield at any cut moment. The irrigation amount had a significant effect on RFV and on CP and WUE ($P < 0.01$) at all cut moment. The P application significantly affected WUE ($P < 0.05$), P concentration and PRE ($P < 0.01$) at all cut moments in both seasons. In general, the interaction W×P was not significant for the productivity indicators evaluated, for the majority of the cut moments ($P > 0.05$).

Phosphorus Concentration of Alfalfa

The P concentration of alfalfa was significantly affected by the irrigation level and P application rate in both years (Table 3). Under the same irrigation amount, P concentration increased gradually (2016) or increased first and then decreased (2017) with increased P fertilizer; the maximum P concentration was attained under the P_2 and P_3 treatments. P concentration ranged from 0.19 to 0.28% for the P_1, P_2 and P_3 treatments, across irrigation levels, cut moments and seasons. The P_1, P_2 and P_3 treatments increased P concentration by 0.05%–0.14% compared with the P_0 treatment (Table 3). Under the same P application treatment, there was no obvious regularity of P concentration in alfalfa under different irrigation treatments, for which the maximum P concentration was attained under W_2 treatments in 2017.

Hay Yield

The hay yield of each cut of alfalfa increased first and then decreased with increased P fertilizer under the same irrigation amount (Table 4). In general, the maximum hay yield was attained under the P_2 treatment and was significantly greater than that in the P_0 treatment ($P < 0.05$), in the majority of the cut moments and across water levels and seasons. Under the W_1 treatment, hay yield of alfalfa was significantly higher than that at the P_0 treatment ($P < 0.05$) except for the second and third cut ($P > 0.05$) during the first growing season. The P_2 treatment resulted in the highest hay yield of alfalfa at all water levels in the second growing season (Table 4). Under the P_0 and P_1 treatments, the hay yield in the W_2 and W_3 treatments was significantly higher than that in the W_1 treatment in the first cut ($P < 0.05$), while under the P_2 and P_3 treatments, there was no significant difference among different irrigation treatments with respect to the hay yield of alfalfa ($P > 0.05$). Except for W_3 treatment in 2017, the hay yield of each cut of alfalfa reached the maximum under W_2 treatment. The maximum hay yield of each cut of alfalfa was attained under the W_2P_2 treatment in 2016 and under the W_3P_2 treatment in 2017.

CP Concentration and RFV

The CP concentration increased first and then decreased with increased P fertilizer; the maximum CP concentration was attained in the P_2 treatment under the same irrigation amount (Table 5). The CP concentration increased first and then decreased with increasing irrigation amount; the maximum CP concentration was attained in the W_2 treatment under the P_2 treatment. P_0, P_1 and P_3 had similar patterns in the first and second cut. The maximum CP concentration was attained in the W_2P_2 treatments under water-P interaction treatments.

The RFV gradually increased with increasing P fertilizer under the same irrigation amount; the maximum hay yield was attained under the P_3 treatment and only in the second cut (2017), and the same treatment.

WUE

Under the same irrigation amount, WUE followed the same trend across P levels as alfalfa hay yield; thus, it increased first and then decreased with increased P fertilizer. The maximum WUE was attained under the P_2 treatment (Table 6). Except for the third cut difference in WUE, the other cuts in all P_2 treatments were significantly higher than the P_0 treatment ($P < 0.05$). The maximum WUE was attained under the P_1 treatment, except for the fourth cut of the P_2 treatment in 2016. The other P application treatments increased with increasing P fertilizer within the same water level. The P_1, P_2 and P_3 treatments increased by 0.20%–4.75% (2016) and 1.31%–6.22% (2017) compared with the P_0 treatment. The WUE in 2017 was higher than that in 2016 for the first three cuts, while the WUE in 2017 was lower than that in 2016 for the fourth cut.

PRE

In this study, P_0 was a treatment without P application, so PRE was not calculated for this treatment. Under the same irrigation level, the PRE gradually increased with P fertilizer; the PRE in the P_1 and P_2 treatments was significantly higher than that in the P_3 treatment ($P < 0.05$) (Table 7). There was no obvious change in PRE with increased irrigation amount under the P_1 and P_2 treatment. Under P_3 treatments, the PRE increased first and then decreased with increasing irrigation amount, with the maximum WUE being attained under the W_2 treatment, except for the second cut in 2016. The maximum PRE was attained under W_1P_1 (2016) and W_2P_1 (2017), with values of 36.09% and 30.72%, respectively, under different P application treatments, which indicated that a reasonable irrigation amount could improve the PRE of alfalfa. The PRE were 7.22%–36.09% and 6.57%–30.72% in 2016 and 2017, respectively. The 2017 value decreased by 0.65-5.37 compared with the 2016 value, and the PRE decreased with increased cuts.

Comprehensive evaluation

We used the following five indicators of alfalfa for a comprehensive evaluation: Phosphorus concentration, hay yield, CP, RFV, WUE (Table 8). According to the comprehensive ranking of alfalfa production indicators under different inoculation treatments, the top three inoculation treatments were as follows: $W_2P_2 > W_2P_1 > W_3P_2$.

Economic benefits

The economic benefits of the best group of treatments are calculated according to the membership function. Economic benefit analysis of alfalfa production in the irrigation of 6.0 ML ha^{-1} and 100 kg P ha^{-1} treatment is shown in Table 9. The net benefit of alfalfa production was 2 505–2 616 \$ ha^{-1}.

Discussion

The hay yield of alfalfa is greatly affected by water and fertilizer conditions[27-28]. Research showed that the application of phosphate fertilizer can significantly increase the photosynthetic rate[21], accelerate the growth of alfalfa plants, and then increase the hay yield of alfalfa within the range of suitable P application, which promotes the accumulation of P in alfalfa plants[29]. In addition, under the condition of drip irrigation, the appropriate rate of phosphate fertilizer significantly promoted the total hay yield of alfalfa[30]. In this study, low P application increased the P concentration of alfalfa plants (Table 3) and then increased the hay yield of each cut of alfalfa. This was in accordance with work reported by Maiorana et al. (2001)[31] in Europe and by Berg et al. (2018)[32] in America south of West Lafayette for the lowest dose of phosphoric fertilizer assured the best qualitative responses of alfalfa. Therefore, the use of low P (0 kg ha^{-1}) application in alfalfa production can achieve relatively high hay yield.

Research showed that crop mass accumulation is related to P application, and it has a certain promoting effect on the accumulation of dry matter in alfalfa[33], but excessive P application could result in a decrease in the dry matter of alfalfa, because there is a certain threshold of absorbed P for dry matter production[34]. In addition, excessive P uptake by plants could have a competitive effect with the uptake of other elements by plants, resulting in unbalanced nutrition, which would reduce plant yield[21]. When phosphorus application exceeds the maximum phosphorus uptake by alfalfa, the hay yield of alfalfa plants decrease, which harms plant growth and development[29].

Moreover, using the relationship between nitrogen (N) and P concentrations, crop nutrition can be examined in more detail[33]. It was showed that P can promote N assimilation and provides a material basis for protein synthesis [35]. Furthermore, the crop yield has a positive shift as N supply increases in conditions of high soil P availability, while has a negative shift in conditions of low soil P availability. In this study, in the range of 0–100 kg P ha^{-1}, alfalfa hay yield of each cut increased gradually with the increase of P application rate (Table 4). This is mainly because (i) P application can promote the increase of N in soil[33], and (ii) the allometric relationships of absorbed P and N with shoot mass lead to the relationship between %P and %N, and this ratio between P and N concentrations increases as %N decreases as a consequence of the dilution of N by increasing crop mass[33]. The functional relationship proposed by Lemaire and Belanger (2020)[35] relating crop N uptake and crop mass accumulation during the time course of crop growth illustrates this very well. Therefore, P concentration is closely linked to absorbed N in plant. However, irrigation promotes the growth of plants and enhances the water absorption function of root system, thus alfalfa can obtain more nutrients and water[3]. Therefore, N concentration is affected by water to some extent, and in turn CP is also affected by water stress[33]. It has been showed that there is a certain threshold for the P absorption by alfalfa plants. Below this threshold, P can promote alfalfa growth and development[23]. When the P application exceeded the maximum absorption of P by alfalfa, P had a negative impact on plant growth and development and alfalfa hay yield decreased. As alfalfa hay yield is closely related to CP concentration, excessive P may limit the availability of N, and then reduce the CP concentration. Of course, the specific impact mechanism needs further research. Consequently, the CP increased first and then decreased with increasing irrigation amount (Table 5).

In this study, the hay yield (Table 4) and CP concentration (Table 5) of each cut of alfalfa reached the maximum under W_2P_2 treatment. The allometric growth function showed that the CP concentration of forages can be directly related to the quantity of forage harvested[35]. Therefore, the water-P interaction may first cause the change of alfalfa yield, and then change the quality (CP concentration) of alfalfa, making the hay yield and CP concentration of alfalfa reach the maximum under W_2P_2 treatment, which indicated that reasonable irrigation and P application could improve the CP concentration of alfalfa. Research showed that ADF and NDF decline allometrically with crop mass accumulation and hence forage production[36]. So, any decline in crop mass, due to either water stress or P deficiency should have an effect on forage quality[35]. At the same time, there was no obvious trend of RFV in response to the irrigation amount and P application (Table 5). This was in accordance with work reported by Lemaire and Belanger (2020)[35] for NDF. This is mainly due to both forage nutritive value decline and plant phenology progression was only correlated with time[35].

Alfalfa WUE and PRE are important criteria for determining whether the irrigation amount and P fertilizer are reasonable. WUE is a physiological index used to describe the growth of alfalfa, especially the relationship between harvest yield and crop water consumption. Research showed that there is a positive link between WUE and hay yield[37]. Previous studies have shown that there are synergistic effects between water and fertilizer and that fertilization has an obvious water-regulating effect[38-39] In this study, although the WUE was highest in the W_1P_2 treatments (Table 6), the alfalfa hay yield of W_1P_2 treatments were relatively low (Table 4), which was mainly due to N nutrition of alfalfa was severely depress by water stress[37], and lower plant N nutrition will lead to lower plant P nutrition[33], which will reduce alfalfa hay yield. At the early stage of alfalfa growth, under drought conditions, increasing irrigation can promote the water absorption and plant growth of alfalfa[40], mainly because excessive irrigation increases alfalfa lodging, which is not conducive to alfalfa photosynthesis or dry matter accumulation, and ultimately reduces the hay yield of alfalfa. Appropriate fertilization can improve WUE and transform “ineffective” water to water that is “effective” for plant growth[41]. The interaction of water and P, to a certain extent, can reduce the irrigation amount and fertilization application in grassland management of alfalfa, achieving the goal of saving water and reducing fertilization costs while maintaining yield.

In the case of water deficit, crop root development is hindered, nutrient absorption capacity is reduced, and fertilizer efficiency is limited. When water is excessive, soil nutrient leaching occurs, soil permeability is reduced, root respiration and nutrient uptake by crops are hindered[42]. In this study, PRE increased first and then decreased with increased irrigation (Table 7). Therefore, the irrigation amount will indirectly affect the distribution of crop roots, which in turn affects the absorption of water and nutrients by roots. On the contrary, the study in Europe showed that water levels did not affect hay yield and PRE of alfalfa[31], which is different from the results of this study, probably because of the rainfall in the experimental area of this study was less than 200 mm, alfalfa was more sensitive to irrigation water, while there are good winter rainfalls (over 600 mm), which levelled the effects of irrigation[31]. It can be seen that the coupling of water and P under drip irrigation can improve the PRE of alfalfa plants.

In addition, land is one of the main limiting factors to get the most economic benefits from planting alfalfa in Xinjiang, China. Because the lease fee of land was 857 \$ ha^{-1}, while the cost of irrigation water (including water fee and electricity fee) was only 257 \$ ha^{-1} (Table 9). Therefore, the most economical way for alfalfa growers is to maximize the hay yield of alfalfa. In this study, the net economic benefits of alfalfa production reached 2 505–2 616 \$ ha^{-1} (Table 9). Studies in northern China showed that the economic benefit of planting alfalfa was significantly better than that of planting grass[43], largely due to the market value of alfalfa was higher than that of grass, while irrigation has little impact on the economic benefit of alfalfa growers.

Conclusions

Water-P interaction significantly improved hay yield, nutrient quality, WUE and PRE of each cut of alfalfa. Suitable increase in the irrigation amount can improve the PRE of alfalfa, so the effective interaction of water and P can promote P through the effect of water and can regulate water through the effect of P. Therefore, moderate irrigation (6.0 ML ha^{-1}) and P fertilizer (100 kg P_2O_5 ha^{-1}) combined with application, the alfalfa has higher WUE and PRE, and can significantly promoted the further improvement of alfalfa hay yield and nutrient quality of each cut.

Abbreviations

WUE, water-use efficiency; PRE, phosphorus-recovery efficiency; CP, crude protein; NDF, neutral detergent fibre; ADF, acid detergent fibre; RFV, relative feeding value; TP, total phosphorus; AP, available phosphorus.

Declarations

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Author contributions

Qianbing Zhang and Junying Liu designed the study. Qianbing Zhang and Junying Liu interpreted the results. Junying Liu, Xuanshai Liu, Shengyi Li and Yanliang Sun performed the experiments. Qianbing Zhang, Shengyi Li and Junying Liu participated in writing the manuscript: Weihua Lu and Chunhui Ma supervised the study. All authors read and approved the final manuscript for publication.

Conflict of Interest

The authors declare that there is no conflict of interest.

References

1. Sun, T., Li,, Wu ,Q., Sheng, T., and Du, M. Effects of alfalfa intercropping on crop yield, water use efficiency, and overall economic benefit in the Corn Belt of Northeast China. *Field Crop. Res.***216**, 109-119. https://doi.org/10.1016/j.fcr.2017.11.007 （2018）
2. Gu, Y.J., Han, L., Fan, J.W.,. Shi, X.P, Kong, M., Shi, X.Y., et al. Alfalfa forage yield, soil water and P availability in response to plastic film mulch and P fertilization in a semiarid environment. *Field Crop. Res.* **215**, 94-103. https://doi.org/10.1016/j.fcr.2017.10.010 （2018）
3. Atikur, R.M. et al. Proteome analysis of alfalfa roots in response to water deficit stress. *Integr. Agric.***15**, 1275-1285. https://doi.org/10.1016/S2095-3119(15)61255-2 （2016）
4. Bai, W.M., and Li,H. Effect of irrigation methods and quota on root water uptake and biomass of alfalfa in the wulanbuhe sandy region of China. *Agric. Water Manage.***62**, 139-148. https://doi.org/10.1016/S0378-3774(03)00075-1 （2003）
5. Ismail, S.M., and Almarshadi,H. Maximizing productivity and water use efficiency of alfalfa under precise subsurface drip irrigation in arid regions. *Irrig. Drain.***62**, 57-66. https://doi.org/10.1002/ird.1705 （2013）
6. Fiasconaro, M.L., Gogorcena,, Muñoz, F., Andueza, D., M. Sánchez-Díaz, and Antolín, M.C. Effects of nitrogen source and water availability on stem carbohydrates and cellulosic bioethanol traits of alfalfa plants. *Plant Sci.* 191-192, 16-23. https://doi.org/10.1016/j.plantsci.2012.04.007 （2012）
7. Zhu, J., Li,, and Whelan, M. Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review. *Sci. Total Envir.* **612**, 522-537. https://doi.org/10.1016/j.scitotenv.2017.08.095 (2018)
8. Jia, Y., Li,M., and Wang, X.L. Soil quality responses to alfalfa watered with a field micro-catchment technique in the loess plateau of China. *Field Crop. Res.* 95, 64-74. https://doi.org/10.1016/j.fcr.2005.02.002 （2006）
9. Hakl J, Kunzová,, and Konečná, J. Impact of long-term organic and mineral fertilization on lucerne forage yield over an 8-year period. *Plant Soil Environ.***62**, 36-41. https://doi.org/10.17221/660/2015-PSE （2016）

10. Fan, J.W., Du Y.L., Wang,R., Turner, N.C., Wang, T., Abbott, L.K., et al. Forage yield, soil water depletion, shoot nitrogen and phosphorus uptake and concentration, of young and old stands of alfalfa in response to nitrogen and phosphorus fertilisation in a semiarid environment. *Field Crop. Res.* **198**, 247-257. https://doi.org/10.1016/j.fcr.2016.08.014 （2016）
11. Lin, J.C., Nosal,, Muntifering, R.B., and Krupa, S.V. Alfalfa nutritive quality for ruminant livestock as influenced by ambient air quality in west-central alberta. *Environ. Pol***149**, 99-103. https://doi.org/10.1016/j.envpol.2006.12.009 （2007）
12. Lissbrant, S., Stratton,, Cunningham, S.M., Brouder, S.M., and Volenec, J.J. Impact of long-term phosphorus and potassium fertilization on alfalfa nutritive value-yield relationships. *Crop. Sci.***49**, 1116-1124. https://doi.org/10.2135/cropsci2008.06.0333 （2009）
13. Berg, W.K., Cunningham,M., Brouder, S.M., Joern, B.C., Johnson, K.D., Santini, J., et al. Influence of phosphorus and potassium on alfalfa yield and yield components. *Crop Sci.***45**, 297-304. https://doi.org/10.2135/cropsci2005.0297 （2005）
14. Schröder, J.J, Smit,L., Cordell, D., and Rosemarin, A. Improved phosphorus use efficiency in agriculture: a key requirement for its sustainable use. *Chemosphere*. **84**, 822-831. https://doi.org/10.1016/j.chemosphere.2011.01.065 （2011）
15. Gao, X., Shi,, Lv, A.,Wang, S., Yuan, S., Zhou, P., et al. Increase phosphorus availability from the use of alfalfa (*medicago sativa* L.) green manure in rice (*oryza sativa* l.) agroecosystem. *Sci. Rep.***6**, 36981. https://doi.org/10.1038/srep36981 （2016）
16. Wang, H.D., Wu, F., Cheng, M.H., Fan, J.L., Zhang, F.C., Zou, Y.F., et al. Coupling effects of water and fertilizer on yield, water and fertilizer use efficiency of drip-fertigated cotton in northern Xinjiang, China. *Field Crop. Res.***219**, 169-179. https://doi.org/10.1016/j.fcr.2018.02.002 （2018）
17. Malhi, S.S., Loeppky, H., Coulman, B., Cill, K.S., Curry, P., and Plews, T. Fertilizer Nitrogen, Phosphorus, Potassium, and Sulphur Effects on Forage Yield and Quality of Timothy Hay in the Parkland Region of Saskatchewan, Canada. *JPlant* Nutr. 27, 1341-1360. https://doi.org/1081/PLN-200025834 （2005）
18. Liu, J.Y., Liu, X.S., Zhang Q.B., Li, S.Y., Sun, Y.L., Lu, W.H.m, and Ma, C.H. Response of alfalfa growth to arbuscular mycorrhizal fungi and phosphate-solubilizing bacteria under different phosphorus application levels. *AMB EXPRESS*. **10**, 1-13.
19. Van Soest, P.J., Robertson,B., and Lewis, B.A. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *J. Dairy Sci.***74**, 3583-3597. https://doi.org/10.3168/jds.S0022-0302(91)78551-2 （1991）
20. Rohweder, D.A., Barnes, F., and Neal, J. Proposed hay grading standards based on laboratory analyses for evaluating quality. *J. Anim. Sci.***47**, 747-759. https://doi.org/10.2527/jas1978.473747x （1978）
21. Fan, J., Hao,D., Malhi, S.S., Wang, Q.J., and Huang, M.B. Influence of 24 annual applications of fertilisers and/or manure to alfalfa on forage yield and some soil properties under dryland conditions in northern China. *Crop. Pasture Sci.***62**, 437-443. https://doi.org/10.1071/CP10370 （2011）

22. Roberts, T.L., and Johnston, E. Phosphorus use efficiency and management in agriculture. Resour. *Conserv. Recy.* **105**, 275-281. https://doi.org/10.1016/j.resconrec.2015.09.013 (2015)

23. Kunrath, T.R., Lemaire,, Sadras, V.O., and Gastal, F. Water use efficiency in perennial forage species: Interactions between nitrogen nutrition and water deficit. *Field Crop. Res.***222**, 1-11. https://doi.org/10.1016/j.fcr.2018.02.031 (2018)

24. Oweis, T.Y., Farahani,J., and Hachum, A.Y. Evapotranspiration and water use of full and deficit irrigated cotton in the Mediterranean environment in northern Syria. *Agric. Water Manage.***98**, 1239-1248. https://doi.org/10.1016/j.agwat.2011.02.009 (2011)

25. Mehlich, A. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Commun. *Soil Sci. Plant.***15**, 1409-1416. https://doi.org/10.1080/00103628409367568 (1984)

26. Zhang, J., Pang,P., Wang, Q., Yang, D., and Guo, Z.G. PRDI can maintain aboveground biomass and increase economic benefits in alfalfa through regulating N:P ratios in roots and leaves. *Field Crops Res.* **253**: 107821. https://doi.org/10.1016/j.fcr.2020.107821 (2020)

27. Wang, C., Ma,L., Yan, X., Han, J., Guo, Y., Wang, Y., et al. Yields of alfalfa varieties with different fall-dormancy levels in a temperate environment. *Agron. J.***101**, 1146-1152. https://doi.org/10.2134/agronj2009.0026 (2009)

28. Malhi, S.S. Relative response of forage and seed yield of alfalfa to sulfur, phosphorus, and potassium fertilization. *J. Plant Nut***34**, 888-908. https://doi.org/10.1080/01904167.2011.544357 (2011)

29. Mallarino, A.P., and Rueber, Alfalfa hay and soil-test phosphorus responses to long-term phosphorus fertilization strategies. *Soil Sci. Soc. Amer. J.***69**, 1118-1128. https://doi.org/lib.dr.iastate.edu/farms_reports/1954 (2013)

30. Sezen, S.M., Yazar, A., Tekin, S. Physiological response of red pepper to different irrigation regimes under drip irrigation in the Mediterranean region of Turkey. *Hortic.***245**, 280-288. https://doi.org/10.1016/j.scienta.2018.10.037 (2019)

31. Maiorana, Convertini, G., Fornaro, F. Yield and quality of alfalfa as affected by water irrigation and phosphorus levels. In: Delgado I. (ed.), Lloveras J. (ed.). Quality in lucerne and medics for animal production. *Zaragoza: CIHEAM.* 131-135. https://doi.org/10.1016/j.resconrec.2015.09.013 (2001)

32. Berg, W.K., Lissbrant, S., Cunningham,M., Brouder, S.M., and Volenec, J.J. Phosphorus and potassium effects on taproot C and N reserve pools and long-term persistence of alfalfa (*Medicago sativa* L.). *Plant Sci.***272**, 301-308. https://doi.org/10.1016/j.plantsci.2018.02.026 (2018)

33. Lemaire,, Sinclair, T., Sadras, V., and Belanger, G. Allometric approach to crop nutrition and implications for crop diagnosis and phenotyping: a review. *Agron. Sustain. Dev.***39**, 1-17. https://doi.org/10.1007/s13593-019-0570-6 (2019)

34. Pieters, A.J. Low sink demand limits photosynthesis under pi deficiency. *J. Exp. Bot.***52**, 1083-1091. https://doi.org/10.1093/jexbot/52.358.1083 (2001)

35. Lemaire, G., and Belanger, Allometries in plants as drivers of forage nutritive value: a review. *Agriculture***10**, 1-17. https://doi.org/10.3390/agriculture10010005.cc (2020)

36. Bai, Z.H, Li,G., Yang, X.Y., Zhou, B.K., Shi, X.J., Wang, B.R., et al. The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. *Plant Soil.***372**, 27-37. https://doi.org/10.1007/s11104-013-1696-y （2013）
37. Tandoh, S., Coulman, B., Biligetu, Assessment of crested wheatgrass (*Agropyron cristatum* L.) accessions with different geographical origins for agronomic and phenotypic traits and nutritive value. *Euphytica.***215**, 1-21. https://doi.org/10.1007/s10681-019-2476-4(0123 （2019）
38. Li, Y., and Su,R. Alfalfa water use and yield under different sprinkler irrigation regimes in north arid regions of China. *Sustainability.* **9**, 1-15. https://doi.org/10.3390/su9081380 （2017）
39. Rathore, V.S., Nathawat,S., Bhardwaj, S., Sasidharan, R.P., Yadav, B.M., Kumar, M., et al. Yield, water and nitrogen use efficiencies of sprinkler irrigated wheat grown under different irrigation and nitrogen levels in an arid region. *Agric. Water Manage.***187**, 232-245. https://doi.org/10.1016/j.agwat.2017.03.031 （2017）
40. Zhang G.Q., Liu. C.W., Xiao, H., Xie, R.Z., Ming, B., Hou, P.,. Liu, G.Z, Xu, W.J., Shen, D.P., Wang, K., Li, S.K. Optimizing water use efficiency and economic return of super high yield spring maize under drip irrigation and plastic mulching in arid areas of China. *Field Crops Res.***211**, 137–146. https://doi.org/10.1016/j.fcr.2017.05.026 (2017a)
41. Zhang, Y.Q., Wang,D., Gong, S.H., Xu, D., and Sui, J. 2017. Nitrogen fertigation effect on photosynthesis, grain yield and water use efficiency of winter wheat. *Agric. Water Manage.***179**, 277-287. https://doi.org/10.1016/j.agwat.2016.08.007 (2017b)
42. Abid, M., Mansour,, Yahia, L.B., Bachar, K., Ben Khaled A., and Ferchichi, A. Alfalfa nutritive quality as influenced by drought in South-Eastern Oasis of Tunisia. *Italian J. Anim. Sci.***15**, 334-342. https://doi.org/10.1080/1828051X.2016.1175916 （2016）
43. Yan, Y.L., Wan, Q., Chao, R., Ge, Y.Q., Chen, Y.L., Gu, R., et al. A comprehensive appraisal of four kinds of forage under irrigation in Xilingol, Inner Mongolia, China. *Rangeland J.*, **40**, 171-178. https://doi.org/10.1071/RJ16084 （2018）

Tables

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Figures

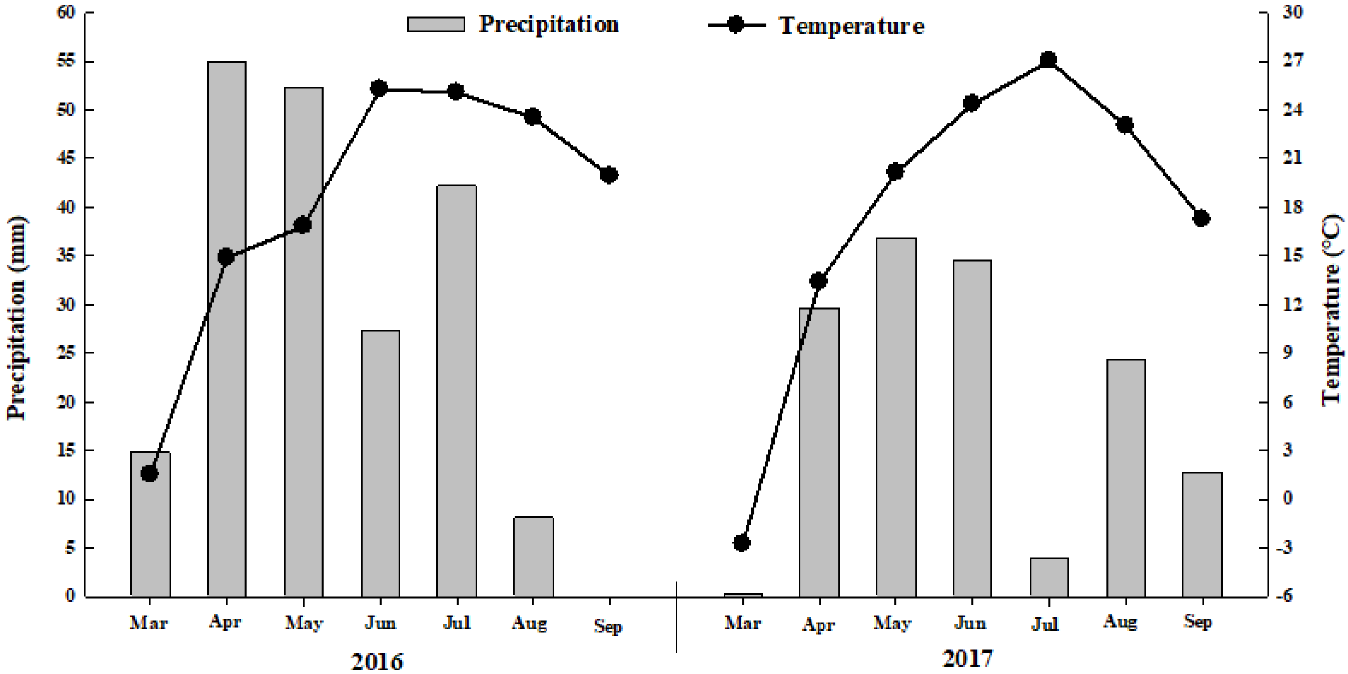
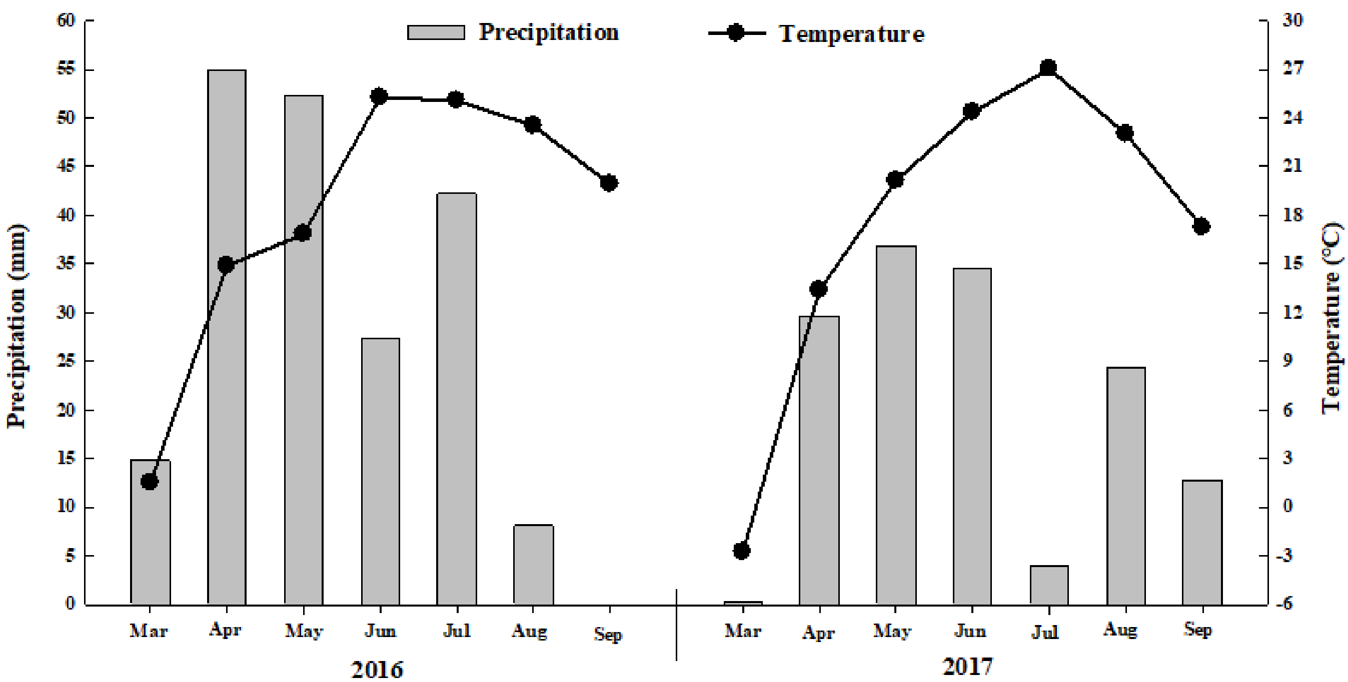


Figure 1

Mean monthly temperatures and accumulated precipitations per month during 2016 and 2017 growing seasons at the meteorological station of Shihezi in Xinjiang.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Mean monthly temperatures and accumulated precipitations per month during 2016 and 2017 growing seasons at the meteorological station of Shihezi in Xinjiang.

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