Experimental study and multi–objective optimization for drip irrigation of grapes in arid areas of northwest China

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ABSTRACT: Grapes are the most important cash crop in Xinjiang. However, the effective utilization of agricultural water and fertilizer in this area is relatively low, which is very unfavourable for the development of Xinjiang grape industry. At present, there is a lack of research based on multi-objective water and fertilizer optimization to guide grape production. Field experiments were thus conducted over three consecutive years (2015–2017) to study the effects of water and fertilizer coupling on the yield, fruit quality, water use efficiency (WUE), fertilizer partial productivity (PFP), and net profits of *Vitis vinifera cv.* "Frey" grapes in northern Xinjiang. The optimum input range of water and fertilizer for multi-objective optimization were determined by using multiple regression and spatial analysis. Five levels of $N–P_2O_5–K_2O$ (180–225–495, 240–300–660, 300–375–825, 360–450–990, 420–525–1155 kg ha^{-1}) were set up in the experiment, designated $F_{60\%}$, $F_{80\%}$, $F_{100\%}$, $F_{120\%}$, and $F_{140\%}$, respectively. Three drip irrigation levels were designated $W_{60\%}$, $W_{80\%}$, $W_{100\%}$, accounting for 60%, 80% and 100% of the ET_c (where ET_c denotes evapotranspiration under sufficient water supply for crops). The results show that at the same fertilization level, the leaf area index (LAI), vitamin C content, titratable acid, soluble solids content, dry matter yield, grape yield, PFP, and net profit increased with an increase in irrigation. They reached their maximum under full irrigation ($W_{100\%}$). Compared to $W_{80\%}$ and $W_{60\%}$ irrigation levels, the WUE at a full ($W_{100\%}$) irrigation was lower, but the PFP was the highest. The maximum grape bunch weight over three years was 407, 383, and 378 g, respectively. The highest harvest index (HI) was 0.460, 0.425, and 0.416, respectively. When the irrigation range was 334–348 mm and the $N–P_2O_5–K_2O$ fertilization range was 320–400–880~392–490–1077 kg ha^{-1}, the grape yield, net profit, WUE, vitamin C content, titratable acid content, and soluble solids content of the fruits reached more than 90% of their maximum values simultaneously. The results of this research provide a scientific reference for water and fertilizer management of drip irrigation in Xinjiang vineyards.

Keywords: Drip fertigation; Water and fertilizer use efficiency; Grape yield; Fruit quality; Net profits

1. Introduction

The Xinjiang region of China has necessary sunshine and temperature conditions for production of high quality grapes and is in fact the main grape-producing area in China. However, the climate in this area is dry. In the growing season, effective precipitation is usually the lowest, and the low utilization rate of water and fertilizer seriously restricts the sustainable development of the grape industry in Xinjiang. Drip irrigation and film mulching technology can precisely apply water and fertilizer to crop root soil through emitters, which has the function of increasing temperature and retaining moisture. Under this irrigation technology, water and fertilizer use has become significantly more efficient (Du et al., 2005; Yu et al., 2013; da Silva et al., 2018).

Ample water is necessary for grape growth (Faci et al., 2014; Centofanti et al., 2019; Petousi et al., 2019). Many scholars have studied irrigation systems suitable for grape growth and reported the effects of irrigation on grape growth (De la Hera et al., 2007; Acevedo–Opazo et al., 2010; Santesteban et al., 2011; Romero et al., 2015; Trigo–Cordoba et al., 2015; Yu et al., 2015; Yin et al., 2016; Pisciotta et al., 2018). Too much or too little drip irrigation under mulch is not conducive to improving grape yields in arid regions (Li et al., 2011a). Appropriate irrigation combined with canopy shading treatment can significantly increase economic benefits (Gil et al., 2018). In the absence of irrigation or deficit irrigation, when drought occurs in spring and summer, grape yields will decrease dramatically (Araujo et al., 2016). During the growing season for grapes, drought stress first reduces the stomatal conductance of leaves, weakening photosynthesis and consequently damaging the photosynthetic apparatus, which, in turn, further weakens photosynthesis (Li et al., 2019). Water deficits reduce grape assimilation, stomatal conductance, and transpiration, although they increase water use efficiency. With more pronounced water stress, the accumulation of dry matter decreases (Weiler et al., 2019). During the growth period, the optimum irrigation amount to achieve high yields whilst using water efficiently is about 240 mm (Li et al., 2011a). An average reduction in water use of 35% could increase the water use efficiency of grapes by 14–23% and reduce the yield of grapes by only 15–18%, without affecting the quality of grapes (Ma et al., 2019). Irrigation levels of 60–70% ET_c (where ET_c denotes evapotranspiration under sufficient water supply for crops) can increase anthocyanin accumulation in grape fruits and improve fruit quality (Ju et al., 2019).

Ample fertilizer is also an essential impact factor for grape growth (Du et al., 2009; Feng et al., 2015; Wang et al., 2016a). The combination of inorganic fertilizer and organic fertilizer results in the highest yield, quality, and agronomic efficiency of grapes (Xiong et al., 2018). Foliar nitrogen spraying increases the content of amino acids in grapes to a greater extent than soil spraying, although the effect of their combination is better (Canoura et al., 2018). At the optimum fertilizer application rate, Shi et al. (2011) found that the Kyoho grape needs to absorb 3.76 g of nitrogen for every 1000 kg of fruit. Fan et al. (2013) found that when $N–P_2O_5–K_2O$ was used at levels of 360–570–1275 kg·ha^{-1} in sandy land, the yield of grape was the highest. Hou et al. (2019a) reported that $N–P_2O_5–K_2O$ of 684–889 kg·ha^{-1} was the best fertilizer use range in extremely arid areas. Schreiner and Osborne (2018) stressed the need to provide adequate phosphate fertilizer to optimize the physiological growth, yield, and quality of grapes. Wu et al. (2018) found that when the proportion of phosphorus and potassium fertilizer increased, the quality of grape fruit improved.

The coupling of water and fertilizer is crucial for grape growth (Wang, 2016b; Zhang et al., 2018; Hou et al., 2019b). Within a certain range, when the water and fertilizer input is increased, the yield and water and fertilizer utilization efficiency will also improve, however excessive water–fertilizer supply will bring obvious negative effects (Zhang et al., 2019a). Applying drip irrigation and fertilization technology to grape production, supplementing nitrogen and phosphorus in the early stage, and increasing potassium fertilizer appropriately after the swelling stage can significantly increase grape yield, improve fruit quality, reduce nutrient leaching, and increase economic benefits to farmers (Zhang et al., 2019b). Wang et al. (2016a) found that when irrigation was 270 mm and $N–P_2O_5–K_2O$ was 225–180–248 kg ha^{-1}, the grape yield and fruit quality reached an ideal point. Zheng et al. (2013) demonstrated that under low nitrogen conditions, a water deficit reduced the grape yield by 32.2–49.9%. With sufficient nitrogen, and despite a water deficit, grape yield did not decrease significantly. In addition, Araguees et al. (2014) found that salt water irrigation and fertilization had a significant effect on soil pH and grape growth. Du et al. (2008) studied the effects of alternate drip irrigation on the water use efficiency (WUE) of grapes. Su et al. (2016) studied the effect of the drip irrigation capillary arrangement on the grape aboveground biomass, while Yang et al. (2009) studied the effect of the drip irrigation pipeline arrangement on the grape water physiological index and yield.

Despite the range of investigations discussed above, there have been few studies on the multi–objective optimization of grape growth, yield, quality, net profits, and environmental benefits based on the two factors: water and fertilizer. Most of these studies used potted and greenhouse

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experiments, which are less representative than field experiments. It is impossible to give practical consideration to multiple optimization objectives such as high production, high water and fertilizer utilization rate and net profits through such constrained experiments. Therefore, the purpose of this paper is to determine an ideal water and fertilizer management method that can improve grape yields, fruit quality, water and fertilizer utilization rate, and net profits, so as to provide a scientific reference for irrigation and fertilization management in the study region and similar areas.

2. Material and methods

2.1. Description of the study area

Field experiments were conducted during the grape growing seasons of 2015, 2016, and 2017 in Shihezi City, Xinjiang, China (85°59'20 E, 44°30'05 N). Shihezi City is located on the northern slope of Tianshan Mountain and the southern margin of the Junggar Basin. It is a typical inland arid area with an altitude of 360 m. The annual sunshine time is 2770 h; annual accumulated temperature above 10 °C is 3651 °C. The frost–free period is 160 d per year. The long–term average annual precipitation of the grape growing season is 106.1–178.3 mm, and the annual evaporation is 1722.5–2260.5 mm. The rainfall in 2015, 2016, and 2017 was 69.0, 120.0 and 109.0 mm, respectively. The depth of the groundwater in the study area is more than 3.5 m. The main physical properties of the 0–60 cm tillage soil layer in the experimental area are shown in Table 1. The soil fertility of 0–60 cm in the test area is shown in Table 2.

Table 1
Main physical properties of the soil in the study area

Soil depth (cm)	Soil texture	Particle mass fraction (%)			Bulk density (g cm^{-3})	Saturated water content (%)	Field water holding capacity (%)	Wilting point (%)
		Sand	Silt	Clay				
0–0	Sandy loam	62.65	32.75	4.6	1.32	44.41	26.51	13.81
10–20	Sandy loam	68.92	26.76	4.32	1.45	43.21	29.16	14.65
20–30	Sandy loam	71.53	23.56	4.91	1.45	44.77	28.22	14.89
30–40	Sandy loam	74.13	22.35	3.52	1.45	48.33	27.27	15.21
40–50	Sandy loam	81.55	15.57	2.88	1.59	48.33	30.00	15.92
50–60	Sandy loam	85.63	11.94	2.43	1.57	48.24	28.03	16.11

Table 2
Fertility characteristics of 0–60 cm soil

organic matter (%)	total nitrogen (%)	total phosphorus (%)	Alkaline hydrolyzed nitrogen (mg kg^{-1})	Available phosphorus (mg kg^{-1})	Available potassium (mg kg^{-1})
0.834	0.038	0.141	33.3	9.8	245

2.2. Experimental design and treatments

The experimental materials were *Vitis vinifera cv.* "Frey" grapes, the main local grape variety. Its grafting rootstock was 5BB, which is widely used in grape growing in areas with severe drought and salinization in northwestern China (Zhang, 2014a). From 2015 to 2017, the age of the grape vines was 10 years, 11 years, and 12 years, respectively. As such, they were high-yield grape vines. Grapes were cultivated in a small terrace and covered with plastic film in large ditches. The ditch depth was 0.2 m and the lower ditch width was 0.8 m. The size of the experimental plot was 50 m long and 3 m wide, with a planting density of 2278 plants per ha (row line spacing was 3 m, planting spacing was 1.5m) (Fig.1). A drip lateral was placed on both sides of the grape plant, 0.3 m and 0.2 m away from the main stem of the grape. The experiment used a single–wing labyrinth drip lateral. The diameter of the drip lateral was 16 mm. The average flow rate of the emitter was 3.2 L h^{-1}. The distance between emitters was 0.3 m.

The phenological period of the Frey grape has clear phases – bud break in early May, flowering in early June, fruit set in mid-June, fruit expanding from late June to mid July, veraison from late July to early August, fruit ripening from mid-August to late August and branch ripening from late August to mid September. During the growing period of the grapes, the maintenance of the vineyards is carried out in terms of frame maintenance, pest control, clearing of the garden and winter soil burying. In the late October, fruit branches are left at intervals of about 10 cm on the main vine with a height of 170 cm and pruned in the form of 1-2-1 (excluding the base buds). The extended branches are pruned at full buds of 0.8 cm in thickness.

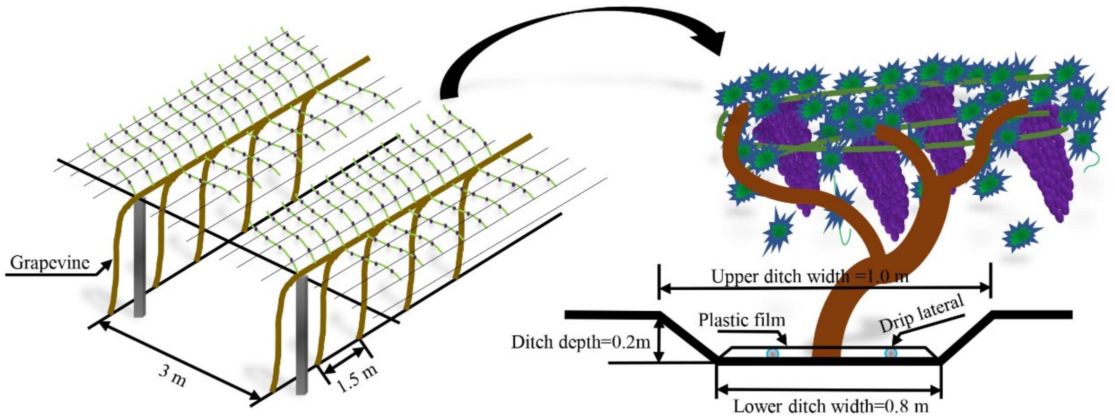


Fig.1 Grape planting and drip irrigation

Table 3
Irrigation schedule of grapes in the experimental area

Number of irrigation	Irrigation Date	Days after bud break	Irrigation amount (mm)			Fertilization amount (kg ha^{-1})				
			$W_{60\%}$	$W_{80\%}$	$W_{100\%}$	$F_{60\%}$	$F_{80\%}$	$F_{100\%}$	$F_{120\%}$	$F_{140\%}$
2015										
1	5.8	1	60	60	60	135	180	230	276	322
2	5.22	15	78	104	130	295	387	500	598	700

3	6.5	29	27	36	45	110	147	173	208	243
4	6.19	43	27	36	45	110	147	173	208	243
5	7.3	57	24	32	40	90	121	154	185	216
6	7.17	71	18	24	30	70	96	116	140	160
7	8.10	95	24	32	40	90	122	154	185	216
Total			258	324	390	900	1200	1500	1800	2100
2016										
1	5.7	1	60	60	60	139	187	233	280	327
2	5.25	19	78	104	130	304	406	507	607	709
3	6.8	33	30	40	50	117	156	195	234	273
4	6.23	48	24	32	40	94	124	156	187	218
5	7.5	60	24	32	40	94	124	156	187	218
6	7.20	75	18	24	30	70	93	117	141	164
7	8.12	98	21	28	35	82	110	136	164	191
Total			255	320	385	900	1200	1500	1800	2100
2017										
1	5.5	1	60	60	60	142	185	230	278	325
2	5.25	21	75	100	125	294	397	490	588	687
3	6.6	33	24	32	40	95	126	159	191	223
4	6.20	47	27	36	45	107	142	180	214	250
5	7.4	61	24	32	40	95	126	159	191	223
6	7.19	76	18	24	30	72	98	123	147	169
7	8.9	97	24	32	40	95	126	159	191	223
Total			252	316	380	900	1200	1500	1800	2100

Note: Grapes usually bud break in May, and irrigation should be arranged immediately then. It ripens from the mid of August, after that, irrigation should be strictly prohibited to facilitate the ripening of the branches and safe wintering. Therefore, in this study, irrigation ceased on 10, 12 and 9 of August in the 2015–2017.

The experiment was conducted in the two-factor crossover design with 15 treatments (fertilization for 5 levels, irrigation for 3 levels), each of which was replicated three times. The field trials were randomly distributed. Five N–P_2O_5–K_2O (4:5:11) fertilization levels were used in the experiment: 180–225–495, 240–300–660, 300–375–825, 360–450–990, and 420–525–1155 kg·ha^{-1}, designated $F_{60\%}$, $F_{80\%}$, $F_{100\%}$, $F_{120\%}$, $F_{140\%}$, respectively, and the five fertilization levels accounted for 60%, 80%, 100%, 120% and 140% of the local fertilization (300–375–825 kg·ha^{-1} N–P_2O_5–K_2O), respectively. Three irrigation levels were set up in the experiment: full irrigation ($W_{100\%}$), medium irrigation ($W_{80\%}$), and low irrigation ($W_{60\%}$). The three irrigation levels accounted for 60%, 80% and 100% of the ET_c (where ET_c denotes evapotranspiration under sufficient water supply for crops). According to the meteorological data provided by the local meteorological station, the reference crop evapotranspiration (ET_0) during the grape growing period was calculated by using the Penman–Monteith formula recommended by FAO–56. According to research results of Zeng (2010), the crop coefficient (K_c) of grape was determined, $ET_c = K_c \times ET_0$. Combining the water requirement of Frey grape with the irrigation habits of local farmers, irrigation was carried out when the soil moisture content falls to the lower limit, generally 55-60%, of the field water holding capacity of the local soil (Zheng et al., 2013). The fertilizer used in the test was instant fertilizer, fertilizations were carried out in the middle stage of irrigation. Fertilizer pots were used for fertilization (the capacity is 20 L). Each fertilizer pot was shared by three experimental plots with the same fertilization level.

2.3. Measurements

2.3.1 Leaf area calculation

Five grapes were randomly chosen from each test area during the main growth stage of the grape branches and leaves. First, we selected three canes from each grape. Then, we selected three branches on each cane and measured their length. Second, the number of branches on each cane was counted, as were the number of leaves on each branch. Finally, the vein length of each leaf was measured. The leaf area of the grapes was measured according to the main vein length (Zeng, 2010):

$$W = 0.8954 \times X^{2.0823} \tag{1}$$

where W is the area of the grape leaves (cm^2), and X is the length of the main vein of grape leaves (cm).

2.3.2 Estimation of Leaf area index (LAI),

Lead area index was computed from:

$$LAI(t) = (B(t) \times I(t) \times W(t) / 10000) \times S \tag{2}$$

where B is the number of branches on a cane, I is the number of leaves on a cane, W is the area of a single leaf, S is the area occupied by a cane, and t is time (Su, 2013).

2.3.3 Dry matter yield

Dry matter yield was determined from:

$$m = 0.0003 \times A^{1.5255} \tag{3}$$

where m is the dry matter mass of each branch (g), and A is the total leaf area of each branch (cm^2), and:

$$M = 10 \times a \times b \times m / S \tag{4}$$

where M is the unit dry matter mass (kg/area), a is the number of canes per plot, b is the number of branches per cane, and S is the area of each experimental plot (m^2) (Wang et al., 2013).

2.3.4 Yield and grape bunch weight

At the ripening stage, five fruit trees were randomly selected for harvesting in each plot. The average value was taken and then converted into hectare yield. The top, middle, and lower parts of five fruit trees selected in each experimental plot were harvested and weighed by four bunches of grape ears, and the average was taken as the grape bunch weight.

2.3.5 Fruit quality

After measuring the yield, 500 g of fresh grape samples were taken from each treatment. The Ministry of Agriculture and Rural China, Food Quality Supervision, Inspection and Testing Center (Shihezi, China) was entrusted to determine vitamin C, titratable acid and soluble solids, and other major quality indicators. 2.6–dichloroindophenol titration was used to determine vitamin C. Titratable acid was determined through indicator titration. The refractometer method was used to determine soluble solids.

2.3.6 Harvest index

The harvest index (*HI*) is the ratio of grape yield to aboveground dry matter accumulation (Xie et al., 2011):

$$HI = Grape\ Yield\,/\,Dry\ Matter\ Yield \tag{5}$$

2.3.7 WUE

WUE was determined from:

$$WUE = Y\,/\,ET \tag{6}$$

where Y is the grape yield, ET is the grape water consumption (Howell et al., 1990), and:

$$ET = P + K + B - C - N - \Delta W \tag{7}$$

where P is the precipitation (mm), K is the groundwater recharge (mm), B is the irrigation amount (mm), C is the deep leakage (mm), N is the surface runoff (mm), and ΔW is the change in soil moisture from the beginning to the end of the experiment. In this study, K, N, and C were neglected (Andreu et al., 1997).

2.3.8 Partial factor productivity

Partial factor productivity (*PFP*) was determined from:

$$PFP = Y\,/\,F \tag{8}$$

where Y is the grape yield, F is the total amount of fertilization (kg·ha^{-1}) (Ierna et al., 2011).

2.3.9 Net profits

Net profits (N_p) was computed by:

$$N_p = G_p - W_c - F_c - L \tag{9}$$

where N_p is the net profit (RMB ha^{-1}), G_p is the gross profit (RMB ha^{-1}), W_c is the water cost (RMB ha^{-1}), F_c is the fertilizer cost (RMB ha^{-1}), and L denotes other inputs (RMB ha^{-1}).

2.4. Data processing

Variance analysis was performed using a DPS data processing system; the Least Significant Difference (LSD) method was used to test the significance of the difference of $P < 0.05$ between treatments. Multivariate regression and the extremum solution was analyzed using non-linear surface fitting. The regression allowed the computation of a binary quadratic function ($z = Ax^2 + 2Bxy + Cy^2 + Dx + Ey + F$). The values of A, B, C, D, E, and F were calculated based on the measured data; convergence of the solution was also assessed.

3. Results

3.1. *LAI and grape bunch weight*

In the three–year experiment, the LAI increased with the increase of fertilization level from $F_{60\%}$ to $F_{120\%}$ under the same irrigation level, however, it decreased for fertilization level up to $F_{140\%}$ (420–525–1155 kg ha^{-1}). Whilst, at the same fertilization level, the increase in grape yield was significantly positively correlated with the increase in irrigation ($P < 0.01$). The LAI of $W_{100\%}\times F_{120\%}$ treatment was the highest, at 5.86, 5.88 and 6.51 m^2 m^{-2} in 2015, 2016, and 2017, respectively. Correspondingly, the LAI of the $W_{60\%}\times F_{60\%}$ treatment was the lowest, at 3.61, 3.69 and 2.22 m^2 m^{-2} respectively. The yield and quality characteristics of grapes were impacted by the soil conditions in the field (Ming, 2008). The coupling effect of water and fertilizer on the LAI was very significant in 2015 ($P < 0.01$), but insignificant in 2016 and 2017 ($P > 0.05$) (see Table 4). The inconsistent phenomenon between the first year and the following two years may be caused by the antecedent soil conditions at the start of the field study, including the heterogeneity of soil nutrients and soil water content in the experimental plot (Ming, 2008). From 2015 to 2017, compared to the maximum LAI each year, the minimum LAI decreased by 38.40, 37.24 and 65.90% respectively, confirming that low water and low fertilizer are very unfavorable to the growth of grape leaves.

Table 4
Effects of irrigation and fertilization on the LAI and grape bunch weight

Treatment		LAI (m^2 m^{-2})			Grape bunch weight (g)		
		2015	2016	2017	2015	2016	2017
Irrigation	Fertilization						
$W_{100\%}$	$F_{60\%}$	4.82fg	4.81de	2.94fg	358g	350hi	357e
	$F_{80\%}$	5.07de	5.44bc	4.43de	383cdef	349hi	348f
	$F_{100\%}$	5.75a	5.87a	5.10cd	375ef	376bc	369bc
	$F_{120\%}$	5.86a	5.88a	6.51a	373f	360fg	378a
	$F_{140\%}$	5.51b	5.69ab	5.72bc	395abc	373cd	371b
$W_{80\%}$	$F_{60\%}$	4.38h	4.50ef	2.47g	383cdef	352h	330g
	$F_{80\%}$	4.68g	4.92d	4.44de	396ab	381ab	329g
	$F_{100\%}$	4.92ef	5.12cd	4.30e	3943bcd	366ef	358e
	$F_{120\%}$	5.30c	5.30c	6.22ab	393bcd	359g	363d
	$F_{140\%}$	5.21cd	5.29c	6.29ab	373f	362efg	364cd
$W_{60\%}$	$F_{60\%}$	3.61j	3.69i	2.22g	382def	345i	320h
	$F_{80\%}$	3.62j	3.87hi	2.63fg	387bcde	376bc	319h
	$F_{100\%}$	3.83i	4.02gh	3.34f	407a	383a	321h
	$F_{120\%}$	4.30h	4.47f	4.96de	385bcdef	360fg	363d

	$F_{140\%}$	4.29h	4.31fg	5.12cd	388bcd	368de	364cd
P							
W		**	**	**	ns	ns	**
F		**	**	**	ns	ns	**
W × F		**	ns	ns	**	**	**

Note: P denotes significance level, W denotes irrigation, F denotes fertilization, * denotes a significant difference ($P < 0.05$), ** denotes an extremely significant difference ($P < 0.01$), and ns denotes an insignificant difference ($P > 0.05$). Different letters following the values denote a significant difference at $P < 0.05$ according to an LSD test– two treatments with the same letter (a,b,c, etc.) indicates insignificant differences. These symbols denote the same in Table 5-7, below.

As for the grape bunch weight, the largest values were 407, 383, and 377 g in 2015, 2016, and 2017, respectively. Correspondingly, the lowest values were 358, 345, and 378 g, respectively. The effect of water and fertilizer coupling was highly significant ($P < 0.01$) (see Table 4). At the $W_{100\%}$ irrigation level, there was no significant difference amongthe mean grape bunch weight over the three years between $F_{100\%}$, $F_{120\%}$, and $F_{140\%}$, and they were significantly higher than the other two fertilization levels. This was the same as that at the $W_{60\%}$ irrigation level.

3.2. *Fruit quality*

From 2015 to 2017, under the same irrigation level, the content of vitamin C, titratable acid, and soluble solids increased first and then decreased with an increase of the fertilization level. They reached their peak values at the $F_{100\%}$ / $F_{120\%}$ fertilization level (Table 5), ranging from 33.09-33.22 mg $100g^{-1}$, 0.528-0.543 %, and 25.13-25.55 %, respectively. Meanwhile, at the same fertilization level, the increase in the content of the three fruit quality indicators was significantly positively correlated with an increase in irrigation ($P < 0.01$). The $W_{100\%}\times F_{100\%}$ treatment had the best fruit quality, while the $W_{60\%}\times F_{60\%}$ treatment had the worst fruit quality over the three years. In general, irrigation and fertilization had very significant coupling effects on the contents of titratable acid and soluble solids ($P < 0.01$). In terms of vitamin C content, except for in 2015, the coupling effect of water and fertilizer was also significant in 2016 and 2017 ($P < 0.01$). In the case of LAI, discussed above, heterogeneity of antecedent soil conditions at the start of the experiment may have existed, however, with the advancement of the experimental program such effects are removed and consequently the coupling effect of water and fertilizer on the fruit quality in years 2 and 3 were more reliably expressed than those in the first year.

Table 5
Effects of irrigation and fertilization on the fruit quality

Treatment		Vitamin C (mg $100g^{-1}$)			Titratable acid (%)			Soluble solids (%)		
		2015	2016	2017	2015	2016	2017	2015	2016	2017
Irrigation	Fertilization									
$W_{100\%}$	$F_{60\%}$	30.60d	29.78bc	28.87de	0.456g	0.461ef	0.450fg	21.69e	21.69f	21.02ef
	$F_{80\%}$	32.29abc	31.99a	31.45c	0.472ef	0.482d	0.478cd	22.48de	23.18e	23.21cd
	$F_{100\%}$	33.22a	32.18a	33.09a	0.528a	0.534a	0.543a	25.13a	26.04a	25.55a
	$F_{120\%}$	33.06ab	31.89a	32.76ab	0.510b	0.528ab	0.520b	24.25b	25.77ab	24.31b
	$F_{140\%}$	32.45abc	30.00b	32.59abc	0.482cde	0.487d	0.479cd	22.95cd	25.55ab	23.18cd
$W_{80\%}$	$F_{60\%}$	29.29e	28.76c	27.98e	0.434h	0.443g	0.439g	20.67f	21.61f	20.48fg
	$F_{80\%}$	30.29d	29.78bc	29.99d	0.490cd	0.494cd	0.486cd	23.32c	24.11cd	23.61bc
	$F_{100\%}$	32.14bc	31.87a	31.73bc	0.494c	0.511bc	0.521b	23.50bc	24.94bc	24.16b
	$F_{120\%}$	32.91abc	32.12a	33.15ab	0.528a	0.528ab	0.534ab	25.13a	25.91a	25.23a
	$F_{140\%}$	32.00c	31.88a	32.17abc	0.480de	0.491d	0.489c	22.85cd	23.70de	22.87d
$W_{60\%}$	$F_{60\%}$	23.00g	22.45f	22.76h	0.410i	0.392i	0.402i	19.51g	19.12h	18.77i
	$F_{80\%}$	23.40g	23.43ef	23.80gh	0.434h	0.421h	0.420h	20.67f	19.96g	19.63h
	$F_{100\%}$	25.63f	25.23d	25.87f	0.483cde	0.463e	0.472de	22.99cd	20.44g	21.33e
	$F_{120\%}$	25.15f	24.39de	24.12fg	0.461fg	0.444fg	0.461ef	21.93e	19.71gh	20.62efg
	$F_{140\%}$	24.68g	23.02f	23.31gh	0.460fg	0.439g	0.460ef	21.88e	19.61gh	20.11gh
P										
W		**	**	**	**	**	**	**	**	**
F		**	**	**	**	**	**	**	**	**
W × F		ns	**	**	**	*	**	**	**	**

3.3. *Dry matter yield, grape yield, and HI*

With the increase of water and nitrogen input, changes to the dry matter yield and grape yield were similar to those of the fruit quality indicators. In the three–year experiment, under the same irrigation level, with the increase of fertilization level, the dry matter yield and yield first increased and then decreased. At the same fertilization level, when the irrigation level increased, the dry matter yield and grape yield also increased. The effects of irrigation, fertilization and water–fertilizer coupling were very significant ($P < 0.01$). They reached their highest value at the $W_{100\%}$ × $F_{120\%}$ / $F_{140\%}$ fertilization level (Table 5), ranging from 52.68 - 62.92 Mg ha^{-1}, and 19.80 – 24.16 Mg ha^{-1}, respectively, and reached their lowest value at the $W_{60\%}$ × $F_{60\%}$ fertilization level, ranging from 31.50 - 38.62 Mg ha^{-1} and 13.69 - 14.67 Mg ha^{-1}, respectively.

Table 6
Effects of irrigation and fertilization on the dry matter yield, grape yield, and HI

Treatment		Dry matter yield (Mg ha^{-1})			Yield (Mg ha^{-1})			HI		
		2015	2016	2017	2015	2016	2017	2015	2016	2017
Irrigation	Fertilization									
$W_{100\%}$	$F_{60\%}$	42.45g	49.36c	44.04g	18.22d	18.95de	17.22g	0.429cd	0.384cde	0.391de
	$F_{80\%}$	46.40d	49.81c	47.02ef	19.22abc	19.32bcd	17.35g	0.414de	0.388bcd	0.369ghi
	$F_{100\%}$	48.76c	52.44a	57.90b	19.78ab	19.99a	22.78b	0.406ef	0.381cde	0.393de
	$F_{120\%}$	53.20a	52.68a	62.92a	19.80a	19.80ab	24.16a	0.372h	0.376de	0.384ef
	$F_{140\%}$	52.21b	50.47b	56.21b	19.80a	19.78abc	20.09d	0.379gh	0.392bc	0.357i
$W_{80\%}$	$F_{60\%}$	39.19h	42.54g	40.89h	17.44e	16.59f	15.31i	0.445ab	0.390bcd	0.374fgh
	$F_{80\%}$	45.35e	46.39e	42.99g	18.03de	18.50e	16.16h	0.398f	0.399b	0.376fg
	$F_{100\%}$	43.43f	47.65d	48.74e	19.14bc	19.14cde	19.56de	0.441bc	0.402b	0.401bcd
	$F_{120\%}$	48.73c	44.95f	54.10c	19.59abc	19.12de	22.33b	0.402ef	0.425a	0.413ab
	$F_{140\%}$	48.75c	44.88f	51.19d	19.05c	18.95de	20.84c	0.391fg	0.422a	0.407abc
$W_{60\%}$	$F_{60\%}$	31.50k	37.13i	38.62i	13.69g	14.67h	14.03k	0.435bc	0.395bc	0.363hi
	$F_{80\%}$	31.10l	41.23h	39.15hi	13.93g	15.32gh	14.67j	0.448ab	0.371e	0.375fgh
	$F_{100\%}$	33.20j	41.64h	39.99hi	15.26f	15.68g	15.95h	0.460a	0.377de	0.399cd
	$F_{120\%}$	39.16h	42.54g	46.09f	14.98f	15.13gh	19.15e	0.382gh	0.356f	0.416a
	$F_{140\%}$	38.31i	37.52i	43.39g	15.31f	15.05gh	18.05f	0.400ef	0.401b	0.416a
P										
W		**	**	**	**	**	**	ns	*	ns
F		**	**	**	**	*	**	**	ns	ns
W × F		**	**	**	ns	**	**	**	**	**

The highest grape yield in 2015, 2016, and 2017 was 19.80, 19.99, and 24.16 Mg ha^{-1} at treatment of $W_{100\%} \times F_{140\%}$, $W_{100\%} \times F_{100\%}$, and $W_{100\%} \times F_{120\%}$, respectively. Correspondingly, the lowest grape yield was 13.69, 14.67, and 14.03 Mg ha^{-1}, respectively, with all three at the treatment of $W_{60\%} \times F_{60\%}$. At the $W_{100\%}$ irrigation level, there was no significant difference in the yield among $F_{100\%}$, $F_{120\%}$ and $F_{140\%}$, and there was no significant difference in the yield between the $F_{60\%}$ and $F_{80\%}$. At the $W_{60\%}$ irrigation level, the yield of the $F_{100\%}$ treatment was significantly higher than that of the $F_{60\%}$, but there was no significant difference with the other three fertilization levels.

However, there were no obvious relationships for the change to the HI under the increase of water and nitrogen gradient. Variance difference analysis showed that the effect of irrigation on the HI was significant in 2016 ($P < 0.05$), and that the effect of fertilization was very significant in 2015 ($P < 0.01$), but that the effect of water and fertilizer coupling on the HI was highly significant ($P < 0.01$) (see Table 6).

3.4. *WUE and PFP*

From 2015 to 2017, the *WUE* increased with the increase of fertilization level to $F_{60\%}/F_{120\%}$ under the same irrigation level. However, it was not helpful for increasing the *WUE* under the fertilization level up to $F_{140\%}$. The PFP shows a clear pattern: increasing with an increase in irrigation, and decreasing with an increase in fertilization. The effects of irrigation, fertilization and water–fertilizer coupling on the PFP were very significant ($P < 0.01$). The PFP of the $W_{100\%} \times F_{60\%}$ was the greatest, ranging from 19.13 - 21.06, and that of $W_{60\%} \times F_{140\%}$ was the lowest, ranging from 7.17 – 8.59 (see Table 7).

Table 7
Effects of irrigation and fertilization on the WUE and PFP

Treatment		WUE (kg m^{-3})			PFP		
		2015	2016	2017	2015	2016	2017
Irrigation	Fertilization						
$W_{100\%}$	$F_{60\%}$	1.35f	1.35f	1.33f	20.24a	21.06a	19.13a
	$F_{80\%}$	1.46e	1.38ef	1.35f	16.02c	16.10c	14.46d
	$F_{100\%}$	1.56d	1.53d	1.64c	13.18e	13.33e	15.19c
	$F_{120\%}$	1.57cd	1.55d	1.76ab	11.00g	11.00g	13.42e
	$F_{140\%}$	1.49e	1.42e	1.50de	9.43i	9.42i	9.57h
$W_{80\%}$	$F_{60\%}$	1.48e	1.36f	1.30f	19.37b	18.43b	17.01b
	$F_{80\%}$	1.63c	1.55d	1.54d	15.03d	15.42d	13.47e
	$F_{100\%}$	1.75a	1.67ab	1.65c	12.76e	12.76f	13.04e
	$F_{120\%}$	1.73ab	1.69a	1.80a	10.89g	10.62gh	12.40f
	$F_{140\%}$	1.72ab	1.62bc	1.73b	9.07i	9.03i	9.92h
$W_{60\%}$	$F_{60\%}$	1.35f	1.35f	1.34f	15.22d	16.30c	15.59c
	$F_{80\%}$	1.55d	1.42e	1.44e	11.61f	12.76f	12.23f
	$F_{100\%}$	1.60cd	1.54d	1.55d	10.17h	10.46h	10.63g
	$F_{120\%}$	1.72ab	1.63bc	1.73b	8.32j	8.40j	10.64g
	$F_{140\%}$	1.69b	1.58cd	1.65c	7.29k	7.17k	8.59i
P							
W		**	**	**	**	**	**
F		**	**	**	**	**	**
W × F		**	**	**	**	**	**

3.5. *Net profits*

Table 8
Effects of irrigation and fertilization on the net profits

Treatment		Water cost (RMB ha^{-1})			Fertilizer cost (RMB ha^{-1})			Gross profit (RMB ha^{-1})			Net profits (RMB ha^{-1})		
		2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017
Irrigation	Fertilization												
$W_{100\%}$	$F_{60\%}$	1560	1540	1520	4068	4068	4068	118423	121663	107594	59101	61283	48803
	$F_{80\%}$	1560	1540	1520	5424	5424	5424	124947	124044	108445	63236	61680	48068
	$F_{100\%}$	1560	1540	1520	6780	6780	6780	128552	128325	142381	64774	63923	75805
	$F_{120\%}$	1560	1540	1520	8136	8136	8136	128707	127124	150972	63414	61500	81864
	$F_{140\%}$	1560	1540	1520	9492	9492	9492	128729	127015	125583	62041	60240	58519
$W_{80\%}$	$F_{60\%}$	1296	1280	1264	4068	4068	4068	113337	106483	95686	55084	48805	40127
	$F_{80\%}$	1296	1280	1264	5424	5424	5424	117207	118780	101002	57207	57777	42413
	$F_{100\%}$	1296	1280	1264	6780	6780	6780	124394	122865	122266	62126	60099	58768
	$F_{120\%}$	1296	1280	1264	8136	8136	8136	127358	122755	139553	63346	58549	72226
	$F_{140\%}$	1296	1280	1264	9492	9492	9492	123841	121685	130240	58796	56335	62768
$W_{60\%}$	$F_{60\%}$	1032	1020	1008	4068	4068	4068	89011	94207	87713	35471	39252	33898
	$F_{80\%}$	1032	1020	1008	5424	5424	5424	90559	98335	91710	35427	41286	35791
	$F_{100\%}$	1032	1020	1008	6780	6780	6780	99184	100694	99684	41576	42025	41154
	$F_{120\%}$	1032	1020	1008	8136	8136	8136	97348	97112	119714	38491	37578	57108
	$F_{140\%}$	1032	1020	1008	9492	9492	9492	99515	96610	112782	39103	35701	49794

Non-scientific designation of water and fertilizer inputs will reduce the gross profit of a vineyard and will greatly decrease its net profits. In the three-year study, the gross profit was 89011–128729, 94207–128325, and 87713–150972 RMB ha^{-1}, respectively. Compared to the lowest gross profit each year, the highest gross profit increased by 45, 36, and 71%, respectively. The annual minimum net profit was 35427, 35701, and 33898 RMB ha^{-1}, respectively, and the maximum net profit was 64774, 63923, and 81864 RMB ha^{-1}, respectively, with a difference between the two of 1.8–2.4 times (see Table 8).

In this study, compared to $W_{100\%}$, the water cost for $W_{80\%}$ reduced by 264, 260, and 256 RMB ha^{-1} over the three respective years, while the water cost for $W_{60\%}$ reduced by 528, 520, and 512 RMB ha^{-1}, respectively. It can be seen that the proportion of water cost in the total investment is very small, but the reduction of irrigation leads to a significant reduction in net profits, which is the main reason why fruit growers are unaware of and unwilling to save water in agriculture. At the same level of irrigation, with an increase in fertilizer, the net profits show a trend of increasing first and then decreasing. Therefore, a high amount of fertilizer input will not lead to a sustained increase in net profits.

3.6. *Effects of water and fertilizer coupling on grape yield, net profits, WUE, PFP, and fruit quality*

In actual planting and production, fruit growers lack an accurate irrigation and fertilization management model. They usually aim at high net profits, and they believe that increasing the amount of irrigation and fertilization is the only way to reduce the risk of lower production. However, the results of this study show that the amount of investment in irrigation and fertilization has a great impact on the grape yield, and further affects net profits. Indeed, low irrigation and low fertilizer are disadvantageous to high grape yields. However, excessive irrigation and fertilization will also reduce net profits. Moreover, over-irrigation not only causes fertilizer loss, but also reduces water use efficiency. In serious cases, it will also cause diffuse pollution from farmlands. Excessive use of chemical fertilizers will first lead to increased production costs, and then waste fertilizer resources and destroy the soil structure. High WUE is critical for agricultural development in arid regions. PFP is an important indicator reflecting the comprehensive effect of local soil nutrient and chemical fertilizer application. Fruit quality is the basic guarantee for fruit growers to improve grape sales. Therefore, grape yield, net profits, WUE, PFP, and fruit quality were chosen as comprehensive evaluation indicators in this experiment.

The independent variables were water and fertilizer inputs, and the dependent variables were the grape yield, net profits, WUE, PFP, vitamin C content, titratable acid content, and soluble solid content. We set the maximum irrigation of $W_{100\%}$ for three years as the upper irrigation limit, the minimum irrigation of $W_{60\%}$ as the lower irrigation limit, the maximum fertilization of $F_{140\%}$ for three years as the upper fertilization limit, and the minimum fertilization of $F_{60\%}$ as the lower fertilization limit. The required irrigation and fertilization amount when the above dependent variables reached their maximum values were calculated (see Table 9).

Table 9
Multiple regression relationships between irrigation and fertilization and each evaluation indicator

Dependent variable Y	Regression equation	R^2	P<
Yield/Y_1	$Y_1 = -0.24918W^2-5.98628*10^{-4}WF-0.00309F^2+193.41527W+11.79723F-27643.71326$	0.747	0.01
Net profits/Y_2	$Y_2 = -1.26771W^2-0.00426WF-0.01651F^2+986.86413W+58.8201F-175305.37402$	0.736	0.01
WUE/Y_3	$Y_3 = -2.43503*10^{-5}W^2-8.81554*10^{-7}WF-3.77308*10^{-7}F^2+0.01646W+0.00165F-2.29008$	0.820	0.01
PFP/Y_4	$Y_4 = -1.55234*10^{-4}W^2-16.22308*10^{-6}WF+3.25059*10^{-6}F^2+0.14765W-0.01182F-0.46455$	0.944	0.01
Vc/Y_5	$Y_5 = -7.32609*10^{-4}W^2+3.88082*10^{-6}WF-4.99398*10^{-6}F^2+0.52265W+0.01561F-74.35159$	0.961	0.01
Titratable acid /Y_6	$Y_6 = -5.48827*10^{-6}W^2-9.78478*10^{-8}WF-1.30754*10^{-7}F^2+0.00406W+4.64165*10^{-4}F-0.57832$	0.893	0.01
Soluble solids /Y_7	$Y_7 = -3.40276*10^{-4}W^2+8.18794*10^{-6}WF-5.87832*10^{-6}F^2+0.23108W+0.01683F-30.4857$	0.861	0.01

Note: W denotes the amount of water used, and F denotes the amount of fertilizer used. Each binary quadratic regression equation is established based on the least-squares method.

Table 10
Solve the maximum value of each evaluation indicator

Y	Y_{max}	W (mm)	F (kg ha^{-1})
Grape yield/Y_1	20.71	387	376-470-1034
Net profits/Y_2	66246.14	387	347-433-953
WUE/Y_3	1.72	306	366-458-1007
PFP/Y_4	19.81	390	180-225-495
Vc/Y_5	33.33	362	342-427-940
Titratable acid /Y_6	0.53	356	327-409-899
Soluble solids /Y_7	25.24	359	337-421-926

The results show that it is impossible to obtain the maximum grape yield, net profit, water use efficiency, fertilizer partial productivity, vitamin C, titratable acid, and soluble solid content at the same time. When the irrigation amount is 387 mm and the input amount of $N–P_2O_5–K_2O$ is 376–470–1034 kg ha^{-1}, the yield reaches its maximum, 20.71 Mg ha^{-1}. When the irrigation amount is 387 mm and the input amount of $N–P_2O_5–K_2O$ is 347–433–953 kg ha^{-1}, the net profit reaches its maximum value of 66246.14 RMB ha^{-1}. When the irrigation amount is 306 mm and the input amount of $N–P_2O_5–K_2O$ is 366–458–1007 kg ha^{-1}, WUE reaches its maximum value of 1.72 kg m^{-3}. When the irrigation amount is 390 mm and the input amount of $N–P_2O_5–K_2O$ is 180–225–495 kg ha^{-1}, PFP reaches its maximum value of 19.81. When the irrigation amount is 362 mm and the input amount of $N–P_2O_5–K_2O$ is 342–427–940 kg ha^{-1}, the vitamin C content reaches its maximum, 33.33 mg $100g^{-1}$. When the irrigation amount is 356 mm and the input amount of $N–P_2O_5–K_2O$ is 327–409–899 kg ha^{-1}, the titratable acid content reaches its maximum, 0.53%. When the irrigation amount is 359 mm and the input amount of $N–P_2O_5–K_2O$ is 337–421–926 kg ha^{-1}, the soluble solid content reaches its maximum, 25.24% (see Table 10).

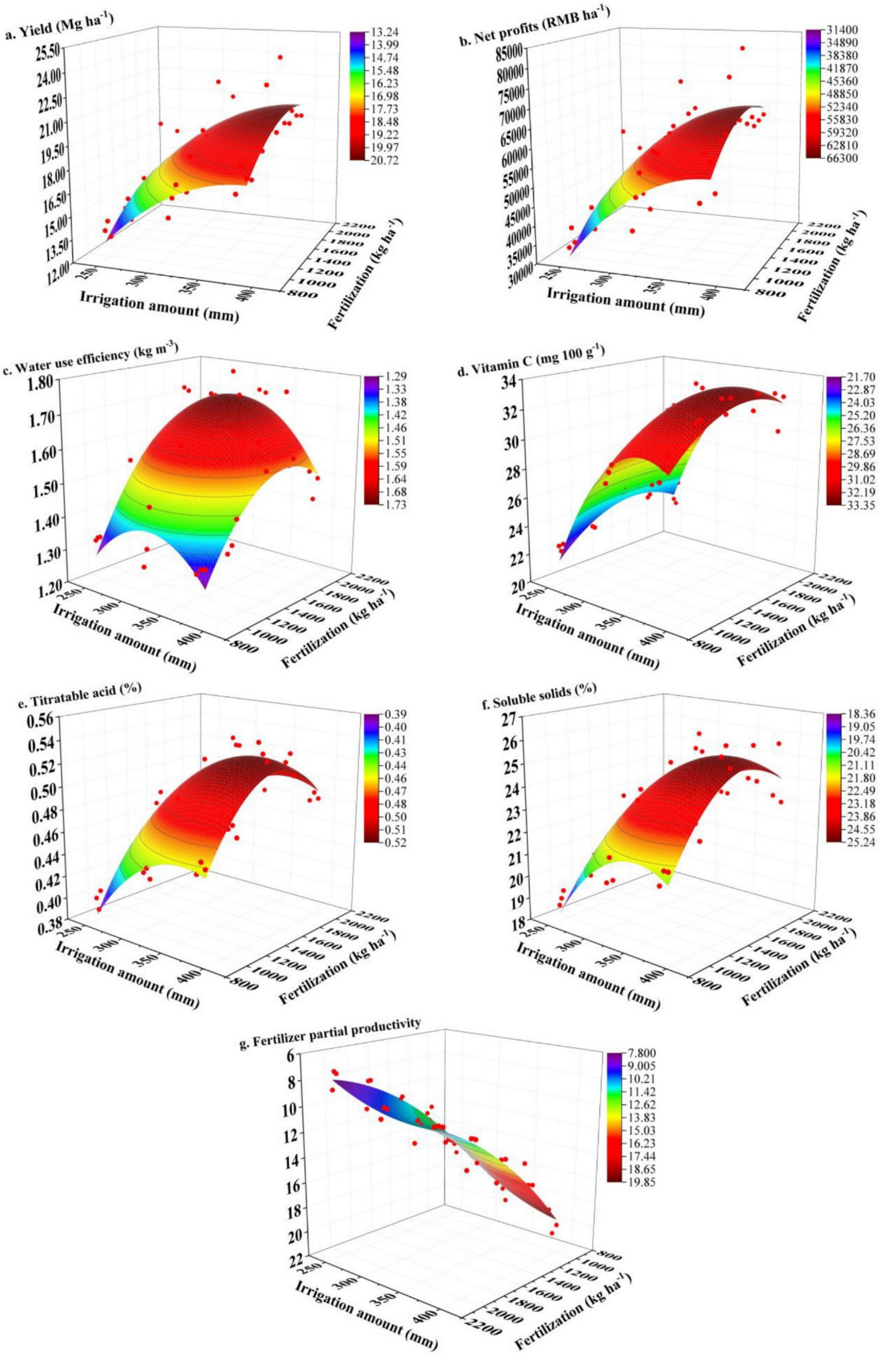
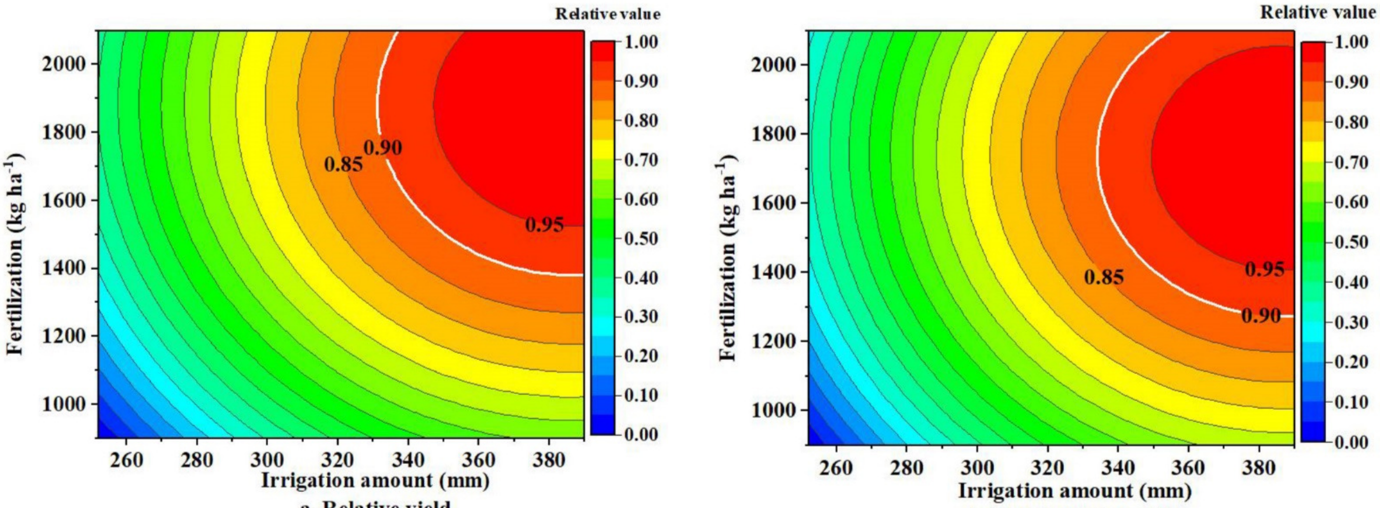


Fig. 2. Three-dimensional surface map of water and fertilizer input for each evaluation indicator. Field observation values of evaluation indicators are represented by red dots in the figure.

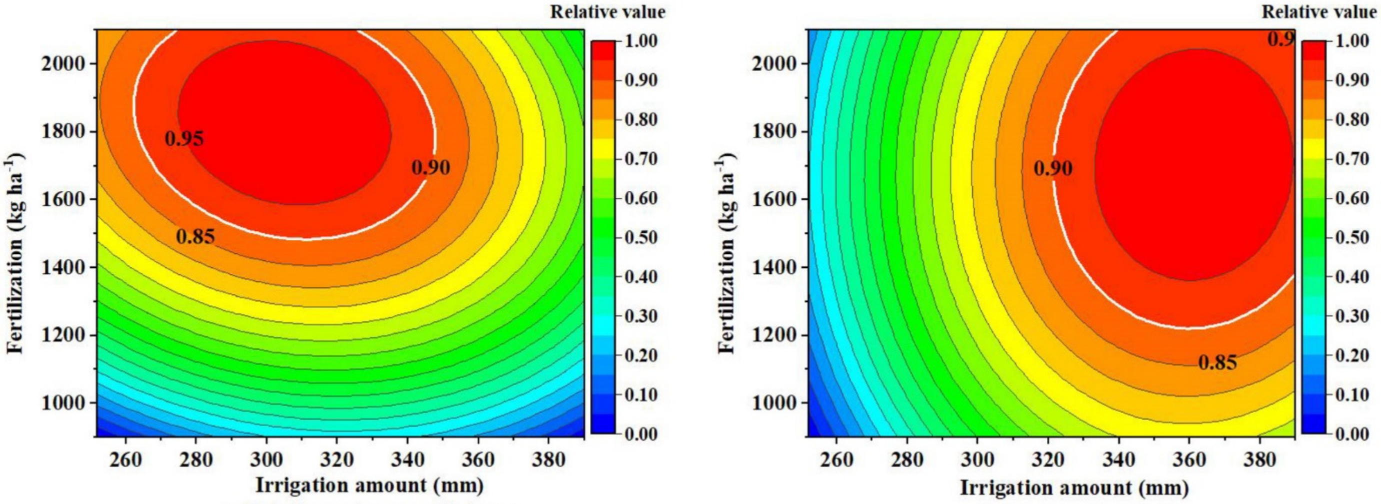
The coupling effect of irrigation and fertilization on the grape yield, net profits, WUE, vitamin C content, titratable acid content, and soluble solid content of fruit has a downward convex shape. When they reach their maximum levels, the amount of irrigation and fertilizer required by crops is similar, however the response trend of PFP to the coupling effect of irrigation and fertilization is the opposite of the above indices. Therefore, the PFP was no longer considered in the comprehensive evaluation (Fig. 2).

Because each evaluation index has different unit dimensions, they cannot be directly and comprehensively evaluated. Therefore, for a comprehensive evaluation, the data from the above evaluation indices were normalized using a linear normalization method, and the data from each index were expanded and compressed according to intervals (0,1) (see Fig. 3).



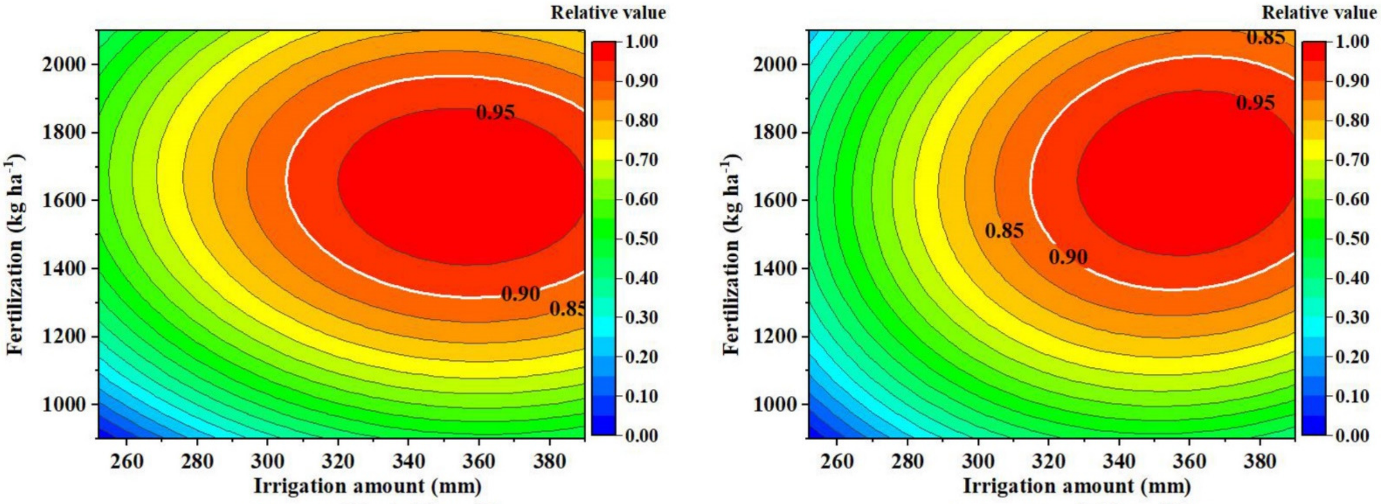
a. Relative yield

b. Relative net profits



c. Relative water use efficiency

d. Relative vitamin C



e. Relative titratable acid

f. Relative soluble solids

Fig. 3. The relationship of relative value of each evaluation index with the amounts of irrigation and fertilization

We define the areas with the maximum values of ≥ 95%, ≥ 90%, and ≥ 85% of each evaluation index as acceptable areas. Then, the boundaries of these three acceptable areas correspond to 0.95, 0.90, and 0.85 isolines in Fig. 3, respectively. It can be seen that within the acceptable range ≥ 0.95, each evaluation index has an overlapping region, but this region is relatively small and slightly deviates from the relative value of the WUE. Within the acceptable region ≥ 0.85, each evaluation index also has overlapping regions, but the overlapping regions are too large, resulting in deviations from the extreme value. The overlapping area of the acceptable area ≥ 0.90 of each evaluation index is the ideal range to meet the evaluation requirements.

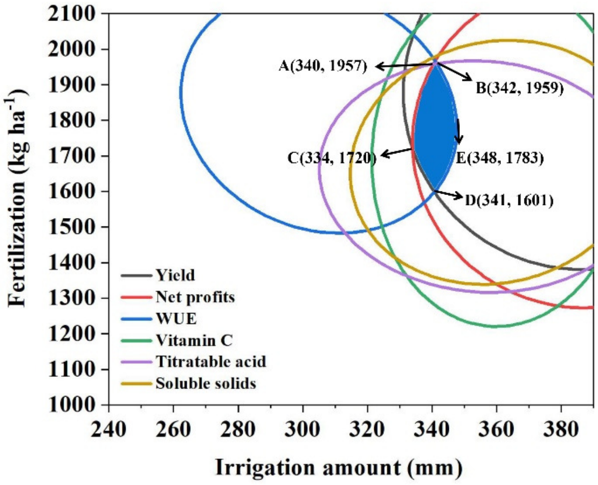


Fig. 4. Comprehensive evaluation of indices. The blue filled-in area in the figure meets the evaluation requirements.

Through the above analysis, the region with each evaluation index ≥ 0.90 is defined as an appropriate water and fertilizer input range. Based on the spatial analysis method, the 0.90 isolines of each evaluation index in Fig. 3 was projected on a plane. Then, a comprehensive evaluation analysis diagram of each index could be obtained. As can be seen from Fig. 4, the blue filled-in area is the overlapping area of reasonable water and fertilizer input ranges for each evaluation index. Therefore, the following conclusions can be drawn: when the irrigation range is 334–348 mm and the N–P_2O_5–K_2O fertilization range is 320–400–880~392–490–1077 kg ha^{-1}, the grape yield, net profits, WUE, vitamin C content, titratable acid content, and soluble solid content of the fruit reached above 90% of their maximum values simultaneously.

4. Discussion

4.1. Effects of irrigation and fertilization on the LAI, fruit quality, dry matter yield, grape yield, and HI

LAI is usually used to reflect the grape growth by providing specific canopy functioning information (Sun et al., 2017). The difference between the growth environment and grape varieties has a considerable effect on the LAI. Shi et al. (2018) found that the LAI peak value for the Jingmi grape was 2.19–4.07 m^2 m^{-2}; White et al. (2019) found that the LAI peaks of four different grape varieties were 3.93–5.04 m^{-2} m^{-2}; Wang et al. (2014) found that the LAI peak value of seedless white grapes was 4.21–4.55 m^{-2} m^{-2}. Generally, when the irrigation amount is increased, the LAI of grapes will also increase (Li et al., 2015). Our research results are basically consistent with the above. As such, in the three–year experiment, the LAI of the grapes increased significantly with an increase in the amount of irrigation. With a $W_{60\%}$ irrigation level, when the input amount of N–P_2O_5–K_2O was less than 300–375–825 kg ha^{-1}, the LAI was less than 3.87 m^{-2} m^{-2}. With $W_{80\%}$ and $W_{100\%}$ irrigation levels, when the N–P_2O_5–K_2O input was 360–450–990~420–525–1155 kg ha^{-1} , the LAI was between 5.21–6.51 m^{-2} m^{-2} in all three years. Thus, it is conducive to the growth of grape leaves by increasing irrigation level.

Water and fertilizer input levels have a considerable effect on the quality of the grape fruit. Wang et al. (2016b) found that with a certain amount of irrigation, the soluble solids content of fruits increased with an increase in applied fertilizer, and the highest soluble solids content reached 19.46%, however, the soluble solids content decreased when excessive fertilization was applied. Fan et al. (2013) pointed out that with the same amount of phosphorus and potassium fertilizer, the vitamin C content showed a trend of first increasing and then decreasing with an increase in supplied nitrogen fertilizer. Hou et al. (2019a) reported that the titratable acid content of fruits also showed a trend of first increasing and then decreasing with an increase in applied fertilizer. The findings of our study are similar to these. Over the three-year study period, irrigation and fertilizer had a very significant effect on fruit quality. When the amount of fertilizer is increased, vitamin C, titratable acid, and the soluble solid content of fruit showed a trend of increasing first and then decreasing at the same irrigation conditions. At low irrigation ($W_{60\%}$), the fruit quality was the worst. With $W_{100\%}$ irrigation and $F_{100\%}$ fertilization, the vitamin C content, titratable acid content, and soluble solid content reached their highest levels. In addition, with medium ($W_{80\%}$) irrigation $F_{120\%}$ fertilization, the soluble solid content also reached its maximum.

The coupling effect of water and fertilizer considerably influences grape yields (Zheng et al., 2013; Intrigliolo et al., 2016; Canoura et al., 2018; Zhang et al., 2019a). Within a certain range, grape yield increases with an increase in water and fertilizer inputs, but when the water and fertilizer inputs exceed a certain threshold, the yield decreases. Therefore, only scientifically-derived levels of water and fertilizer input can realize ideal grape yields (Zhang et al., 2018; Zhang et al., 2019a). Under the condition of high water and fertilizer input, the dry matter yield and grapes yield increases, however the HI decreases significantly (Wang et al., 2013). The results of our study were similar. Under the same irrigation conditions, with an increase in applied fertilizer, grape yield showed a trend of increasing first and then decreasing. With $W_{100\%}$ irrigation and $F_{120\%}$ fertilization, the grape yield was the highest. Although the grape yield reached its maximum in 2015 and 2016 with $W_{100\%}$ irrigation and $F_{100\%}$ fertilization, there was no significant difference between the grape yield and that of the $F_{120\%}$ treatment. The highest HI was obtained with $W_{80\%}$ irrigation in 2016, and the highest HI was obtained at $W_{60\%}$ irrigation in 2015 and 2017.

When the input of water and fertilizer is appropriate, the LAI of the grapes will increase, which is more conducive to the photosynthesis of the grapes, thus obtaining a high yield. Within a certain range, with an increase in the LAI, the grape yield also increases. Low amounts of water and fertilizer will lead to a low LAI, weakening the photosynthesis of the grapes. This is not conducive to the synthesis of nutrients, nor conducive to high yields. When irrigation increases, the LAI increases, as do the dry matter yield and grape yield, vitamin C, titratable acid, and soluble solid content. In our three–year study, with $W_{100\%}$ irrigation and 360–450–990 kg ha^{-1} N–P_2O_5–K_2O, the LAI, dry matter yield, and grape yield were at their highest levels, or there were no significant differences from the highest level. When the irrigation level was $W_{100\%}$ and the input amount of N–P_2O_5–K_2O was 300–375–825 kg ha^{-1}, the vitamin C content, titratable acid, and soluble solids in the fruits reached their highest values.

4.2. Effects of irrigation and fertilization on the WUE, PFP, and net profits

Appropriate irrigation and fertilizer input is conducive to improving the WUE of grapes (Zhang et al., 2014b). Zhang et al. (2019a) showed that irrigation and fertilization have a significant effect on the WUE. In our study, irrigation, fertilization, and the coupling of irrigation and fertilization had a very significant effect on water use efficiency. The WUE at $W_{100\%}$ irrigation was lower than the WUE at $W_{60\%}$ and $W_{80\%}$ irrigation. The highest water use efficiency in the three-year study period came with $W_{80\%}$ irrigation. Under the same irrigation level, within a certain range, the water use efficiency increases with an increase in applied fertilizer.

In a certain range, increasing the irrigation level can improve the yield, and a higher fertilizer input can improve the fertilizer partial productivity. However, if excessive fertilizer is applied, the balance between the grape vegetative growth and physiological growth will be destroyed, resulting in excessive nutrient absorption, delayed ripening, and, ultimately, a reduced yield (Shi et al., 2011; Wang et al., 2018). In the case of low irrigation, appropriate nitrogen application can also achieve higher fertilizer partial productivity (Ma et al., 2010). In our study, the irrigation had a very significant effect on the PFP. When the amount of irrigation increased, PFP also showed an increasing trend under the same fertilization level. The PFP reached the highest value under $W_{100\%}$ irrigation. Fertilization had a very significant impact on the fertilizer partial productivity in all three years. Under the same irrigation level, the PFP showed a downward trend with an increase in the amount of fertilization. Although the PFP of the three irrigation levels was the highest under $F_{60\%}$ fertilization treatment, the yield and fruit quality could not meet the production requirements. Therefore, medium and high fertilization levels are more beneficial to increasing the yield and fertilizer partial productivity.

The ultimate goal of fruit growers is economic gain. This study shows that under the same irrigation level, with an increase in fertilizer application, the net profit first increases and then decreases. In other words, excessive fertilizer input will not increase the income of fruit growers. Reducing irrigation will lead to obvious net profit losses. The net benefit of $W_{100\%}$ irrigation is 1.8–2.4 times that of $W_{60\%}$ irrigation. This is consistent with the results of Li et al. (2011b). They found that when the irrigation decreased by 42.8%, the grape yield decreased by 23.38%, and the economic benefits were also significantly reduced. Therefore, in areas without water shortages, adequate irrigation is feasible. In water–deficient areas, however, it is necessary to seek a water and fertilizer management scheme that takes into account both economic benefits and water and fertilizer conservation.

4.3. Effects of water and fertilizer coupling on grape growth and production

Based on long–term field observation data, combined with multiple regression and spatial analysis methods, we can establish an accurate model of the relationship between irrigation and fertilization and crop yields, quality, and net profits (Wang et al., 2018; Hou et al., 2019a). In this study, we established a model of the relationship between the irrigation and fertilization and the grape yield, fruit quality, WUE, and net profits. The results show that when the irrigation range was 334–348 mm and the N–P_2O_5–K_2O fertilization range was 320–400–880~392–490–1077 kg ha^{-1}, the grape yield, net profits, WUE, vitamin C content, titratable acid content, and soluble solid content of the fruit could reach more than 90% of their maximum values simultaneously.

5. Conclusions

More effective use of water and fertilizer resources, as well asproper water and fertilizer management schemes, are one of theurgent matters facing China. Based on data obtained from field experiments conducted over three consecutive years (2015–2017), this paper studied the effects of water and fertilizer coupling on the yield, fruit quality, WUE, PFP, and net profits of *Vitis vinifera cv*. "Frey" grapes, grown in a typical inland arid area, and gave out the multi–objective optimization for drip irrigation of grapes in arid areas of northwest China.

The results showed that the maximum bunch weights in the three–year experiment were 407, 383 and 378 g, respectively;and that the highest HI were 0.460, 0.425, and 0.416, respectively. It was difficult to obtain the grape yield, WUE, PFP and economic benefits at the same time, as so as the best fruit quality. With increased irrigation levels, LAI, fruit quality, and dry matter yield increased, with significant improvement in grape yield, PFP and economic benefits. However, the WUE at full ($W_{100\%}$) irrigation was lower than that at medium and low ($W_{80\%}$, $W_{60\%}$) irrigation levels. Under the same irrigation level, when N-P_2O_5-K_2O was applied at a dose of 360-450-990 kg ha^{-1}, the LAI, fruit quality, dry matter yield, grape yield and WUE reached the maximum, although the bunch weight, PFP, HI and economic benefits did not. Meanwhile, with an increase in the amount of fertilizer applied, the PFP showed a significant downward trend. Compared to full ($W_{100\%}$) irrigation levels, low ($W_{60\%}$) irrigation levels were not conducive to the efficient use of fertilizers, and the PFP was the lowest. Multiple regression analysis showed that when the irrigation range was 334-348 mm and the N-P_2O_5-K_2O fertilization range was 320-400-880 ~ 392-490-1077 kg ha^{-1}, the grape yield, economic benefits, WUE, and fruit quality could reach more than 90% of their maximum values.

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