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 (FPP), and net profits of Vitis vinifera cv. ‘Trey’. 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-P2O5-K2O (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 Wac, Wbc, Wbc, Wbc, and Wbc, respectively. Three drip irrigation levels were designated Wabc, Wabc, Wabc, accounting for 60%, 80% and 100% of the ETc (where ETc 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, FPP, and net profit increased with an increase in irrigation. They reached their maximum under full irrigation (Wabc). Compared to Wabc and Wabc irrigation levels, the WUE at a full (Wabc) irrigation was lower, but the FPP was the highest. The maximum grape bunch weight over three years was 407, 383, and 378 g, respectively. The highest harvest index (HI) was 0.46, 0.425, and 0.416, respectively. When the irrigation range was 334–348 mm and the N–P2O5–K2O 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 efficiency 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 Herat 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% ETc (where ETc 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–P2O5–K2O 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–P2O5–K2O 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 production (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–P2O5–K2O 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, Arauques 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...
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 Tienshan 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.

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 1.5 m) (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.

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>Soil texture</th>
<th>Particle mass fraction (%)</th>
<th>Bulk density (g cm⁻³)</th>
<th>Saturated water content (%)</th>
<th>Field water holding capacity (%)</th>
<th>Wilting point (%)</th>
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</thead>
<tbody>
<tr>
<td>0-0</td>
<td>Sandy loam</td>
<td>62.65</td>
<td>32.75</td>
<td>4.6</td>
<td>1.32</td>
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<tr>
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<td>26.76</td>
<td>4.32</td>
<td>1.45</td>
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</tr>
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<td>23.56</td>
<td>4.91</td>
<td>1.45</td>
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<td>5.52</td>
<td>1.45</td>
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<td>2.88</td>
<td>1.59</td>
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<tr>
<th>Number of irrigation</th>
<th>Irrigation Date</th>
<th>Days after bud break</th>
<th>Irrigation amount (mm)</th>
<th>Fertilization amount (kg ha⁻¹)</th>
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<tr>
<td></td>
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<td></td>
<td>W60% W80% W100% F60% F80% F100%</td>
<td>F120% F140%</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1</td>
<td>5.8</td>
<td>1</td>
<td>60  60  60  135  180  230  276  322</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5.22</td>
<td>15</td>
<td>78  104  130  295  387  500  598  710</td>
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</tr>
</tbody>
</table>
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-P2O5-K2O (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 F4:5:11, F6:0:0, F8:5:11, F10:0:0, and F12:0:0, respectively. Three irrigation levels were set up in the experiment: full irrigation (W100%), medium irrigation (W80%), and low irrigation (W60%). The three irrigation levels accounted for 60%, 80%, and 100% of the ETc. According to the meteorological data provided by the local meteorological station, the reference crop evapotranspiration (ET0) during the grape growing period was calculated using the Penman–Monteith formula recommended by FAO–56. According to research results of Zeng (2010), the crop coefficient (Kc) of grape was determined, ETc = K × ET0. 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. Three irrigation levels were set up in the experiment: full irrigation (W100%), medium irrigation (W80%), and low irrigation (W60%), respectively. Three irrigation levels accounted for 60%, 80%, and 100% of the ET0. 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):

\[ W = 0.8954 \times X^{0.023} \]

where \( W \) is the area of the grape leaves (cm²), and \( X \) is the length of the main vein of grape leaves (cm).

#### 2.3.2 Estimation of Leaf area index (LAI)

Leaf area index was computed from:

\[ \text{LAI}(t) = \left( \frac{B(t) \times \text{I}(t) \times I(t) / 10000} {S} \right) \times S \]

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:

\[ m = 0.0003 \times A^{1.2325} \]

where \( m \) is the dry matter mass of each branch (g), and \( A \) is the total leaf area of each branch (cm²), and:

\[ M = 10 \times a \times b \times m / S \]

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 (m²) (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):

\[ HI = \frac{\text{Grape Yield}}{\text{Dry Matter Yield}} \]  

(5)

2.3.7 WUE

WUE was determined from:

\[ \text{WUE} = \frac{Y}{ET} \]  

(6)

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

\[ ET = P + K + B - C - N - \Delta W \]  

(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 \( \Delta W \) 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:

\[ \text{PFP} = \frac{Y}{F} \]  

(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:

\[ N_p = G_p - W - F - L \]  

(9)

where \( N_p \) is the net profit (RMB ha\(^{-1}\)), \( G_p \) is the gross profit (RMB ha\(^{-1}\)), \( W \) is the water cost (RMB ha\(^{-1}\)), \( F \) 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 \( W_{60\%} \times F_{120\%} \) 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 \( W_{140\%} \times F_{120\%} \) 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

<table>
<thead>
<tr>
<th>Treatment</th>
<th>LAI (m(^2)·m(^{-2}))</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation</td>
<td>Fertilization</td>
<td></td>
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<tr>
<td>( W_{60%} )</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F_{60%} )</td>
<td></td>
<td>4.82</td>
<td>4.81</td>
<td>2.94</td>
<td>358</td>
<td>350</td>
<td>357</td>
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<td>( F_{100%} )</td>
<td></td>
<td>5.05</td>
<td>5.44</td>
<td>4.43</td>
<td>383</td>
<td>349</td>
<td>349</td>
</tr>
<tr>
<td>( F_{120%} )</td>
<td></td>
<td>5.35</td>
<td>5.87</td>
<td>5.10</td>
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<td>379</td>
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<td>( F_{140%} )</td>
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<td>( F_{160%} )</td>
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<td>5.72</td>
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<td>( W_{120%} )</td>
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<tr>
<td>( F_{60%} )</td>
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<td>4.90</td>
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<td>340</td>
<td>334</td>
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<td>( F_{100%} )</td>
<td></td>
<td>3.62</td>
<td>3.87</td>
<td>2.68</td>
<td>387</td>
<td>378</td>
<td>371</td>
</tr>
<tr>
<td>( F_{120%} )</td>
<td></td>
<td>3.83</td>
<td>4.07</td>
<td>3.34</td>
<td>407</td>
<td>383</td>
<td>321</td>
</tr>
<tr>
<td>( F_{140%} )</td>
<td></td>
<td>4.08</td>
<td>4.47</td>
<td>4.96</td>
<td>398</td>
<td>363</td>
<td>363</td>
</tr>
</tbody>
</table>

Table 4: Effects of irrigation and fertilization on the LAI and grape bunch weight.
irrigation, fertilization and water–fertilizer coupling were very significant (P < 0.01). They reached their highest value at the W

indicators was significantly positively correlated with an increase in irrigation (P < 0.01). The W

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 with an increase of the fertilization level. They reached their peak values at the F

Table 6

Table 5

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). Di: erent letters following the values denote a significant di: erence 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 354, 345, and 378 g, respectively. The effect of water and fertilizer coupling was highly significant (P < 0.01) (see Table 4). At the W

W × F  ** ns ** ns ** ns ** ns ** ns ** ns ** ns ** ns

W  ** ns ** ns ** ns ** ns ** ns ** ns ** ns ** ns

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 W

Table 7

Treatment  Vitamin C (mg 100g

Table 5

Effects of irrigation and fertilization on the fruit quality.

Table 6

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

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 grape 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

Table 7

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

Table 8

Effects of irrigation and fertilization on the water–fertilizer coupling.
The highest grape yield in 2015, 2016, and 2017 was 19.80, 19.99, and 24.16 Mg ha\(^{-1}\) at treatment of W\(_{100}\) × F\(_{40}\), W\(_{100}\) × F\(_{60}\), and W\(_{100}\) × F\(_{140}\), 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\(_{60}\) × F\(_{100}\).

At the W\(_{60}\) 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\(_{40}\) and F\(_{60}\). At the W\(_{100}\) irrigation level, the yield of the F\(_{40}\) 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\(_{40}\)/F\(_{100}\), under the same irrigation level. However, it was not helpful for increasing the fertilization under the irrigation level up to F\(_{100}\). 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\(_{30\%}\) x F\(_{40\%}\) was the greatest, ranging from 19.13 - 21.06, and that of W\(_{60\%}\) x F\(_{40\%}\) was the lowest, ranging from 7.17 – 8.59 (see Table 7).

#### Table 7

<table>
<thead>
<tr>
<th>Treatment</th>
<th>WUE (kg m(^{-2}))</th>
<th>PFP</th>
</tr>
</thead>
<tbody>
<tr>
<td>W(<em>{60}) x F(</em>{100})</td>
<td>1.35f</td>
<td>1.35f</td>
</tr>
<tr>
<td>W(<em>{100}) x F(</em>{100})</td>
<td>1.46a</td>
<td>1.36f</td>
</tr>
<tr>
<td>W(<em>{100}) x F(</em>{120})</td>
<td>1.56c</td>
<td>1.55k</td>
</tr>
<tr>
<td>W(<em>{100}) x F(</em>{140})</td>
<td>1.57cd</td>
<td>1.55d</td>
</tr>
<tr>
<td>W(<em>{140}) x F(</em>{100})</td>
<td>1.49e</td>
<td>1.42c</td>
</tr>
<tr>
<td>W(<em>{140}) x F(</em>{120})</td>
<td>1.48e</td>
<td>1.34f</td>
</tr>
<tr>
<td>W(<em>{140}) x F(</em>{140})</td>
<td>1.63c</td>
<td>1.55d</td>
</tr>
</tbody>
</table>

#### Table 8

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Fertilizer cost (RMB ha(^{-1}))</th>
<th>Gross profit (RMB ha(^{-1}))</th>
<th>Net profit (RMB ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>W(<em>{60}) x F(</em>{100})</td>
<td>1.35f</td>
<td>1.35f</td>
<td>1.35f</td>
</tr>
<tr>
<td>W(<em>{100}) x F(</em>{100})</td>
<td>1.46a</td>
<td>1.36f</td>
<td>1.35f</td>
</tr>
<tr>
<td>W(<em>{100}) x F(</em>{120})</td>
<td>1.56c</td>
<td>1.55k</td>
<td>1.64c</td>
</tr>
<tr>
<td>W(<em>{100}) x F(</em>{140})</td>
<td>1.57cd</td>
<td>1.55d</td>
<td>1.76ab</td>
</tr>
<tr>
<td>W(<em>{140}) x F(</em>{100})</td>
<td>1.49e</td>
<td>1.42c</td>
<td>1.50de</td>
</tr>
<tr>
<td>W(<em>{140}) x F(</em>{120})</td>
<td>1.48e</td>
<td>1.34f</td>
<td>1.30f</td>
</tr>
<tr>
<td>P</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>W</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>F</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>W × F</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
</tbody>
</table>

#### 3.5. Net profits

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\(_{60}\) 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 W60% for three years as the upper irrigation limit, the minimum irrigation of W40% as the lower irrigation limit, the maximum fertilization of F60% for three years as the upper fertilization limit, and the minimum fertilization of F40% 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).

The results show that it is impossible to obtain the maximum grape yield, net profit, water use efficiency, fertilizer partial productivity, vitamin C content, titratable acid, and soluble solid content at the same time. When the irrigation amount is 387 mm and the input amount of N–P–K is 347–470–1034 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–K 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–K 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–K 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–K 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–K 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–K is 337–421–926 kg ha⁻¹, the soluble solid content reaches its maximum, 25.24% (see Table 10).

### Table 9

| Dependent variable | Regression equation | R² | P (|-
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield/Y</td>
<td>0.34911W + 3.98628P + 0.00399F + 1.1.726W + 11.754F</td>
<td>0.747</td>
<td>0.01</td>
</tr>
<tr>
<td>Net profits/Y</td>
<td>1.26771W - 0.03420W - 0.01651F + 0.986.86413W + 58.820F</td>
<td>0.736</td>
<td>0.01</td>
</tr>
<tr>
<td>WUE/Y</td>
<td>2.43050P + 8.81554P + 3.77230P + 0.01466W + 0.00165F + 2.290F</td>
<td>0.820</td>
<td>0.01</td>
</tr>
<tr>
<td>PFP/Y</td>
<td>1.53524P + 16.2530P + 3.2509P + 0.1476W + 0.11812F + 0.48455</td>
<td>0.944</td>
<td>0.01</td>
</tr>
<tr>
<td>Titratable acid/Y</td>
<td>7.26209P + 3.88032P + 4.99398P + 5.22526W + 0.13161F + 74.5319</td>
<td>0.961</td>
<td>0.01</td>
</tr>
<tr>
<td>Soluble solids/Y</td>
<td>-5.48827P + 9.78478P + 3.07554P + 0.0040F + 4.64165P + 0.37832</td>
<td>0.893</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Note: Y 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

<table>
<thead>
<tr>
<th>Y variable</th>
<th>W (mm)</th>
<th>F (kg ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grape yield/Y</td>
<td>20.71</td>
<td>387</td>
</tr>
<tr>
<td>Net profits/Y</td>
<td>66246.14</td>
<td>387</td>
</tr>
<tr>
<td>WUE/Y</td>
<td>1.72</td>
<td>306</td>
</tr>
<tr>
<td>PFP/Y</td>
<td>19.81</td>
<td>390</td>
</tr>
<tr>
<td>Titratable acid/Y</td>
<td>33.33</td>
<td>362</td>
</tr>
<tr>
<td>Soluble solids/Y</td>
<td>0.53</td>
<td>356</td>
</tr>
</tbody>
</table>

Solve the maximum value of each evaluation indicator

The results show that it is impossible to obtain the maximum grape yield, net profit, water use efficiency, fertilizer partial productivity, vitamin C content, titratable acid, and soluble solid content at the same time. When the irrigation amount is 387 mm and the input amount of N–P–O–K 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–O–K 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–O–K 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–O–K 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–O–K 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–O–K 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–O–K 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).
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 ≥ 0.90 of each evaluation index is the ideal range to meet the evaluation requirements.

![Comprehensive evaluation of indices. The blue filled-in area in the figure meets the evaluation requirements.](image)

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–P₂O₅–K₂O 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 of the jingmi grape was 2.19–4.07 m² m⁻²; White et al. (2019) found that the LAI peaks of four different grape varieties were 3.93–5.04 m² m⁻²; Wang et al. (2014) found that the LAI peak value of seedless white grapes was 4.21–4.55 m² 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 W80% irrigation level, when the input amount of N–P₂O₅–K₂O was less than 300–375–825 kg ha⁻¹, the LAI was less than 3.87 m² m⁻². With W85% and W90% irrigation levels, when the N–P₂O₅–K₂O input was 360–450–990–420–525–1155 kg ha⁻¹, the LAI was between 5.21–6.51 m² 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 (W80%), the fruit quality was the worst. With W85% irrigation and F120% fertilization, the vitamin C content, titratable acid content, and soluble solid content reached their highest levels. In addition, with medium (W85%) irrigation F120% 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 W80% irrigation and F120% fertilization, the grape yield was the highest. Although the grape yield reached its maximum in 2015 and 2016 with W85% irrigation and F120% fertilization, there was no significant difference between the grape yield and that of the F120% treatment. The highest HI was obtained with W85% irrigation in 2016, and the highest HI was obtained at W80% 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 W100% irrigation and 360–450–990 kg ha−1 N–P2O5–K2O, 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 W30% and the input amount of N–P2O5–K2O was 300–575–825 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 W100% irrigation was lower than the WUE at W30% and W60% irrigation. The highest water use efficiency in the three-year study period came with W60% 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 W100% 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 F30% 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 W60% irrigation is 1.8–2.4 times that of W30% 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 grape yield, fruit quality, WUE, and net profits. The results show that when the irrigation range was 334–348 mm and the N–P2O5–K2O 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 as water and fertilizer management schemes, are one of the urgent 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 (W100%) irrigation was lower than that at medium and low (W60%, W30%) irrigation levels. Under the same irrigation level, when N–P2O5–K2O was applied at a dose of 360–450–990 kg ha−1, the LAL, 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 (W100%) irrigation levels, low (W60%) 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–P2O5–K2O 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.

Acknowledgement

We acknowledge the financial support from the National Natural Science Foundation Program (U1803244, 51669029) and the National Key Development Program (2016YFC050406).

References


