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Response of Wine Grape Quality to Rainfall, Temperature, and Soil Properties in Hexi Corridor

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Abstract. **This study aimed to clarify the relationship between grape (*Vitis vinifera* L.) quality and environmental factors (climate and soil), and to elucidate the theoretical basis and provide technical guidance for the rational planning of the cultivation area and the precise regulation of the cultivation mode in the future. The fruits of three different grape cultivars, Pinot Noir, Merlot, and Vidal, as well as soil samples and meteorological data were collected from three wine grape growing areas (Wuwei, Zhangye, and Jiayuguan) in the Hexi Corridor, Northwest China. Principal-component analysis (PCA) and correlation analysis were conducted to understand the relationship of grape quality with weather conditions and soil properties. The results showed that the titratable acid content of grape berries was significantly negatively correlated with average temperature from August to September, average minimum temperatures from August to September, and from April to October, mean annual minimum temperature, growing degree days from August to September, and soil total nitrogen content, and significantly positively correlated with average rainfall from April to October, annual mean rainfall, and soil available potassium content. In addition, the pH of grape juice was significantly negatively correlated with annual mean rainfall and soil available potassium content. However, it was significantly positively correlated with average temperature and average minimum temperature from August to September, average minimum temperature from April to October, growing degree days from August to September, as well as soil total nitrogen content. In addition, the results of PCA showed that the fruit quality scores of 'Vidal' in Jiayuguan, 'Merlot' in Zhangye, and 'Pinot Noir' in Wuwei were the highest, respectively. In conclusion, the contents of titratable acid, pH, and Brix° are greatly affected by climate and soil factors. 'Vidal', 'Merlot', and 'Pinot Noir' were suitable for planting in Jiayuguan, Zhangye, and Wuwei, respectively. Nowadays, few reports focus on the relationship between grape quality and soil and climate conditions. Based on the investigation and analysis of the differences of climate, soil, and grape berries quality in the three production areas of Hexi Corridor, the relationship among climate, soil, and grape quality by using statistical methods was studied, which could provide references for clarifying the reasons why environmental factors affect grape quality and select the suitable area for wine grape cultivation.**

Grape (*Vitis vinifera* L.) quality is easily affected by the ecological conditions of the production area during the growing season (Hosseini et al. 2014; Lebon et al. 2006; Sun 2017). Climate and soil are the main ecological factors that affect the quality of wine grapes and hence the quality of wine (Van Leeuwen and Seguin 2006; Zhang et al. 2007a). Climate plays a leading role in the formation of wine grape quality and flavor (Han et al. 2001). Light, temperature, and rainfall are the main meteorological factors (Hewett 2006), and soil texture and elemental composition are the main soil-related factors that affect the quality of wine grapes.

As energy source for plant photosynthesis, light has a great influence on the development of grape berries. At the later stages of plant growth and development, light can increase the strength of the fruit (sink), promote the input and distribution of photosynthates from the leaf (source) to the fruit, and increase the accumulation of sugar in the fruit (Smart 1987; Spayd et al. 2002). A reduction in light intensity decreases the sugar content, vitamin content, and sugar-to-acid ratio of grape berries (Hang et al. 2016). Effective growing degree days (GDD), calculated based on the main daily temperatures and a base temperature of 10 °C, is an important heat index, which has a great influence on the ripening and sugar content of grape berries (Kok 2020; Mori et al. 2007). A higher effective GDD can increase the sugar content of the fruit, reduce the fruit acid content, and inhibit formation of phenolic (Spayd et al. 2002; Tarara et al. 2008) and aroma substances (de Orduna 2010), resulting in a rough and uncoordinated wine taste. However, low effective GDD is associated with low sugar and high acid contents of grape berries with thick skin and poor quality (Wang et al. 2006). Water availability, which is determined by precipitation levels, plays an important role in the quality formation of wine grapes. Mild drought stress during berry expansion can reduce the grape yield by up to 60%. At the later stages of berry development, mild drought stress reduces the sugar content (Brix°) of grape berries and harms the acid reduction process (Deluc et al. 2009; Liu et al. 2016). The elemental composition and pH of soil also affect grape fruit quality. Grape plants show vigorous growth in soil with high nitrogen (N) content; however, the content of aroma substances in wine grape is high when plants are grown in soil with moderate N content. Arno et al. (2012) pointed out that the content of calcium ions (Ca^{2+}) in soil is positively correlated with the content of sugar in berries. In another study, the amount of magnesium (Mg) in soil has been positively correlated with the acid content of berries; N has been shown to enhance vine vigor and increase yield, but it is not conducive to the accumulation of sugars and phenols in grape fruit; phosphorous (P) and potassium (K) have been shown to increase the sugar content and decrease the acid content of grape berries (Baiano et al. 2011). Morlat and Jacquet (2003) reported that soil pH ranging from 4.0 to 8.5 was optimal for the growth of grape vines; pH lower than 5.5 or higher than 8.0 harms the growth of grape vines, reducing the grape yield and quality.

In recent years, the grape and wine industry in the Hexi Corridor, located in northwestern China (36–40° N latitude), has been developing rapidly. This region has a hot and dry climate, with ample sunshine and little rainfall. The soil in this region is mainly composed of gravel and sandy, with high salt and alkali contents. Over the years, three representative wine grape producing areas have emerged in the Hexi Corridor, including Zhangye, Wuwei, and Jiayuguan, each of which has different climatic conditions and soil properties. Because of the limited number of studies conducted to date, our understanding of the effects of soil and climate-related factors on grape quality in the Hexi Corridor is minimal. Therefore, in this study, we

Table 1. Meteorological data collected from three different grape producing areas in the Hexi Corridor.

No.	Region	Altitude (m)	Location		Frost-free season (d)	Mean annual temp (°C)	Mean annual precipitation (mm)	Row orientation	Training system	Soil type
			Longitude (E)	Latitude (N)						
X1	Jiayuguan	1,580	98°21′1.65″	39°49′55.04″	130	9.0	112.8	North-South	Single cordons	Gravel, sandy loam
X2	Zhangye	1,444	100°19′49.36″	39°15′22.12″	175	9.7	98.9	North-South	Single cordons	Red gravel
X3	Wuwei	1,450	102°52′14.96″	37°50′12.16″	160	8.6	191.9	East-West	Single cordons	Gravel, sandy loam

examined the relationship of wine grape quality with soil and climate conditions in the three grape production areas in the Hexi Corridor. The results of this study will serve as a reference point for clarifying the reasons why environmental factors affect wine grape fruit quality, and will assist in the selection of a suitable area for wine grape cultivation all over the world.

Materials and Methods

Grape sampling. This study was carried out at the Basic Experiment Teaching Center (West Building) of Gansu Agricultural University in 2021. When the wine grapes were suitable for picking (the time of harvest was based on the minimum Brix° level of the grapes; the minimum Brix° of 'Pinot Noir', 'Merlot', and 'Vidal' is 18.5, 17, and 16, respectively), samples were collected from the main wine manors in the Hexi Corridor: Mogao Wine, Guofeng Wine, and Zixuan Wine vineyard. During sampling, three main varieties of each manor were selected and 15 grape vines with good growth and no diseases and pests were randomly selected. Three grape bunches were harvested from the shady and sunny sides of each grape vine, and 150 berries were randomly selected from the upper, middle, and lower parts of each bunch. The harvested berries were packaged on the same day, quickly transported back to the laboratory (within 6 h), and stored at 4 °C until needed for fruit quality analysis. Three biological replicates were performed for fruit quality index.

Soil sampling. The "s" type sampling method was used for multipoint sampling in each test area, and five sampling points were determined between rows. Soil samples with a depth of 0 to 60 cm were collected from each sampling point in layers (20 cm is a layer). Before taking the soil samples, a 5-cm layer of floating soil and sundries on the surface was removed. Then, a uniform amount of soil was sampled from each soil layer using a ring knife and an aluminum box. The soil samples collected from each test area were mixed according to the level, and plant residues, stones, and animals were removed from the pooled samples. The cleaned soil samples were transferred into bags, which were then sealed and placed in an incubator with ice bags. At the same time, undisturbed soil samples collected from each sampling point were transferred into aluminum boxes in their original structural state and taken back to the laboratory.

Meteorological survey. Climate-related data were collected from the meteorological institutions at each of the three different production areas (Table 1).

Measurement of grape quality indices. The 100-grain weight of grape berries was measured using Ae224 electronic analytical balance (Shanghai Shunyu Technology Instrument Co., Ltd., Shanghai, China). The identity and contents of sugar and acid compounds in the grape berries were determined using the FOSS DK-3400 multifunctional wine analyzer [FOSS (Beijing) Science and Trade Co., Ltd, Beijing, China]. The titratable acid content of grape berries was determined using the NaOH neutralization titration method (Balic et al. 2014). Total phenol and tannin contents were measured using the Folin-Ciocalteu (McDonald et al. 2001) method and Folin-Denis method (Schanderl 1970), respectively. The Brix° was determined using a PR-101 α Digital display total sugar instrument (ATAGO company of Japan, Tokyo, Japan). The anthocyanin content of grape berries was determined using the Liang method (Liang et al. 2008), with slight modifications.

Measurement of soil indices. The total salt, available P, and available K contents of soil were determined according to soil agrochemical analysis (Lewis et al. 1991). To determine the soil K^+ and Na^+ contents, the soil samples were air-dried, ground in self-sealing bags, and passed through a 0.5-mm sieve. Then, the soil K^+ and Na^+ contents were measured using flame spectrophotometer FP6450 (Shanghai Yidian Scientific Instrument Co., Ltd, Shanghai, China) (Netzer et al. 2014).

Data analysis. The statistical analysis of data were conducted using Microsoft Excel 2010 (Redmond, WA, USA). PCA and correlation analysis were conducted using the SPSS 23.0 software (IBM, Corp, Armonk, NY, USA).

Results

Analysis of the quality berries produced in different areas of the Hexi Corridor. The quality indices of different varieties of grapes in the three production areas are summarized in Table 2. The berries of Merlot grape cultivar grown in Zhangye showed the highest contents of malic acid (4.9 $mg \cdot g^{-1}$), tartaric acid (3.26 $mg \cdot g^{-1}$), and total tannins (12.03 $mg \cdot g^{-1}$), and the pH of these grapes (4.57) was significantly higher than those of 'Merlot' grapes grown in Wuwei and Jiayuguan ($P < 0.05$). In addition, the reducing sugar content and Brix value of 'Merlot' grapes grown in Zhangye were 212.88 $mg \cdot g^{-1}$ and 26.88%, respectively. The 'Merlot' grapes grown in Wuwei showed the highest 100-grain weight (167.03 g). No significant differences were observed in the citric acid, titratable acid, total anthocyanin, fructose, and glucose contents of 'Merlot' grapes among the three regions. The 'Pinot Noir' grape grown in Wuwei showed the highest malic acid (2.35 $mg \cdot g^{-1}$), titratable acid (0.69%), reducing sugar (224.53 $mg \cdot g^{-1}$), total tannin (11.99 $mg \cdot g^{-1}$), and total phenol (48.93 $mg \cdot g^{-1}$) contents and 100-grain weight (166.27 g). The 'Pinot Noir' grape grown in Jiayuguan showed the highest citric acid (0.62 $mg \cdot g^{-1}$) and tartaric acid (3.36 $mg \cdot g^{-1}$ contents and Brix° (23.7%). The 'Pinot Noir' grape showed no significant difference in glucose content and pH among the three regions. The Brix value and tartaric acid, reducing sugar, fructose, total tannin, and total phenol contents of 'Vidal' grape were the highest in Jiayuguan (23.9%, 3.79 $mg \cdot g^{-1}$, 201.03 $mg \cdot g^{-1}$, 87.98 $mg \cdot g^{-1}$, 10.36 $mg \cdot g^{-1}$, and 61.25 $mg \cdot g^{-1}$, respectively). There was no significant difference in the malic acid, citric acid, titratable acid, and glucose contents and grape pH of 'Vidal' among the three production areas.

Physical and chemical properties of soil in the three different areas of the Hexi Corridor. The physical and chemical properties of soil in the three production areas were quite different (Table 3). Zhangye showed the highest average soil pH (8.09), followed by Wuwei (8.03) and Jiayuguan (7.89), and the average value of soil pH showed no significant difference between Wuwei and Zhangye regions. The content of K^+ in Wuwei (3.65 $mg \cdot g^{-1}$) was significantly higher than that in Zhangye and Jiayuguan, and its value was the lowest in Jiayuguan (2.77 $mg \cdot g^{-1}$). The Na^+ (2.77 $mg \cdot g^{-1}$), total salt (2.54 $mg \cdot g^{-1}$), and available P (21.87 $mg \cdot g^{-1}$) contents of soil in Jiayuguan were significantly higher than those in Wuwei and Zhangye; the latter area showed the lowest contents of Na^+ (2.62 $mg \cdot g^{-1}$), total salt (0.4 $mg \cdot g^{-1}$), and available P (14.6 $mg \cdot g^{-1}$). The contents of available P (186.88 $mg \cdot g^{-1}$) and total N (0.59 $g \cdot kg^{-1}$) in the Wuwei area were significantly higher than those in Jiayuguan and Zhangye; the latter area showed the lowest contents of available K (151.03 $mg \cdot g^{-1}$) and total N (0.26 $g \cdot kg^{-1}$). The contents of soil nutrients

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Table 2. Quality of grape berries of three varieties grown in three areas in the Hexi Corridor.

Variety	Region	Malic acid content ($mg\cdot g^{-1}$)	Citric acid content ($mg\cdot g^{-1}$)	Tartaric acid content ($mg\cdot g^{-1}$)	Titratable acid content (%)	Grape pH	Reducing sugar content ($mg\cdot g^{-1}$)	Fructose content ($mg\cdot g^{-1}$)	Glucose content ($mg\cdot g^{-1}$)	Brix° (%)	Total anthocyanin content ($mg\cdot g^{-1}$)	Total phenol content ($mg\cdot g^{-1}$)	Total tannin content ($mg\cdot g^{-1}$)	100-grain wt (g)
Merlot	Jiayuguan	1.29 ± 0.04 b	0.41 ± 0.02 a	2.78 ± 0.17 b	0.62 ± 0.23 a	4.24 ± 0.22 b	212.88 ± 0.58 a	88.51 ± 1.06 a	92.13 ± 3.27 a	26.57 ± 0.87 a	11.22 ± 1.13 a	52.93 ± 4.51 a	8.72 ± 0.25 b	138.3 ± 6.2 b
	Wuwei	1.43 ± 0.16 b	0.48 ± 0.06 a	2.44 ± 0.14 b	0.73 ± 0.06 a	4.01 ± 0.01 b	206.43 ± 3.53 b	88.1 ± 2.19 a	94.22 ± 4.32 a	21.57 ± 0.76 c	12.73 ± 2.42 a	35.98 ± 0.02 b	7.58 ± 0.15 c	167.03 ± 16.3 a
	Zhangye	1.9 ± 0.13 a	0.47 ± 0.06 a	3.26 ± 0.28 a	0.58 ± 0.17 a	4.57 ± 0.04 a	199.22 ± 1.19 c	84.12 ± 6.38 a	86.98 ± 3.94 a	24.33 ± 0.25 b	13.54 ± 0.38 a	49.45 ± 1.5 a	12.03 ± 0.01 a	138.83 ± 6.82 b
Pinot Noir	Jiayuguan	2.15 ± 0.05 a	0.62 ± 0.03 a	3.36 ± 0.12 a	0.54 ± 0.01 b	4.12 ± 0.1 a	199.17 ± 0.9 c	81.63 ± 1.83 b	92.01 ± 9.26 a	23.7 ± 0.46 a	4.63 ± 0.3 c	43.78 ± 1.13 a	9.24 ± 0.54 b	155.03 ± 11.67 ab
	Wuwei	2.35 ± 0.23 a	0.57 ± 0.03 ab	3.08 ± 0.27 a	0.69 ± 0.06 a	3.48 ± 0.63 a	224.53 ± 5.17 a	91.98 ± 1.51 a	95.5 ± 5.89 a	22.17 ± 0.59 b	6.14 ± 0.21 b	48.93 ± 4.5 a	11.99 ± 0.18 a	166.27 ± 7.27 a
	Zhangye	1.6 ± 0.2 b	0.51 ± 0.06 b	2.47 ± 0.07 b	0.51 ± 0.06 b	4.17 ± 0.03 a	215.33 ± 1.72 b	95.43 ± 7.05 a	93.4 ± 8.45 a	22.87 ± 0.7 ab	8.47 ± 0.68 a	37.4 ± 0.69 b	9.69 ± 0.2 b	147.63 ± 6.36 b
Vidal	Jiayuguan	2.18 ± 0.39 a	0.52 ± 0.02 a	3.79 ± 0.43 a	0.71 ± 0.02 a	3.93 ± 0.12 a	201.03 ± 2.24 a	87.98 ± 6.64 a	80.5 ± 0.99 a	22.9 ± 0.44 a	0.05 ± 0.01 b	61.25 ± 3.02 a	10.36 ± 0.1 a	171.37 ± 5.39 a
	Wuwei	1.75 ± 0.25 a	0.54 ± 0.04 a	3.53 ± 0.17 ab	0.77 ± 0.11 a	3.82 ± 0.26 a	188.7 ± 4.35 b	77.95 ± 3.71 b	80.24 ± 3.32 a	20.03 ± 1.59 b	0.19 ± 0.08 a	22.35 ± 1.65 c	5.05 ± 0.1 c	151.87 ± 6.5 b
	Zhangye	2.01 ± 0.09 a	0.55 ± 0.02 a	3.13 ± 0.1 b	0.69 ± 0.06 a	3.95 ± 0.09 a	189.27 ± 2.63 b	78.78 ± 2.76 ab	77.35 ± 2.27 a	20.93 ± 1.46 ab	0.11 ± 0.01 ab	41.06 ± 2.3 b	9.51 ± 0.32 b	155.07 ± 7.63 b

Data represent mean ± *SD*. Different lowercase letters indicate significant differences among the three different regions ($P < 0.05$).

were the highest in Wuwei, and those of various ions were the highest in Jiayuguan.

Analysis of climate in the three main grape production areas of the Hexi Corridor. Climate has a significant impact on grape planting and wine production. As shown in Table 4, the three main grape production areas in the Hexi Corridor showed considerable differences in climate. During the growing season (April–October), maturation period (August–September), and the whole year, the annual average temperature, annual average maximum temperature, annual average minimum temperature, and GDD were the highest in Zhangye. Among the three regions, Wuwei was the coldest, and Jiayuguan showed the lowest annual average maximum temperature. The annual sunlight duration was the highest in Jiayuguan, and rainfall was the highest in Wuwei and lowest in Zhangye.

Correlation analysis of grape quality, soil physical and chemical properties, and climatic conditions in different grape production areas. The results of correlation analysis are shown in Fig. 1. The titratable acid content of grape berries was significantly negatively correlated with average temperature from August to September, average minimum temperature from August to September, average minimum temperature from April to October, annual mean minimum temperature, GDD from August to September, and total N content. The average rainfall from April to October, annual mean rainfall, and available K were significantly positively correlated with the titratable acid content of grape berries, indicating that the average temperature from August to September, average minimum temperatures from August to September and from April to October, annual mean minimum temperature, GDD from August to September, and increase in total N are not conducive to the accumulation of titratable acid in grape berries. The increase of average rainfall from April to October, annual mean rain, and available K content were conducive to the accumulation of titratable acid in grape berries.

Grape pH was significantly negatively correlated with annual mean rainfall and available K (correlation coefficients: −0.673 and −0.674, respectively), indicating that the pH of grape berry juice decreases with the increase in rainfall during ripening. However, the grape pH was significantly positively correlated with average temperature and average minimum temperature from August to September, average minimum temperature from April to October, GDD from August to September, and total N content, indicating that the pH of grape berry juice increases gradually with the increase in temperature during ripening. Brix° showed a significant negative correlation with average rainfall from August to September and soil Na^{+} content (correlation coefficients: −0.680 and −0.694, respectively), indicating that the increase in rainfall during fruit ripening and the excess amount of Na^{+} in soil are not conducive to the accumulation of sugars in grape berries. Thus, we conclude that the titratable acid content, pH, and Brix° of grape berries are greatly affected by each climate and soil parameter tested in this study. No significant correlation was detected between the other quality indices and each climate and soil parameter.

PCA of grape quality in different areas. To evaluate the effects of climate and soil parameters on the quality of 'Merlot', 'Pinot Noir', and 'Vidal' grapes in three production areas, we performed PCA (Table 5). Two principal components (PCs; PC1 and PC2) were extracted from the three varieties through PCA, and the cumulative contribution rate reached 100%, indicating that the two PCs extracted from the three varieties could explain all the information of the original quality indicators. The variance contribution rates of PC1 and PC2 in 'Merlot' grape were 58.92% and 41.08%, respectively; the corresponding values were 58.83% and 41.17%, respectively, in 'Pinot Noir' grape, and 68.24% and 31.76%, respectively, in 'Vidal' grape. The indices with the greatest contribution to PC1 were total tannin content, grape pH, and glucose content in 'Merlot'; citric acid and Brix° in 'Vidal'; and titratable acid content, total tannin content, and grape pH in 'Pinot Noir'. The indices contributing the most to PC2 were citric acid, fructose, and total anthocyanin contents in 'Merlot'; total phenol, total anthocyanin, and malic acid contents and Brix° in 'Vidal'; and tartaric acid and glucose contents in 'Pinot Noir'.

The PCA results of 'Merlot', 'Pinot Noir', and 'Vidal' grapes in the three regions are shown in Table 6. The quality of the same variety planted in different regions varied greatly, and the dominant varieties suitable for planting in different regions also varied. 'Merlot' showed the highest quality score in Zhangye among the three production areas, which indicated that the quality of 'Merlot' berries in Zhangye was better than that in Jiayuguan and Wuwei. The 'Pinot Noir' berries showed the highest quality score in Wuwei among the three production areas, which indicated that the quality of 'Pinot Noir' berries in Wuwei was better than that in Jiayuguan and Zhangye. The 'Vidal' berries showed the highest quality score in Jiayuguan among the three production areas, which indicated that the quality of 'Vidal' berries in Jiayuguan was better than that in Wuwei and Zhangye. Together, our results suggest that 'Merlot', 'Pinot Noir', and 'Vidal' are suitable for large-scale planting in Zhangye, Wuwei, and Jiayuguan, respectively.

Discussion

Suitable soil is essential for the quality and yield of grapes (Ghimire et al. 2014; Poni et al. 2018). The effect of nitrogen on the composition and quality of grapes is usually a combination of its direct effect on grape metabolism and its indirect effect related to its strong influence on vigor and yield, resulting in influencing the soluble solids, reducing sugars, total soluble sugars, ratio of high soluble solids content/titratable

Table 3. Physical and chemical properties of soil in the three grape production areas in the Hexi Corridor.

Region	Soil pH	K^+ (mg·g^{-1})	Na^+ (mg·g^{-1})	Total salt (mg·g^{-1})	Available P (mg·g^{-1})	Available K (mg·g^{-1})	Total N (g/kg)
Jiayuguan	7.89 ± 0.01 b	2.8 ± 0.07 c	2.77 ± 0.03 a	2.54 ± 0.15 a	21.87 ± 2.18 a	156.15 ± 3.21 b	0.55 ± 0.08 a
Wuwei	8.03 ± 0.07 a	3.65 ± 0.04 a	2.49 ± 0.16 b	0.58 ± 0.13 b	15.07 ± 0.22 b	186.88 ± 0.89 a	0.59 ± 0.03 a
Zhangye	8.09 ± 0.03 a	3.24 ± 0.05 b	2.62 ± 0.05 ab	0.4 ± 0.13 b	14.6 ± 0.23 b	151.03 ± 1.18 c	0.26 ± 0.03 b

Data represent mean ± *SD*. Different lowercase letters indicate significant differences among different regions ($P < 0.05$).

acidity, and grape pH (Baiano et al. 2011; Lima et al. 2021; Thomidis et al. 2016). Approximately 50% of the potassium absorbed by the vine accumulates in the berry, mainly concentrated in the peel. Potassium and phosphorus together affect grape anthocyanin synthesis (Brunetto et al. 2015; Zheng et al. 2020). Soil pH affects the dissolution and availability of mineral elements in the soil. Studies show that pH ranging from 4 to 8.3 is optimal for the growth of wine grape plants (Wang et al. 2006). The soil pH in three main grape production areas of the Hexi Corridor was ~8.0, which was conducive for the growth of wine grapes. Analysis of the quality of grape berries in the three production areas showed that the 100-grain weight of 'Merlot', 'Pinot Noir', and 'Vidal' was the lowest in the Zhangye area. This may be because K and P promote the growth of flowers and fruits (Conradie 1986), and the contents of both of these elements were the lowest in Zhangye. However, correlation analysis did not find a significant correlation between K and P contents and 100-grain weight in this study. This suggests that 100-grain weight is unaffected by soil K and P contents independently, but is greatly affected by both these factors together. Sun et al. (2012) showed that an increase in soil N, P, and K contents had a significant impact on the sugar content of grapes, with N having the greatest impact. Our results showed that the reducing sugar content of the berries of three varieties ('Merlot', 'Pinot Noir', and 'Vidal') varied greatly among the three different production areas. The 'Merlot', 'Pinot Noir', and 'Vidal' berries in Jiayuguan region showed the highest Brix value of grape berries, and total N content of soil in the Jiayuguan was the highest. The results of this study are similar to those of Sun et al. (2012), with the exception of some differences, which suggest that the content of soluble sugars is affected not only by soil N content but also by soil P content and other factors (Wheeler and Pickering 2003; Pinamonti 1998). Analysis of correlation between soil nutrient levels and fruit quality showed that available K content of soil is significantly positively and negatively correlated with the titratable acid content and pH of grape berries, respectively, which is consistent with the research results of Wang (2018), indicating that the higher content of soil available K is conducive to the accumulation of titratable acid in grape berries. This may be because a change in the K content of soil affects the K^+ content of grape berries, thus changing the level of acidity in vacuoles (Pratelli et al. 2002), which alters the acid content of grape berries.

Climate has the greatest impact on the quality of wine grapes. Climatic factors such as light, temperature, and water affect the quality of grapes and determine the distribution of production area, growth and development of grapevine plants, as well as chemical composition of grape berries (Wang et al. 2020). The four major wine-producing areas in China have unique ecological environments. The experimental area used in this study is located in the Gansu Province of China, which experiences a semiarid climate with large differences between day and night temperatures. This region receives minimal sunlight and low annual rainfall (40–200 mm), which is similar to the conditions in the wine and grape producing area of Ningxia but very different from those in Hebei (semihumid climate and 700 mm of annual rainfall). Therefore, the same variety may show different characteristics in different regions of Gansu Province. Bergqvist et al. (2001) reported that increasing the light intensity decreases the content of titratable acid in grape berries but increases the content of total phenols. In this study, we found that the titratable acid content of the berries of all three cultivars was the lowest in Wuwei, whereas their Brix° and total phenol content were the highest in Jiayuguan. Moreover, the number of light hours in Jiayuguan was higher than that in Wuwei. Our results were consistent with research of Wang and Huang (2003), indicating that light is an important factor affecting grape color and sugar and acid contents.

Through the correlation analysis of climate and quality indicators, we found that the GDD from August to September was significantly positively correlated with grape pH, which is consistent with the research results of Hu (2021) on Helanshan Cabernet Sauvignon grapes, indicating that GDD from August to September improves the grape pH (Zhang et al. 2007b). Similar results were also observed in our experiment. As shown in Tables 2 and 4, the Wuwei production area showed the lowest GDD (522.9 in Wuwei vs. 616.5 in Zhangye and 576.2 in Jiayuguan, on average) from August to September. Meanwhile, the titratable acid content of grapes in this region was the highest among the three production areas (the concentration of titratable acid in Wuwei was 17.7% and 23.7% higher than in the other two areas), suggesting that the higher the GDD from August to September, the lower the grape acid content. Zsófi et al. (2014) showed that water deficit irrigation accelerates the maturation process and the Brix° of grape berries, and delays the degradation of starch, but it has no effect on the berry color and hardness. In addition, we found that average rainfall amount from August to September was significantly negatively correlated with the Brix° of grape berries, which is similar to the research results of Zhang et al. (2007), who investigated the correlation between precipitation during fruit growth and Brix° of grapes in the Bohai Bay area, China. The negative correlation between precipitation and Brix° may be because water stress reduces the photosynthetic capacity of mature grape leaves (Flexas et al. 1999), changes the time of dry matter accumulation during berry growth, and changes the time of dry matter accumulation from the fruit setting stage to the color conversion stage. Nonstressed grapes accumulate dry matter after the color conversion period (Gómez-del-Campo

Table 4. Climate data during the grape growing season (April–October) and ripening period (August–September) in the studied regions.

	Avg temp (°C)			Avg maximum temp (°C)			Avg minimum temp (°C)		
Region	Aug–Sep	Apr–Oct	Yr	Aug–Sep	Apr–Oct	Yr	Aug–Sep	Apr–Oct	Yr
Jiayuguan	19.4	16.9	9.0	26.9	24.0	16.4	12.8	10.5	2.9
Wuwei	18.6	16.7	8.6	27.5	24.9	17.7	11.6	9.4	1.2
Zhangye	20.1	17.8	9.7	28.2	25.4	17.8	13.8	11.0	3.0
	GDD (°C)			Sunlight duration (h)			Rain (mm)		
Region	Aug–Sep	Apr–Oct	Yr	Aug–Sep	Apr–Oct	Yr	Aug–Sep	Apr–Oct	Yr
Jiayuguan	576.2	1,641.1	1,643.0	549.1	1,823.3	2941.1	22.1	84.0	112.8
Wuwei	522.9	1,582.7	1,586.0	458.8	1,650.1	2791.8	93.7	178.9	191.9
Zhangye	616.5	1,782.0	1,792.2	525.3	1,789.6	2917.7	47.0	87.5	98.9

Table 5. PCA of the effects of climate and soil parameters on the berry quality of three grape cultivars in different production areas.

	'Merlot'		'Pinot Noir'		'Vidal'	
	FAC-1	FAC-2	FAC-1	FAC-2	FAC-1	FAC-2
Malic acid content	0.108	−0.079	0.086	0.122	0.103	−0.036
Citric acid content	−0.001	−0.174	0.004	0.173	−0.063	−0.18
Tartaric acid content	0.12	0.028	0.026	0.17	0.045	0.203
Titratable acid content	−0.104	−0.09	0.12	0.029	−0.073	0.161
Total tannin content	0.121	−0.003	0.12	−0.027	0.095	−0.092
Reducing sugar content	−0.088	0.119	0.094	−0.109	0.095	0.095
Fructose content	−0.114	0.059	0.033	−0.167	0.096	0.088
Glucose content	−0.121	−0.004	0.111	−0.069	0.013	0.223
Grape pH	0.12	0.028	−0.121	−0.012	0.079	−0.147
100-grain weight	−0.084	−0.125	0.112	0.068	0.099	0.071
Brix°	0.039	0.165	−0.102	0.094	0.103	0.036
Total anthocyanin content	0.07	−0.142	−0.015	−0.172	−0.103	0.034
Total phenol content	0.068	0.144	0.101	0.096	0.105	−0.006
Characteristic value	8.248	5.752	8.237	5.763	9.553	4.447
Rate of contribution (%)	58.917	41.083	58.834	41.166	68.236	31.764
Cumulative contribution rate (%)	58.917	100	58.834	100	68.236	100

FAC-1 and FAC-2 represent the first principal component and the second principal component.

et al. 2002), which inhibits the growth of terminal buds and secondary shoots, facilitates the entry of excess sugar into the fruit, and improves Brix° of the fruit.

Zsófi et al. (2011) and He et al. (2016) showed that precipitation affects the sugar and acid contents of grape berries. In the current study, the average rainfall from April to October and average annual rainfall were significantly positively correlated with the titratable acid content of grape. Consistent with our results, de Orduna (2010) reported that precipitation hindered the increase in sugar content and decrease in acid content. This shows that during the growth of wine grapes, the amount of rainfall was directly correlated with the acid content of grape berries (Du et al. 2013). However, because this study used the data of only the Hexi Corridor, it has certain limitations. The specific impact of meteorological and soil factors on wine grape quality need to be further explored. Therefore, future research can be carried out in other areas to combine the long-term meteorological and soil factors of those areas with the internal quality indicators of grape to scientifically analyze the relationship between ecological conditions and quality indicators.

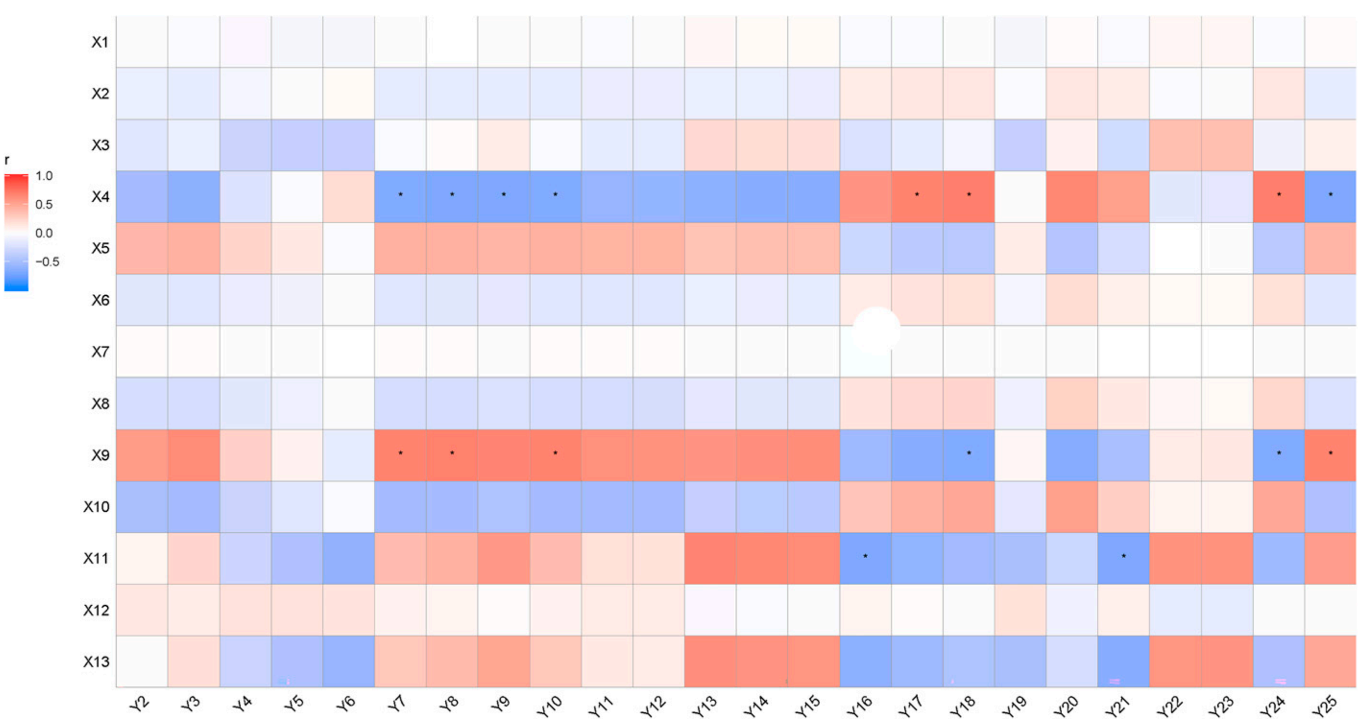

Fig. 1. Correlation analysis between climate and soil parameters vs. grape quality indices. The y-axis shows meteorological indicators (Y1–Y18) and soil indicators (Y19–Y25): Y1, average temperature from August to September; Y2, average temperature from April to October; Y3, annual mean temperature; Y4, average maximum temperature from August to September; Y5, average maximum temperature from April to October; Y6, annual mean maximum temperature; Y7, average minimum temperature from August to September; Y8, average minimum temperature from April to October; Y9, annual mean minimum temperature; Y10, growing degree days (GDD) from August to September; Y11, GDD from April to October; Y12, annual mean GDD; Y13, sunlight duration from August to September; sunlight, sunlight duration from April to October; Y15, annual mean sunlight duration; Y16, average rainfall from August to September; Y17, average rainfall from April to October; Y18, annual mean rainfall;, Y19, soil pH; Y20, soil K^+; Y21, soil Na^+; Y22, total salt; Y23, available P; Y24, available K; Y25, total N. The x-axis indicates grape quality indicators (X1–X14): X1, malic acid; X2, citric acid; X3, tartaric acid; X4, titratable acid; X5, total tannins; X6, reducing sugars; X7; fructose; X8, glucose; X9, grape pH; X10, 100-grain weight; X11, Brix°; X12, total anthocyanins; X13, total phenols. Asterisks indicate significant differences (*$P < 0.05$, **$P < 0.01$).

Table 6. Principal-component analysis of the same grape variety from different grape production areas.

Variety	Region	FAC-1	FAC-2	Fq	Ranking
'Merlot'	Jiayuguan	−0.2972	1.1158	0.2833	2
	Wuwei	−0.8177	−0.8153	−0.8167	3
	Zhangye	1.1143	−0.3005	0.5335	1
'Pinot Noir'	Jiayuguan	−0.5756	1.0010	0.0735	2
	Wuwei	1.1547	−0.0021	0.6785	1
	Zhangye	−0.5791	−0.9990	−0.7520	3
'Vidal'	Jiayuguan	1.0269	0.5281	0.8684	1
	Wuwei	−0.9708	0.6253	−0.4638	3
	Zhangye	−0.0561	−1.1533	−0.4047	2

FAC-1 and FAC-2 represent the first principal component and the second principal component, and Fq represents the comprehensive score of each principal component.

Conclusion

In this study, the Jiayuguan area showed the highest citric acid and total phenol contents and Brix°; Zhangye showed had the highest grape pH and the lowest 100-grain weight; Wuwei showed that highest titratable acid content. The titratable acid content of grape was significantly negatively correlated with the average temperature from August to September, average minimum temperature from August to September, average minimum temperature from April to October, annual mean minimum temperature, GDD from August to September, and soil total N content. The annual mean rainfall and soil available K content were significantly positively correlated with the titratable acid content. The pH of grape berries was significantly negatively correlated with the amount of annual rainfall and the available K content of soil, and significantly positively correlated with the average temperature from August to September, average minimum temperature from August to the September, average minimum temperature from April to October, GDD from August to September, and soil total N. The results of PCA showed that the quality scores of 'Vidal', 'Merlot', and 'Pinot Noir' grapes were the highest in Jiayuguan, Zhangye, and Wuwei, respectively. This showed that the suitable cultivation area of 'Pinot Noir' was Wuwei, 'Merlot' was Zhangye, and 'Vidal' was Jiayuguan.

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