

# Composition of *Vitis vinifera* L. cv. Pinot noir Fruit and Wines from Carneros Appellation in Response to Potassium Fertilization and Supplemental Irrigation

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**Abstract:** The influence of potassium (K) fertilization and supplemental irrigation on the composition of *Vitis vinifera* L. cv. Pinot noir fruit at harvest and on the composition of the finished wines was determined for two consecutive years: 1989 and 1990. K fertilization and, to a lesser extent, supplemental irrigation increased the concentration of K in the fruit and in the wines. Both fruit and wine K responded quicker to irrigation treatments (same year) than to K fertilization (second year after application). There was neither an irrigation nor a K fertilizer treatment effect on fruit or wine pH in 1989, and no correlation between fruit K concentration and fruit pH was observed that year. This was attributed to large differences in titratable acidity between treatments. There was a positive correlation between fruit K and pH, as well as wine K and pH, in 1990. Supplemental irrigated vines had higher fruit and wine TA and lower total anthocyanins in the fruit at harvest and in the finished wines. Other than fruit pH and K concentration, K fertilization did not have any significant effect on fruit composition. Duo-trio evaluation of the wines tested for differences in aroma or taste. The specific combination of K fertilization and supplemental irrigation (K-Supp) was different than the other treatment combinations in 1989 and 1990. These sensory differences were not observed in wines that had undergone malolactic fermentation. Therefore, aroma and taste differences in wines due to irrigation or K fertilization were dependent upon wine style.

**Key words:** potassium, fertilization, irrigation, Pinot noir, fruit, wine, composition

Although potassium (K) deficiencies occur in premium winegrapes grown on clay soils common in California's North Coast region, the research used to establish criteria for K requirements of grapevines has been conducted primarily on soils with little clay and low cation exchange capacity (CEC). The response of vine K status to applied K varies among soil types. On heavier soils, the propensity to fix K is greater, the hazard of leaching is diminished, and water-holding capacity is considerably greater. The availability of both soil and fertilizer K can be improved in many soils by maintaining higher soil water content (Barber et al. 1963, Kuchenbuch et al. 1986). Excess K uptake may also be a concern in winegrape production, since it reportedly can lead to a high fruit pH at harvest and high wine pH (Hepner et al. 1985, Williams and Matthews 1990).

Under K deficiency conditions, K fertilization promotes fruit maturation and anthocyanin synthesis and, hence, fruit quality (Cook and Carlson 1961, Morris and Cawthon 1982, Shaulis 1961). However, K fertilization under adequate or high soil K conditions can lead to wines with a higher pH, lower color in red wine, and a reduction in wine quality

(Dundon et al. 1984, Freeman and Kliever 1983, Somers 1977). Supplemental irrigation, which can improve K availability and uptake, generally results in lower anthocyanin concentration and wine color (Williams and Matthews 1990) and either has no effect on (Matthews et al. 1990) or increases (Freeman 1984, Hepner and Bravdo 1985) wine pH. One consequence of high wine pH is a reduction in wine color, so it is important to understand the consequences of irrigating or applying K fertilizers to vineyards planted with cultivars noted for low color, such as Pinot noir.

For over 50 years there has been little or no research on K nutrition in the North Coast (Ulrich 1942). Therefore, we investigated soil, water, and vine characteristics that may be important in vineyard K nutrition in the North Coast. The objectives of this study were to determine the responses of several aspects of fruit and wine composition to irrigation and K fertilizer treatments applied to increase vine K status at a site of low K availability. The following article presents the results of this study using Pinot noir grapevines in the Carneros appellation in which an increased vine K status (petiole K concentrations) due to both supplemental irrigation and K fertilization was observed (Sipiora et al. 2005).

## Materials and Methods

Experiments were conducted in a commercial vineyard in the Carneros appellation in California planted in 1977 to grapevine, *Vitis vinifera* cv. Pinot noir (Gamay Beaujolais clone) on *Vitis rupestris* cv. St. George rootstock on a

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gravelly clay loam (Haire series) (Lambert and Kashigawi 1978). Vines were spaced at 2 m x 3 m and trained on a bilateral cordon system. All vines were pruned to the same number of two-bud spurs each year and managed with standard commercial practices except where noted otherwise.

The field study was designed as a 2 by 2 factorial with rates of irrigation and  $K_2SO_4$  fertilizer as factors and with five replications using five-vine plots as previously described (Sipiora et al. 2005). Briefly, the two rates of  $K_2SO_4$  (K) were 0 kg per vine (control) and 3.6 kg per vine; and the two rates of drip irrigation were the standard 40 L per week per vine (Std) and a supplemental irrigation rate of 160 L per week per vine (Supp). The aim of supplemental irrigation rate was to maintain soil water content close to field capacity (Sipiora et al. 2005). Specific treatments were as follows:

K fertilization	Irrigation	Code
0 kg/vine	Standard	0-Std (control)
3.6 kg/vine	Standard	K-Std
0 kg/vine	Supplemental	0-Supp
3.6 kg/vine	Supplemental	K-Supp

**Fruit and petiole composition.** Berry samples were collected once at fruit maturity (>20 Brix) from each plot. Subsamples of 100 berries were wrapped in cheesecloth, crushed, and pressed by hand in a mortar. Analyses of pH, soluble solids (Brix), and titratable acidity (TA) were performed on decanted juice in accordance with Amerine and Ough (1980). The concentration of K was determined by atomic emission spectroscopy. Disk samples of berry dermal tissue (0.20 cm<sup>2</sup>) were taken from a 10-berry subsample, and total anthocyanins were determined by the method described by Kliewer (1977). Vine K status was determined from petiole K concentrations in samples of basal petioles (n = 25) taken at harvest from each plot.

**Microvinification methods.** All fruit was harvested from replicates and combined by treatment (0-Std, 0-Supp, K-Std, K-Supp) before being destemmed and crushed. The crushed fruit was separated into two wines lots per treatment in 1989 and four wine lots per treatment in 1990. A 50 mg/L sulfite addition was made to the musts, and they were inoculated with the Montrachet yeast strain (UCD 522). The musts were punched down twice daily and pressed at 5% soluble solids in 1989 and at 1% soluble solids in 1990. After pressing in 1990, two wine lots per treatment were inoculated with *Leuconostoc oenos* (ML-34) to initiate malolactic fermentation, and the other two lots received an additional 25 mg/L sulfite. One month after pressing, all wines were cold-stabilized, membrane-filtered (0.80 µm in 1989 and 0.45 µm in 1990), given an additional 12 mg/L sulfite, and bottled.

**Wine composition.** Wine pH, TA, volatile acidity (VA), and ethanol were assayed three months after pressing in

accordance with Amerine and Ough (1980). Wine K concentration was measured by atomic emission spectroscopy. Spectral analysis of wine color was performed on finished wines using the methods described by Somers and Evans (1974).

**Sensory evaluation.** Duo-trio difference tests were performed for aroma and taste separately following procedures outlined by Amerine and Roessler (1976). Judges were chosen from a pool of 19 students and staff at the University of California, Davis (11 male, 6 female, ages 21 to 48); all had at least one year experience in wine tasting. All difference testing for a given wine pair was performed on a single day in an isolated booth. All experiments were conducted double blind. Wines were presented in black glasses to mask color differences. The judges were asked to choose the sample that was different from the reference. Judges evaluated the wines for aroma first and then for taste.

One wine lot per treatment was selected for sensory analysis in 1989, while a blend of the two wine lots from each treatment for both the malolactic and nonmalolactic wines was used for the 1990 duo-trio tests. In 1989, there were 11 judges, and each judge was given the wine comparison four times (n = 44). In 1990, there were 12 judges, and each treatment comparison was replicated twice (n = 24).

**Statistical analysis.** Analysis of variance was performed on the compositional data from 1989 and 1990. The experimental design for the 1989 wines was a 2 (K level) x 2 (irrigation level) factorial with three replications. Malolactic fermentation became a third factor in the 1990 experimental design. The wines made in 1990 represented all the combinations of three factors: K fertilization level, irrigation level, and malolactic fermentation. Analysis of variance was performed as a 2 x 2 x 2 factorial. A regression analysis was also performed between petiole K and fruit K and between K and pH in the juice and finished wines.

## Results

**Fruit composition.** In 1989 fruit composition (Brix, juice K, pH, TA, and skin anthocyanins) was not significantly influenced by K fertilization, even though mean juice K was 200 mg/L greater in the K-Supp treatment than in the control (0-Std) (Table 1). The pH of the fruit ranged from 3.14 to 3.29, with the 0-Std having the highest pH and the K-Supp having the lowest, although the K-Supp treatment had highest petiole (Sipiora et al. 2005), juice, and wine K (Table 2), and the 0-Std treatment had the lowest. There was no significant relationship ( $r^2 = 0.02$ ) between juice pH and K in 1989 (Figure 1A). There was a wide range in fruit TA with a 2.8 g/L difference between the 0-Std and the K-Supp treatments (Table 1). Fruit TA was significantly increased by ~1.8 g/L by supplemental irrigation. The TA was also ~1.0 g/L greater in response to K, although the differences were statistically not significant. The concentration of anthocyanins was significantly reduced by supplemental irrigation, but not by K fertilization. There were no significant differences in Brix attributable to either K fertilization or supplemental irrigation.

In contrast to fruit composition in 1989, K fertilization did significantly increase both the concentration of K and pH in the fruit at harvest in 1990 (Table 1). Consequently, the 0-Std control had the lowest fruit pH. In contrast to results from 1989, there was a positive and highly significant relationship ( $r^2 = 0.77$ ) between juice pH and K in 1990 (Figure 1B), when juice K was, in general, lower for all treatments. Once again K fertilization did not affect TA, Brix, or anthocyanins in the fruit at harvest. In 1990, the range in fruit TA values was not as wide as the range in 1989. Yet, for the second consecutive year, there was higher TA in supplemental irrigated treatments. Supplemental irrigation did not have any significant influence on pH, K concentration, or Brix. Although the mean concentrations of anthocyanins were lower in the fruit of supplemental irrigated treatments, the difference was not statistically significant as it was in 1989.

**Table 1** Petiole K and juice composition at harvest in 1989 and 1990.

Treatment	Harvest petiole K (% dry wt)	pH	Juice K <sup>+</sup> (mg/L)	TA (g/L)	Brix	Anthocyanins (mg/cm <sup>2</sup> )
<b>1989</b>						
0-Std	0.24	3.29	1550	9.6	21.4	0.31
0-Supp	0.51	3.25	1673	11.4	22.5	0.26
K-Std	0.58	3.22	1691	10.7	22.1	0.30
K-Supp	1.23	3.14	1759	12.4	20.9	0.22
Significance <sup>a</sup>						
K fertilization	***	ns	ns	ns	ns	ns
Irrigation	***	ns	ns	**	ns	*
<b>1990</b>						
0-Std	0.35	3.10	1311	8.9	22.3	0.31
0-Supp	0.64	3.13	1389	9.9	22.8	0.29
K-Std	1.23	3.23	1558	9.0	23.1	0.31
K-Supp	1.88	3.19	1540	10.1	22.2	0.26
Significance <sup>a</sup>						
K fertilization	***	***	***	ns	ns	ns
Irrigation	**	ns	ns	***	ns	ns

<sup>a</sup>ns, \*, \*\*, and \*\*\* indicate not significant or significant at  $p \leq 0.05$ , 0.01, and 0.001, respectively. Data are means from five replications of each treatment.

**Fruit K and petiole K relationship.** Leaf petiole and fruit K status were evaluated to determine whether a consistent relationship could be established between the two aspects of vine K nutrition at harvest. There was a highly significant, second-order relationship between fruit K and harvest petiole K in both years (Figure 2), although the concentration of juice K was about 250 mg/L higher in 1989 than in 1990. Petiole and juice K were lowest in the 0-Std treatment both years.

In 1989, the concentration of petiole K at harvest showed a 100% increase over the 0-Std treatment by supplemental irrigation (0-Supp) and K fertilization (K-Std) alone, while the combination of K fertilization and supplemental irrigation (K-Supp) increased harvest petiole K by 400% (Table 1). In 1990, K fertilization increased petiole K to a larger extent than supplemental irrigation, and again the combination of K fertilization and supplemental irrigation (K-Supp) increased the concentration of harvest petiole K by over 400%.

As with petiole K, the concentration of K in the fruit of the 0-Std treatment was the lowest both years. In contrast to the degree of increase in petiole K, fruit K concentration was only increased by a maximum of 13% in 1989 and by 19% in 1990 by the K-Supp treatment. Interestingly, fruit K was not higher in the K-Supp than in the K-Std treatment in 1990, even though harvest petiole K was higher in the K-Supp by about 66% (Table 1).

Seasonal differences in the concentration at harvest of both petiole and fruit K were found. The concentration of petiole K at harvest in 1989 ranged from 0.25% to 1.23% dry weight, while the range was 0.35% to 1.89% in 1990. In contrast, fruit K concentration was generally 250 mg/L higher in 1989 than in 1990 (Table 1).

**Wine composition.** There was no significant effect of either K fertilization or irrigation on wine pH in 1989, even though both treatments

**Table 2** Composition of 1989 Pinot noir wines from Carneros.

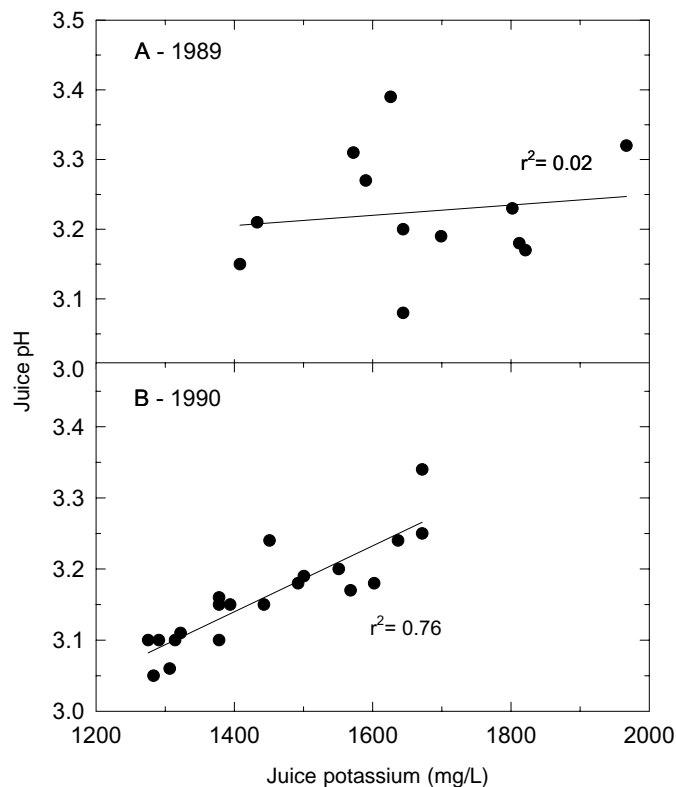
Treatment	pH	Wine K <sup>+</sup> (mg/L)	TA (g/L)	Color density <sup>a</sup>	Color hue <sup>b</sup>	Total antho (mg/L)	Ionized antho (mg/L)	Alpha <sup>c</sup>	Ethanol (%v/v)	VA (g/L)
0-Std	3.56	720	7.4	3.11	0.56	159	30	18.5	11.6	0.16
0-Supp	3.54	868	8.4	2.27	0.44	123	24	19.5	11.6	0.21
K-Std	3.57	840	7.4	3.76	0.65	176	34	19.2	11.0	0.26
K-Supp	3.50	1095	8.4	2.18	0.71	93	18	16.7	10.9	0.28
Significance <sup>d</sup>										
Fertilization (K)	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
Irrigation (I)	ns	*	**	**	ns	**	*	ns	ns	ns
K * I	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

<sup>a</sup>Color density is the sum of A420 and A520.

<sup>b</sup>Color hue is A420 divided by A520.

<sup>c</sup>Alpha is degree of ionization.

<sup>d</sup>ns, \*, \*\*, and \*\*\* indicate not significant or significant at  $p \leq 0.05$ , 0.01, and 0.001, respectively.

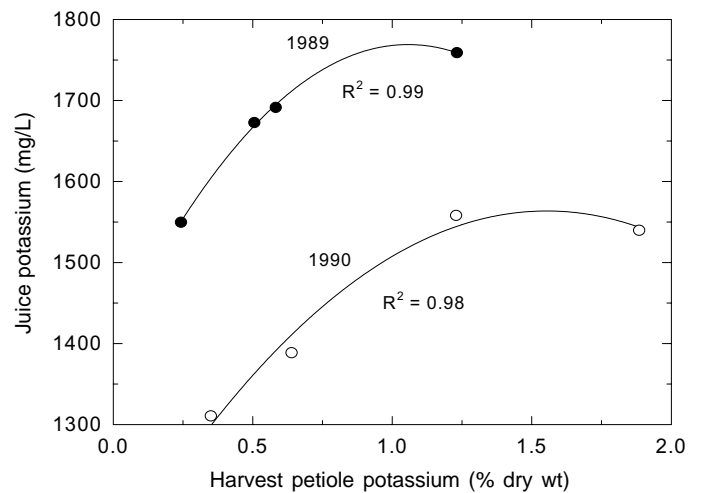


**Figure 1** Relationship between juice K concentration and juice pH during both years of this study: (A) 1989 and (B) 1990.

significantly increased the concentration of wine K (Table 2). Similar to the results from fruit analysis, the highest concentration of K in the wines was found in the K-Supp treatment and the lowest found in the 0-Std treatment. TA was higher in wines from supplemental irrigated treatments than with standard irrigation. There was no effect of K application on wine TA, yet supplemental irrigation increased wine TA by 1.0 g/L.

Color density ( $A_{420} + A_{520}$ ), color hue ( $A_{420}/A_{520}$ ), total anthocyanins, ionized anthocyanins, and degree of ionization were also not significantly affected by K fertilization in 1989 (Table 2). The amounts of total and ionized anthocyanins as well as wine color density were reduced by supplemental irrigation. Since neither wine pH nor the degree of ionization was significantly affected by irrigation, supplemental irrigation reduced wine color by reducing the total anthocyanins in the wines. Statistical analysis showed that there was no effect of either K application or supplemental irrigation on wine ethanol levels, in agreement with the lack of treatment effects on fruit soluble solids. The mean volatile acidity of the wines was greater in both supplemental irrigation and K application treatments, but not significantly.

In 1990, wines were made with and without malolactic fermentation. The pH of the wines ranged from 3.47 to 3.96 (Table 3). There was a significant positive effect of K fertilization, supplemental irrigation, and malolactic fermentation on wine pH. There was also an important and significant ( $p \geq 0.05$ ) interaction between K fertilization and malolactic fer-



**Figure 2** Relationship between harvest petiole K concentration and juice K concentration during both years of this study: 1989 and 1990. Data points for petiole samples represent the means for five replications of each treatment: 0-Std, 0-Supp, K-Std, and K-Supp.

mentation. K fertilization increased wine pH at both the standard and supplemental irrigation levels, and this effect was significantly greater for wines undergoing malolactic fermentation. Supplemental irrigation had little or no effect on the pH of nonmalolactic wines; however, it did have an effect when wines underwent malolactic fermentation.

There were significant differences in wine K due to both K application and irrigation (Table 3, consistent with the results in 1989). As with pH, there was a significant interaction between K fertilization and malolactic fermentation. The range of wine K between treatment combinations was higher for malolactic wines than for nonmalolactic wines. Similarly, the differences in wine K between supplemental and standard irrigation at both K fertilization levels were greater when wines underwent malolactic fermentation. Malolactic fermentation reduced wine TA by ~1.4 to 2.1 g/L (Table 3), attributed solely to catabolism of organic acid during malolactic fermentation. The other treatments did not significantly alter wine TA, although K fertilization increased the concentration of malate in nonmalolactic wines.

There was a significant decrease in ionized anthocyanins, the degree of ionization, and an increase in color hue in the wines due to K fertilization in 1990 (Table 3). Supplemental irrigation resulted in a significantly lower concentration of total ionized anthocyanins and lower color density in the wines. A significant increase in color hue (browning) was associated with supplemental irrigation in wines that underwent malolactic fermentation. Supplemental irrigation did not have an effect on the degree of ionization of anthocyanins, which means that, similar to the results from 1989, the effect of supplemental irrigation on color was mainly due to reduced anthocyanin concentration in the skin of the berries. Malolactic wines had a lower degree of ionization and higher color hue (browning).

**Table 3** Composition of 1990 Pinot noir wines from Carneros with and without completion of malolactic fermentation.

Treatment	pH	Wine K <sup>+</sup> (mg/L)	TA (g/L)	Color density <sup>a</sup>	Color hue <sup>b</sup>	Total antho (mg/L)	Ionized antho (mg/L)	Alpha <sup>c</sup>	Ethanol (%v/v)	VA (g/L)
<b>Nonmalolactic wines</b>										
0-Std	3.49	825	6.7	3.27	0.61	129	30	23.6	12.5	0.23
0-Supp	3.47	808	7.1	2.67	0.62	106	23	21.6	12.8	0.21
K-Std	3.59	1125	7.1	3.21	0.71	115	25	21.5	13.7	0.22
K-Supp	3.63	1189	7.2	2.18	0.72	89	18	20.5	12.6	0.24
<b>Malolactic wines</b>										
0-Std	3.49	588	5.3	1.87	0.71	109	15	13.4	12.6	0.41
0-Supp	3.65	841	5.3	2.09	0.77	124	14	11.6	13.3	0.40
K-Std	3.90	1266	5.2	2.58	0.84	173	18	10.3	13.7	0.40
K-Supp	3.96	1475	5.1	1.82	0.92	134	12	9.0	12.6	0.51
Significance <sup>d</sup>										
Fertilization (K)	***	**	ns	ns	***	ns	*	*	ns	*
Irrigation (I)	*	*	ns	**	*	*	***	ns	ns	*
Malolactic (M)	**	ns	***	***	***	**	***	***	ns	***
K * I	ns	ns	ns	ns	ns	ns	ns	ns	*	**
K * M	*	**	ns	ns	ns	***	*	ns	ns	ns
I * M	ns	*	ns	ns	ns	ns	ns	ns	ns	*
K * I * M	ns	ns	ns	ns	ns	ns	ns	ns	ns	*

<sup>a</sup>Color density is the sum of A420 and A520.

<sup>b</sup>Color hue is A420 divided by A520.

<sup>c</sup>Alpha is degree of ionization.

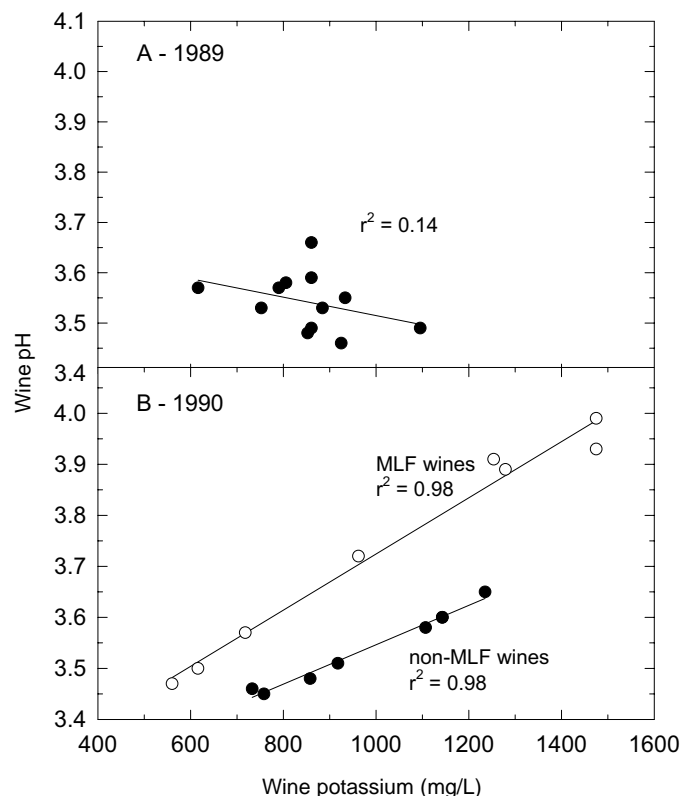
<sup>d</sup>ns, \*, \*\*, and \*\*\* indicate not significant or significant at  $p \leq 0.05$ , 0.01, and 0.001, respectively.

There were no significant treatment effects on ethanol concentration. There was a twofold increase in volatile acidity in malolactic wines compared with nonmalolactic wines (Table 3). There were smaller significant effects of K application and irrigation on volatile acidity. The K-Supp treatment wines had a higher volatile acidity than wines from the other viticulture treatments after undergoing malolactic fermentation.

There was no significant correlation ( $r^2 = 0.14$ ) between wine K and wine pH in 1989 (Figure 3A). The relationship of wine K to wine pH in 1990 was highly significant for both malolactic wines ( $r^2 = 0.98$ ) and nonmalolactic wines ( $r^2 = 0.98$ ), as shown in Figure 3B. The slope of the regression equation was different between wines having undergone malolactic fermentation and those that did not, while the intercept was not different.

**Sensory difference tests.** The 1989 wine from the K-Supp treatment was easily differentiated in both aroma and taste from the wines made from either the 0-Supp or the K-Std treatments (Table 4). There was a less significant difference in aroma between the 0-Std and 0-Supp wines and in taste between the 0-Std and K-Std wines.

Similar to the results from 1989 difference tests, wine from the K-Supp treatment was significantly different from the three other treatments (0-Std, K-Std, 0-Supp) in both the aroma and taste of wines not undergoing malolactic fermentation (Table 5). In contrast to the results from 1989, there were no aroma or taste differences between the 0-Std and 0-Supp treatment or the 0-Std and K-Std treatment. Differences in aroma and taste of wines due to irrigation and K



**Figure 3** Relationship between wine K concentration and wine pH during both years of this study: (A) 1989 and (B) 1990.

fertilization treatments among the malolactic wines were not observed, with the exception of the 0-Std and K-Std comparison, which was not evident before malolactic fermentation.

**Table 4** Duo-trio difference tests for aroma and taste of 1989 wines (n = 44).

Comparison	Aroma <sup>a</sup>	Taste <sup>a</sup>
0-Std vs 0-Supp	28 *	23 ns
0-Std vs K-Std	26 ns	28 *
K-Std vs K-Supp	43 ***	39 ***
0-Supp vs K-Supp	43 ***	33 ***

<sup>a</sup>ns, \*, \*\*, and \*\*\* indicate not significant or significant at  $p \leq 0.05$ , 0.01, and 0.001, respectively.

## Discussion

These field trials in a commercial, drip-irrigated vineyard with Pinot noir vines that exhibited low vine K status (based upon bloomtime petiole analysis) have shown earlier (Sipiora et al. 2005) that soil application of 3.6 kg per vine of  $K_2SO_4$  or of supplemental irrigation increased bloomtime petiole K and maintained higher petiole K throughout the season. In the present study we found that, in addition to independent effects of supplemental irrigation, the increased vine K status was associated with several changes in fruit and wine composition and wine sensory attributes.

Both K fertilization and supplemental irrigation increased the concentration of K in harvested fruit. Although the analysis of variance indicated significant increases only in response to K fertilization, we have established that maintaining high soil water content at this site increases vine K status (Sipiora et al. 2005), and in this study we show that there was a strong and positive correlation between harvest petiole K and fruit K. In addition, it is important to note that only the K in the pulp was measured in the fruit at harvest. K has been shown to accumulate in the skin of the berry (Iland and Coombe 1988), and differences in the K in skins or in the extractability of K during crushing or fermentation may have gone undetected in the fruit K assay. Both K fertilization and supplemental irrigation increased the concentration of K in the finished wines during both years of this study. And, the range from lowest to highest K concentration in wines was wider than the range in the musts in both seasons. Thus, the results indicate that fruit and wine K concentration, as well as petiole K concentration, were increased by both K fertilization and supplemental irrigation. The concentration of K was increased more in the harvest petioles (approximately 100 to 400% above controls) than in either the fruit (0 to 19%) or the wine (0 to 115%) by both supplemental irrigation and K fertilization, indicating that large differences in vine K status are needed before changes in fruit and wine K are observed.

There was no increase in petiole or fruit K until the second year (1989) after the application of fertilizer in the spring of 1988. Supplemental irrigation, on the other hand, increased uptake of K and the concentration of fruit and wine K in both the K-fertilized and the nonfertilized plots the first year it was imposed (1989). Freeman and Kliever

**Table 5** Summary of duo-trio difference tests for aroma and taste of 1990 wines with or without malolactic fermentation (n = 24).

Comparison	Aroma <sup>a</sup>	Taste <sup>a</sup>
<b>Nonmalolactic wines</b>		
0-Std vs 0-Supp	16 ns	15 ns
0-Std vs K-Std	12 ns	13 ns
0-Std vs K-Supp	18 *	20 ***
K-Std vs K-Supp	19 **	18 *
0-Supp vs K-Supp	17 *	22 ***
<b>Malolactic wines</b>		
0-Std vs 0-Supp	14 ns	8 ns
0-Std vs K-Std	20 ***	17 *
0-Std vs K-Supp	11 ns	15 ns
K-Std vs K-Supp	15 ns	14 ns
0-Supp vs K-Supp	13 ns	13 ns

<sup>a</sup>ns, \*, \*\*, and \*\*\* indicate not significant or significant at  $p \leq 0.05$ , 0.01, and 0.001, respectively.

(1983) also reported a more rapid response in vine K status to increased irrigation than to K fertilization. It would appear, therefore, that in the short-term vine K status is more responsive to irrigation than to K fertilization on certain soils. Consequently, proper irrigation management should be more effective in regulating fruit and wine K from year to year on those soils.

The relationship between K and pH in the fruit and wine was dependent upon seasonal factors, and probably upon differences in the titratable acidity of the juice and wines among the various treatment combinations. Fregoni and Vercesi (1995) also observed a good correlation between must K and pH of Pinot noir grown in Italy in one season and not in another. There was no correlation between either fruit K and pH or wine K and pH in 1989, a year in which the TA of the fruit and subsequent wine was greatly increased in the supplemental irrigated treatments compared to standard irrigation. In 1990, the effect of supplemental irrigation on the TA of the fruit and wines was not as large, and there was a significant correlation between K and pH in the fruit and wines. According to the general relationship between pH and K (Boulton 1980), a good correlation between fruit pH and K is not expected unless the total acidity of the fruit and the relative proportion of tartaric acid to malic acid remain constant among treatments. Thus, it is not surprising that there was no correlation in 1989, since both irrigation and, to a lesser extent, K fertilization had an effect on the TA of the fruit and possibly on the ratio of malic acid to tartaric acid.

Given that supplemental irrigation increased fruit TA both years while K fertilization had no significant effect, it would appear that, as for fruit K, irrigation is more effective in controlling parameters of fruit acidity (Freeman and Kliever 1983). However, a significant increase in malic acid from 0.8 to 1.1 g/L because of K fertilization was observed in the 1990 wines (without malolactic fermentation), indicating that K fertilization may also play a role (data not shown).

While wine pH of 3.63 and 3.65 was observed in nonmalolactic and in malolactic wines from unfertilized vines, very high pH of 3.90 or greater developed in the malolactic wines from fertilized vines. Such high wine pH has been observed when the following conditions occur simultaneously: high soil K levels, warm regions (low fruit acid levels), and production of red wines, which normally undergo malolactic fermentation (Dundon et al. 1984, Freeman 1984, Hepner and Bravdo 1985, Hepner et al. 1985, Somers and Evans 1974). The pH values of the wines in this study were not as high as in those studies, probably because of the relatively cooler climate in the Carneros region and the moderate level of K in the soils (Sipiora et al. 2005).

Adequate color is often a major concern in wines made from Pinot noir fruit, because of the low amount of berry anthocyanins in contrast to other red varieties (Bissell et al. 1989, Somers and Evans 1974). The parameters of color measured in this study (color density, total anthocyanins, and ionized anthocyanins) have all been used as indicators of wine quality (Freeman 1984, Hepner and Bravdo 1985, Hepner et al. 1985, Somers and Evans 1974). Supplemental irrigation decreased the concentration of total anthocyanins in the fruit and wines in this study, not the degree of ionization or ionized anthocyanin content, while K fertilization had no influence on total anthocyanins in the fruit or wines. In a previous irrigation study, Freeman (1984) found contrasting results where irrigation had a greater influence on the degree of anthocyanin ionization than on total anthocyanins in Shiraz wines, and this was in part attributed to great differences in wine pH. However, the results from this trial are similar to results from previous irrigation studies with Cabernet franc in Napa, in which differences in color density and total anthocyanins were observed, although wine pH (and probably degree of ionization) was not influenced by irrigation (Matthews and Anderson 1988).

K fertilization resulted in a lower concentration of ionized anthocyanins and degree of ionization in the wines in 1990 only, attributable to the higher pH of wines that year. The higher color hue in K-Std and K-Supp wines in both seasons indicated that these wines may also have suffered the effects of oxidative browning more than wines from nonfertilized treatments. The reason for this greater propensity for browning is not known, nor was it expected.

Malolactic fermentation appears to have had a different impact on wines from 0-Std treatment compared to wines from K-Std, 0-Supp, or K-Supp treatments in 1990 (Table 3). First, malolactic fermentation did not raise pH of 0-Std wines. The K concentration was generally higher in wines undergoing malolactic, with the exception of the 0-Std treatment, which had a lower K concentration. Total anthocyanins were also higher in malolactic wines except for 0-Std. In addition, color density decline, as well as decline in ionized anthocyanins, associated with malolactic fermentation was twice as large in the 0-Std treatment than in any of the other treatments, even when wine pH was not affected by malolactic fermentation. A color loss without a change

in pH was not expected, since the color of anthocyanins is pH-dependent (Somers and Evans 1974).

The K-Supp treatment combination was also differentiated from the other combinations in that (1) it had the lowest concentration of total anthocyanins in the fruit and wines and (2) it was consistently differentiated during sensory tests from the other combinations in both aroma and taste in nonmalolactic wines. The results of the duo-trio difference tests on nonmalolactic wines of both 1989 and 1990 indicated that there was a highly significant difference in aroma and taste between the K-Supp treatment and the other treatments. To become reproducibly detectable evidently required the combination of fertilizer and supplemental irrigation, as there was no consistent difference between the 0-Std wines and wines made with only K fertilization or supplemental irrigation. The differences were lost during malolactic fermentation or masked by other volatile compounds produced during malolactic fermentation.

Previous sensory evaluation of Napa Valley Cabernet franc wines made from different irrigation regimes has shown that each one of the sensory characteristics (appearance, aroma, taste) can be influenced by vineyard irrigation practices and that visual differences (such as color) were more readily detected than differences in either aroma or taste (Matthews et al. 1990). The results from this study indicated that irrigation effects on the aroma and taste of Pinot noir are highly dependent upon wine style (with or without malolactic fermentation). Irrigation and K fertilization effects on aroma and taste were more discernible in wines that had not undergone malolactic fermentation.

## Conclusions

Both K fertilization and supplemental irrigation increased concentrations of fruit and wine K. These increases were associated with higher petiole K levels at harvest and there was a significant correlation between harvest petiole K and fruit K in both years of this trial. The increased concentrations in fruit and wine K resulted in higher fruit and wine pH in only one of the two years.

K fertilization had little influence on fruit composition. It did increase fruit K concentration in both seasons; however, it only had an effect on fruit pH in one season. Brix, titratable acidity, and concentration of anthocyanins in the skin were not affected by K fertilization.

K fertilization can impact the composition of Pinot noir wines. K fertilization can increase wine K and wine pH, which impact anthocyanin equilibrium and color. It may also increase malic acid concentration in wines not subjected to malolactic fermentation. Finally, K fertilization may lead to increased browning in wines.

Fruit titratable acidity was consistently higher at harvest due to supplemental irrigation. Even with large differences in fruit acidity, fruit pH remained unchanged by irrigation. There was no response in Brix to irrigation. The

concentration of anthocyanins in the skins was diminished by supplemental irrigation.

The K concentration in finished wines was increased by supplemental irrigation, yet that did not result in large pH differences. The effects of supplemental irrigation on titratable acidity in finished wines were not observed every year. Supplemental irrigation consistently reduced the concentration of total anthocyanins, and hence color density, in finished wines.

Perceptible impacts of K fertilization and supplemental irrigation on the aroma or taste of finished wines were more notable when wines did not undergo malolactic fermentation. In addition, the aroma and taste of these Pinot noir wines were only impacted when both K fertilization and supplemental irrigation were applied; K fertilization or supplemental irrigation alone did not impact the sensory characteristics of finished wines. If wines underwent malolactic fermentation, then aroma and taste differences were not as obvious.

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