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Training System Effects on Sunlight Penetration, Canopy Structure, Yield, and Fruit Characteristics of 'Frontenac' Grapevine (*Vitis* spp.)

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*Trellis or training systems influence many aspects of grapevine growth and production. This study investigated the effects of four trellis styles (Geneva double curtain, high cordon, Smart-Dyson, and vertical shoot positioned) on the fruit-zone light environment, fruit chemical composition, and yield of 'Frontenac' grapevines (*Vitis *spp.) grown on a fertile site near Crete, Nebraska over two growing seasons. Photosynthetically active radiation was measured above the canopy and within the fruiting zone at berry set, veraison, and harvest. At all sampling dates in 2008, vines grown on Geneva double curtain and high cordon had higher mid-day transmittances than vines grown on Smart-Dyson and vertical shoot positioned. In 2009, transmittance relationships among training systems were similar. In both years, leaf layer number was lower for Geneva double curtain and high cordon than for Smart-Dyson and vertical shoot positioned. In 2008, Geneva double curtain vines had higher fruit yield than vertical shoot positioned, Smart-Dyson, and high cordon. In 2009, Geneva double curtain yielded more than vertical shoot positioned and high cordon. In 2008, Geneva double curtain had higher pH and °Brix than other trellises; titratable acidity was lower in Geneva double curtain and high cordon than in Smart-Dyson and vertical shoot*

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positioned. In 2009, fruit composition results were not related to transmittance. We propose Geneva double curtain training as a viable choice for Midwestern growers.

KEYWORDS trellis, photosynthetically active radiation, transmittance, canopy microclimate, fruit composition

INTRODUCTION

In grapevines (*Vitis* spp.), the light environment within the canopy (both light quantity and quality) is the most important factor influencing yield, fruit composition (Dokoozlian and Kliewer, 1995; Smart and Robinson, 1991), fruitfulness (Howell et al., 1991; Shaulis et al., 1966), fruit ripening, and hardiness of buds and canes (Howell et al., 1991). Sunlight transmittance and distribution through the canopy can be optimized by selecting the appropriate trellis or training system (Louarn et al., 2008; Reynolds et al., 2004). Trellises allow growers to manipulate the vines' vigor and canopy structure, thereby influencing the canopy light environment (Dokoozlian and Kliewer, 1995; Howell et al., 1991), as well as wind and humidity conditions within the canopy (Kliewer and Smart, 1989).

The exact effects of sunlight exposure on fruit composition are complex. Many researchers have observed a positive correlation between sugar concentration and sunlight exposure of fruit (Cartechini and Palliotti, 1995; Crippen and Morrison, 1986a; Gao and Cahoon, 1994; Macaulay and Morris, 1993; Smart et al., 1988; Spayd et al., 2002), although some have reported no such effect (Cortell and Kennedy, 2006; Downey et al., 2004; Zoecklein et al., 2008). Smart and associates (1988) found that artificially shaded 'Cabernet Sauvignon' vines had lower berry weight and higher titratable acidity (TA) than control vines, while pH was unaffected. Macaulay and Morris (1993) reported higher pH and lower TA in sun-exposed fruit and in the wines made from them. However, Wolf and associates (2003) found that pH and TA were the same for 'Shiraz' grown on five different trellis systems; a similar study also found pH and TA unaffected by trellis style (Reynolds et al., 2004). Such contradictory claims likely stem from differences in the climate, soil characteristics, and cultivars used in the various studies (Crippen and Morrison, 1986b).

This study investigated the effects of four training systems on the fruit-zone light environment, fruit chemical composition, and yield of 'Frontenac' grapes grown on a fertile site in southeast Nebraska. The goal of this research was to establish a recommendation for growers inquiring about an appropriate training system for 'Frontenac', a relatively new cultivar receiving considerable attention in Midwest vineyards.

MATERIALS AND METHODS

Plant Materials and Research Site

Research for this study was conducted at a commercial vineyard near Crete, Nebraska during the 2008 and 2009 growing seasons. 'Frontenac' vines planted in 2004–2005 were trained to four different trellis styles (Geneva double curtain [GDC], high cordon [HC], Smart-Dyson [SD], and vertical shoot positioned [VSP]). Rows were oriented north-south with vines 2.4 m apart and rows 3 m apart. The training systems were applied to entire rows. Each vine was assigned a number; sample plants from each treatment were selected using a random number generator ($n = 20$ for GDC, HC, and SD; $n = 30$ for VSP). The number of sample plants was constrained by the time it took to record light measurements.

Light Measurements

Radiative flux of photosynthetically active radiation (PAR) was measured with an LI-191 line quantum sensor (LI-COR Biosciences, Lincoln, NE, USA) and recorded by a 720 series Polycorder data logger (Wescor Environmental Products, Logan, UT, USA) both above the canopy and within the fruit zones of sample plants at three dates during each growing season (approximately berry set, veraison, and harvest). On each sampling date, PAR measurements were obtained for each plant between 1200 and 1400 hr, within 1 hr of solar noon. Sample plants were marked so that the instrument could be inserted into the canopy in the same place each time. Percent transmittances were calculated by dividing the fruit-zone PAR value by the ambient PAR (measured above the canopy).

Point Quadrat Canopy Analysis

On 8 August of both years, point quadrat analysis was performed as described by Smart and Robinson (1991). Three insertions were made for each sample plant. Point quadrat data were used to compute leaf layer number (LLN). A large LNN value indicates greater leaf area and thus a greater canopy.

Fruit Analyses: Harvest Variables

Fruit was harvested on 15 August 2008 and 19 August 2009. Thirty randomly-selected berry samples were collected from each sample plant, placed in resealable plastic bags, and frozen until laboratory analysis. Berry samples were weighed, thawed, wrapped in cheese cloth, and then crushed with a mortar and pestle. Juice was reserved for analysis and fruit solids were returned to their bags and refrozen. Juice pH was measured with an Orion digital pH-meter, model 611 (Thermo Fisher Scientific, Waltham, MA, USA). Soluble solids (°Brix) content was measured using an Atago PR-101 digital refractometer (Bellevue, WA, USA). Titrable acidity (TA) was determined by titration with NaOH, using a Kimax Automatic Titratable Acidity Test, model 620F-1 (Vineland, NJ, USA).

Statistics

All statistical analyses were performed using SAS/STAT® Version 9.2 (SAS Institute, Cary, NC, USA). Harvest variable, point quadrat, and mid-day transmittance data were analyzed using the MIXED procedure. All significance tests used $\alpha = .05$. Correlation analyses were performed using the GLIMMIX procedure.

RESULTS AND DISCUSSION

At all sampling dates in 2008, vines grown on GDC and HC trellises had higher mid-day transmittances than vines grown on SD and VSP training systems (Table 1). In 2009, transmittance relationships between trellises were similar to those in 2008, except at harvest GDC had higher percent transmittance than HC and at veraison VSP had higher percent transmittance than SD (Table 1). In both years, leaf layer number was lower for GDC and HC than for SD and VSP (Table 2). GDC and HC had less dense canopies (higher transmittances and lower LLN) than the other trellises in this study. Open canopies optimize yield and fruit composition; they facilitate pruning, harvesting, and spray penetration. They also tend to have fewer disease problems because of their favorable canopy microclimates (Smart and Robinson, 1991). Light penetration is generally negatively correlated with LLN (Vanden Heuvel, 2004). In this study, training systems with low LLN

TABLE 1 2008 and 2009 Mid-Day Photosynthetically Active Radiation Transmittances (% PAR Trans.) of 'Frontenac' Grown on Four Training Systems in Southeast Nebraska

Trellis	June 25 2008 (% PAR trans.)	July 31 2008 (% PAR trans.)	August 29 2008 (% PAR trans.)	June 29 2009 (% PAR trans.)	August 08 2009 (% PAR trans.)	September 18 2009 (% PAR trans.)
GDC	0.49a[z]	0.18b	0.40a	0.27a	0.11b	0.62a
HC	0.48a	0.23a	0.36a	0.25a	0.22a	0.52b
SD	0.16b	0.08c	0.16b	0.09b	0.11a	0.30c
VSP	0.21b	0.06c	0.21b	0.11b	0.20b	0.33c

[z]Means within columns followed by different letters are significant at $p \leq 0.05$.
GDC: Geneva double curtain; HC: High cordon; SD: Smart-Dyson; VSP: Vertical shoot positioned.

TABLE 2 Yield and Leaf Layer Number of 'Frontenac' Grown on Four Training Systems in Southeast Nebraska

Trellis	Mean yield 2008 (kg/plant)	Mean yield 2009 (kg/plant)	Mean LLN 2008	Mean LLN 2009
GDC	2.36	4.21a[z]	1.60a	0.98a
HC	1.10	2.52c	1.68a	1.22a
SD	1.34	3.73ab	2.40b	2.13b
VSP	1.34	3.01bc	2.37b	2.01b

[z]Means within columns followed by different letters are significant at $p \leq 0.05$.
See Table 1 for key to Trellis acronyms.

values did have correspondingly high transmittances, though the correlation was not statistically significant.

GDC had the highest fruit yield of all trellises in both years of study (Table 2), which is consistent with previous studies comparing the yield of GDC and other horizontally divided canopies to single-canopy controls (Reynolds et al., 1995; Shaulis et al., 1966; Smart et al., 1982). Generally, sunlight penetration and yield are positively correlated because increased shoot exposure improves bud fruitfulness (Cartechini and Palliotti, 1995; Perez and Kliewer, 1990; Shaulis et al., 1966; Smart et al., 1982). Because HC had such high transmittance values, one would expect it to yield more than VSP, the only other single-canopy training system. However, HC suffered damage from birds because they were able to access its fruit through the netting. If the crop had been better protected, perhaps HC would have produced a higher yield than VSP.

In 2008, GDC and HC with lower LNN values and higher transmittances had lower TA than VSP and SD (Table 3); this is in agreement with the findings of Smart et al. (1988) and Macaulay and Morris (1993) who observed higher TA in shaded treatments. However, the trellises did not differ in TA the following year. Although the transmittance relationships between training systems were similar in both years, transmittance values were different, all the training systems had lower transmittances early in the season and higher transmittances late in the season in 2009. In both years, all of the trellises

TABLE 3 Fruit Characteristics of 'Frontenac' Grown on Four Training Systems in Southeast Nebraska

Trellis	Mean berry weight 2008 (g)	Mean berry weight 2009 (g)	Mean °Brix 2008	Mean °Brix 2009	Mean pH 2008	Mean pH 2009	Mean TA 2008 (g/L)	Mean TA 2009 (g/L)
GDC	1.08a[z]	0.85ab	22.5a	20.4b	3.06a	3.10a	17.9a	15.7a
HC	1.10a	0.82a	21.5ab	19.7b	2.95b	3.05b	18.6a	14.6a
SD	1.12a	0.88b	20.8bc	21.6a	2.93b	3.12a	20.9b	15.2a
VSP	1.09a	0.88b	20.4c	21.4ab	2.92b	3.12a	20.4b	15.0a

[z]Means within columns followed by different letters are significant at $p \leq 0.05$.
See Table 1 for key to Trellis acronyms.

exceeded the ideal TA concentration, which is between 0.6 and 0.8% for red grape musts (Dharmadhikari and Wilker, 2001). However, this higher acidity is consistent with observations of 'Frontenac' fruit chemistry.

Fruit pH (Table 3) was not dependent on transmittance in this study, in agreement with Smart and associates (1988). In 2008, GDC had higher pH than other trellises although HC had comparable canopy conditions; in 2009, HC fruit had the lowest pH although transmittances were similar. °Brix (Table 3) seemed to correspond to fruit-zone transmittance in 2008, with GDC and HC higher than VSP and SD intermediate. Many others have observed the same pattern (Cartechini and Palliotti, 1995; Crippen and Morrison, 1986a; Gao and Cahoon, 1994; Macaulay and Morris, 1993; Smart et al., 1988, Spayd et al., 2002). However, in 2009 SD with low transmittance and high LNN values had the highest °Brix; this result cannot be explained by canopy light environment. In 2008, berry weight did not differ between training systems, while in 2009 SD and VSP produced larger berries than HC; GDC berry weight was intermediate (Table 3). Regression analysis showed only very weak correlations between fruit composition variables and percent transmittance at veraison.

CONCLUSION

Results of this study are in agreement with previous findings that GDC-trained vines have favorable, less-dense canopy conditions. We also found GDC maximized fruit yield, and in one year improved °Brix and pH. Although we acknowledge that trellis selection must incorporate other concerns, such as aesthetic and other personal preferences and existing structures, we propose GDC as a viable choice for Midwestern growers planning to establish new plantings of 'Frontenac' or converting existing vineyards from less productive systems.

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