Influence of Grapevine Training Systems on Vine Growth and Fruit Composition: A Review

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Abstract: Training a grapevine involves a manipulation of vine form. The type of training may lead to differences in total leaf area and the percentage of leaf area well-exposed to light. Consequently, the ability for a grapevine to photosynthesize efficiently depends upon its training system and the accompanying light microclimate of its leaves. In addition to altering the light microclimate of the canopy, training may impact numerous other variables such as fruit bud differentiation, cluster exposure, vine water status, and leaf transpiration. Modification of vine training systems to achieve balance between vine vigor and yield has led to divided canopy systems that might simultaneously increase yield and improve fruit composition through optimization of canopy light microclimate. Consequently, many training systems have been identified as being capable of improving wine quality through a combination of enhanced canopy and fruit microclimate.

Key words: fruit composition, leaf area, photosynthesis, vine balance, yield

General Aspects of Training Grapevines

Training is the physical manipulation of a plant's form. There is evidence that it was performed in the ancient vineyards of the Middle East, Greece, and Rome (Winkler et al. 1974), and today many training systems can be encountered, several of which are indigenous to the viticultural regions in which they are found. The first training systems were likely designed to keep the fruit off the ground and to facilitate harvest. Training systems, regardless of their complexity (i.e., single versus double curtain), can be distilled to four basic combinations: (1) head/spur, basically a short trunk and several two-node bearing units (e.g., bush vine); (2) head/cane, a short trunk with one or more longer bearing units (e.g., Guyot); (3) cordon/spur, horizontal extension(s) of the trunk with several two-node spurs (e.g., midwire cordon); and (4) cordon/cane, similar to head/spur but with longer bearing units (e.g., Sylvoz) (Figure 1). Canes are usually tied in head-trained systems but can be free-hanging in conjunction with cordons. The myriad of training systems that are found throughout the world therefore include two main components: the amount of perennial wood, which is reflected in the height of the trunk and the presence/absence of cordons, and the pruning method, which may be either cane- or spur-pruning, although occasionally encompasses both.

Training a grapevine accomplishes many objectives. First, the perennial wood and canes can be disposed in such a way as to manipulate the exposure of leaf area to maximize the interception of light, leading to higher yield potential, optimization of the leaf area to fruit ratio, higher quality, and better disease control. Second, bearing units are distributed on a trellis to facilitate movement of equipment through the vineyard or to otherwise facilitate mechanization of vineyard operations. Third, trunks and canes are disposed so as to avoid competition for light between vines. Fourth, proper training can provide that a renewal zone is formed, which ensures that the vine form is perpetuated and yield is maintained. Lastly, the amount of perennial wood can be varied to reduce the hazard of winter injury. The training system of choice is the one that satisfies all these objectives adequately within the confines of a particular site and cultivar, including the growth habit of the cultivar, its winter hardiness, the fruitfulness of its base buds, and the adaptability of the system to mechanization.

The study of training systems is a highly multidisciplinary endeavor. A thorough assessment of a system requires knowledge of vine photosynthesis, sugar and acid metabolism, micrometeorology, and many other fields. Consideration of basic horticultural principles, primarily pruning, also become intertwined with that of training. Because these many objectives must be met, it is not surprising that training systems vary considerably throughout the world. Many have been used commercially for a single cultivar (Concord) or within a single viticultural area such as Chautauqua County, New York (Gladwin 1919).

A complete summary of all research into training systems in grapes is beyond the scope of this review. All aspects of vine growth, development, yield, and fruit composition may be affected by a modification in training. Here we examine how the many factors affecting fruit composition exert their influence within the confines of a specific training system, as affected by the pruning method and

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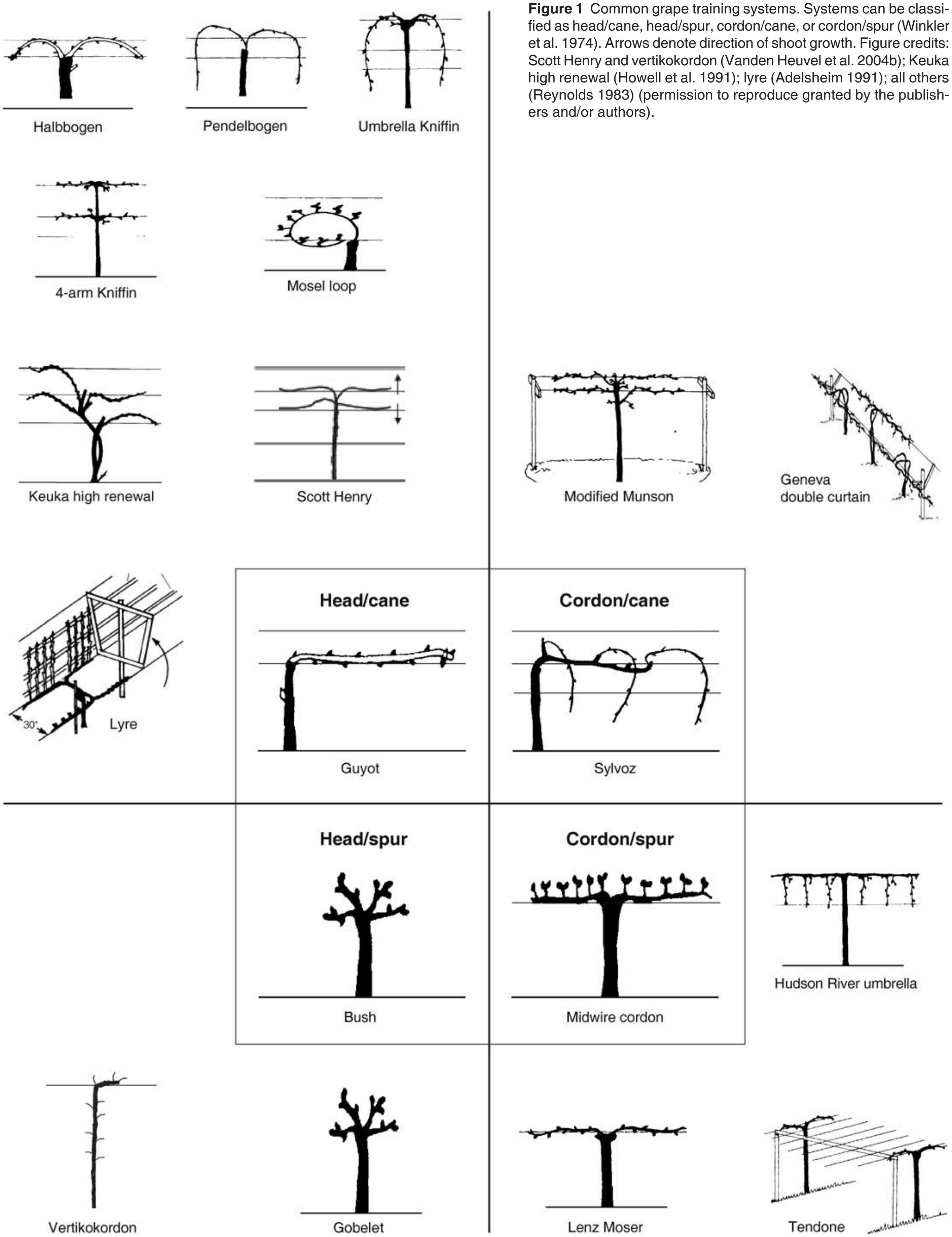

Figure 1 Common grape training systems. Systems can be classified as head/cane, head/spur, cordon/cane, or cordon/spur (Winkler et al. 1974). Arrows denote direction of shoot growth. Figure credits: Scott Henry and vertikokordon (Vanden Heuvel et al. 2004b); Keuka high renewal (Howell et al. 1991); lyre (Adelsheim 1991); all others (Reynolds 1983) (permission to reproduce granted by the publishers and/or authors).

trellis configuration that is inherent to the training system. One must accept the tenet that a particular training system is a microenvironment in which the fruit grows and is matured. Although we have focused predominantly on cool climates, we have nonetheless addressed training systems in warm climate zones.

Impacts of Training on Canopy Environment

Modifying the total amount and distribution of vine leaf area through defoliation, pruning, and training alters the microclimate of the canopy. The amount of leaf area that can be consistently exposed to the sun is a major consideration in the choice of a training system; it is affected by the disposition of the bearing units, the trellis height, and the associated type of pruning. A volume of literature has acknowledged the effects of all of these on vine growth, development, and yield. In general, it has been established that not only growth and yield but also quality is directly proportional to the ratio of exposed leaf area to fruit weight (i.e., crop load). A range of 7 to 14 cm^2 total leaf area per gram of fruit is required to achieve fruit maturity (Howell 2001). This wide range is dependent on environment, with higher ratios required in cool climates, so that important physiological functions such as bud initiation/differentiation, crop ripening, carbohydrate storage, wood and bud maturation, and acclimation/tolerance to cold can all be accomplished with the available exposed leaf area (Howell 2001). The threshold leaf area:fruit weight ratio is also greatly impacted by the ratio of exposed versus nonexposed leaves, a relationship that is directly affected by training system (Dokoozlian and Kliewer 1995).

The effects of the amount of exposed leaf area on fruit composition are best appreciated by recognizing the role played by photosynthesis and the factors influencing its efficiency. All yield and fruit composition variables ultimately depend on the photosynthetic activity of the leaves. Numerous studies have demonstrated the effects of leaf temperature, light environment, orientation, and leaf age on photosynthesis (reviewed by Poni and Intrieri 2001). After the interdependence between these factors and leaf area are established, then a concrete evaluation of the effects of leaf area on fruit composition can be made.

The relevance of vine photosynthesis within the context of training systems lies in the ability of the total leaf area to exploit all sources of photosynthetically active radiation (PAR). Paramount is the use of diffuse radiation and sunflecks by leaves in the interior of the canopy. Thus, modifications in training vines may not only increase the amount of leaf area exposed to high-intensity direct radiation (Smart 1973, Smart et al. 1977) but may increase the interception of diffuse radiation (Smart 1973) and improve the radiation microclimate of the remainder of the foliage (Smart et al. 1982). More recent work has indicated that the proportion of interior leaves to exterior leaves may also affect carbon balance of the vine (Vanden Heuvel et al. 2002).

Most pruning and training practices are based on the concepts that increasing the exposed leaf area improves fruit quality and that optimal exposure of leaf area can be manipulated by management practices such as training.

Development of divided canopies to improve light interception. Canopy division involves a modification to the configuration of the trellis so that two or more canopies are created from the initial single canopy or curtain. The overall effects are typically higher yields, enhanced node fruitfulness resulting from a reduction in canopy shade, and improved fruit composition (Smart et al. 1985a, 1985b). The initial models of divided canopies were horizontally divided. The Munson system, a forerunner to the Geneva double curtain (GDC) (Figure 1), was described as an alternative training system for Concord (Gladwin 1919). Munson involves a high trunk (~1.8 m) and four canes tied in opposite directions on wires ~1 m apart in the horizontal plane and could improve both yield and fruit composition in Concord compared with the 4-arm Kniffin system (4AK; Figure 1) (Couvillon and Nakayama 1970). The GDC is the most noteworthy horizontally divided system, however, and was first described by Shaulis et al. (1966). Instead of canes, the GDC consists of parallel bilateral cordons with spurs retained along these cordons. The shoots are positioned outward and downward to create two distinct canopies, a positioning that is crucial to achieve the full impact of the GDC. Although the GDC was developed for procumbently growing cultivars, particularly Concord, the system has been adapted worldwide on *Vitis vinifera* cultivars (Cargnello 1982, Cargnello and Lisa 1982).

Horizontally divided training systems devised exclusively for *V. vinifera* include the lyre trellis (Figure 1) (Carbonneau et al. 1978, Carbonneau 1979, Carbonneau and Huglin 1982) and its variants. The system typically involves pairs of canes trained on parallel wires that are spaced ~1 m in the horizontal plane and 1 m high. The shoots are managed by vertical shoot-positioning to create two distinct canopies. Support for the trellis normally consists of row and end posts set into the soil to form a V-shaped configuration. Variants on this design have included U-shaped and Y-shaped trellis configurations (Kliewer et al. 1988).

Training systems can also be vertically divided, the most well-known of which is the Scott Henry (Figure 1) (Henry 1991). Later modifications include the Smart–Dyson (Reynolds and Wolf 2008), which consists of a bilateral cordon ~1 m in height, with both upward- and downward-facing spurs retained along its length. Shoots originating from the upward-facing spurs are vertically positioned upward, while those originating from the downward spurs are likewise positioned downward. A further modification is the Ballerina, which does not involve downward spur placement, but instead relies completely upon a combination of both upward and downward vertical shoot-positioning to create a divided canopy (Reynolds and Wolf 2008). All of these systems, like the GDC, have the capability of reducing canopy density, increasing fruitfulness and yield, and improving fruit composition. Although these systems have become popular, vertical canopy division has a few key drawbacks. The Scott Henry system frequently shows effects of dominance of the upper canopy over the lower one, such that shoots trained vertically upward are normally much more vigorous than their downward-positioned counterparts (Henry 1991). The Smart–Dyson and Ballerina systems overcome this drawback to some degree, but positioning shoots downward reduces their vigor. Other vertically divided systems include the Te Kauwhata two tier (Smart and Robinson 1991), which consists of two vertically shoot-positioned canopies "stacked" atop each other, with hedging performed inbetween to separate the canopies.

The arrangement and volume of a canopy is influenced by the trellising system, which in turn affects canopy density, and hence impacts on light interception by both the leaves and the clusters. The leaf area density of grapevine canopies is significantly greater compared to canopies of other perennial crops (Schultz 1995). The percentage of leaves located in the interior of the canopies versus the canopy surface area differs between growing systems (Katerji et al. 1994, Schultz 1995, Smart et al. 1990). In California, three leaf layers were found to be an efficient number across the fruiting zone of a vertical nonpositioned canopy (Williams et al. 1987), while in Australia, 1.5 leaf layers were determined to be an optimum (Smart et al. 1990). These differences are likely due to geographic location and to a discrepancy in the definition of an "efficient" canopy. There is no universally accepted recommendation for leaf layer number of a canopy as it is affected by geography and cultivar.

An accurate description of canopy light environment greatly assists in the explanation of yield and fruit composition differences between training systems, although unfortunately this data is not included in all training studies. The measurement and reporting of microclimate changes induced by treatment allows for the separation of direct effects from indirect effects due to altered microclimate. It has been suggested that the measurement of microclimatic parameters as indicators or predictors of fruit composition and wine quality, particularly throughout the growing season, may replace the use of less easily measurable fruit and wine composition components (such as aromatic compounds) (Marais et al. 1999).

It is likely that training and trellising systems have always had some theoretical basis. Classical reports acknowledged the importance of optimization of the light environment by training (Bioletti 1922). Later work suggested that low trellising produced inferior fruit because of poor leaf exposure and excessive shade (Shaulis and Robinson 1953). However, the first comprehensive examination of the effects of training on vine microclimate was the introduction of GDC (Shaulis et al. 1966). Working with Concord, researchers linked low Brix in treatments to short canopy length (and therefore high shoot density) and increased proportion of interior shoots (and therefore poor light penetration). Reduced shoot exposure was directly related to diminished net carbon assimilation rate. Shoot positioning decreased the proportion of shaded basal leaves from 42 to 9% (Shaulis et al. 1966). This decrease would be expected because the double-curtain effect allowed for narrower canopies, with an associated increase in exposed leaf area per meter of row, while the position of the cordons and shoots provided for more space at the top of the trellis. Elimination of internal canopy shading of excessively large vines through horizontal canopy division led to increased harvest juice soluble solids at a given crop size. As might be expected, the veritable doubling of canopy length per acre likewise increased yields by 40 to 90% because of an increase in buds per vine and an increase in bud fruitfulness (Shaulis et al. 1966). These results implied that training could improve leaf and berry exposure (and thereby temperature) and therefore improve yield by improving flower bud initiation and subsequent fruitfulness and fruit composition.

Surprisingly, there was little improvement in the interception of direct solar radiation by GDC-trained vines when computer modeling was applied (Smart 1973); however, subsequent studies showed GDC training (when compared to Hudson River umbrella; Figure 1) allowed for higher incident light in the canopy interior and higher photosynthetic flux density for node-2 leaves (Smart et al. 1982). Interior leaf photosynthetic rates were also higher for GDC-trained vines. GDC and the open lyre were reported to be more efficient with respect to intercepting radiation compared to a single curtain and espalier systems (Mabrouk and Sinoquet 1998).

A similar attempt at using divided canopies was made in Georgia (Couvillon and Nakayama 1970). In the southern United States, excessively high temperatures often inhibit leaf photosynthesis, increase respiration, and reduce fruit coloration and Brix. Higher Brix, anthocyanins, and evenness of ripening were observed when the modified Munson (a divided canopy system) was used on Concord. Researchers attributed the superiority of the system to increased leaf exposure and a higher area leaf to fruit weight ratio.

Similar experiments were conducted on divided canopies under Australian conditions, but no compositional changes were observed; however, several yield components were increased by both dividing the canopy and lengthening the canopy (hence reducing shoot crowding) (Shaulis and May 1971). Shoot positioning had no effect. The micrometeorological effects of GDC were likewise observed in this study in terms of a greater percentage of exposed leaves and canes and higher leaf temperatures. Unfortunately, these changes in vine microclimate did not exert nearly the same positive influence as they did under New York conditions, likely because of substantial climactic differences between the sites. These results were subsequently confirmed (May et al. 1973).

Horizontal division of a canopy (e.g., GDC) requires rows of great enough width to allow passage of equipment and to minimize interrow shading due to canopy width and height. Greater row width is not typically necessary if the canopy is divided vertically, although consideration of the ultimate trellis height (and possible interrow shading) must be made for systems such as the Scott Henry, which often exceed 2 m in height, to properly accommodate the two canopies.

Relationship between structural indices and canopy light microclimate. Density of a grapevine canopy is dependent upon the system to which it is trained. Point quadrat analysis (PQA) and measurement of photosynthetically active radiation (PAR) in the fruiting zone are two common methods of indicating canopy density in vine-training studies. The correlation of leaf layer number (LLN) to PAR in the fruiting zone can be strong. LLN correlates very well for vertically shoot-positioned (VSP) systems with PAR in the fruit zone (r = -0.93), but less strongly with non-VSP systems (r = -0.79) (Gladstone and Dokoozlian 2003). For a combination of systems, correlations of PAR to LLN have been reported as approximately r = -0.70 (Gladstone and Dokoozlian 2003, Vanden Heuvel et al. 2004b). At individual phenological stages (berry set, veraison, and preharvest), the relationship was not as strong, likely because of changes in leaf area over the season. Despite a near doubling of leaf area between berry set and harvest, only minimal changes in canopy light environment have been observed during fruit development (Dokoozlian and Kliewer 1995). Because of allocation of leaves within the canopy space, an increase in leaf area may not necessarily be reflected in an increase in LLN in the fruiting zone. In general, the relationship between PAR and PQA is strong enough that either expression is useful for studies of canopy density, although neither gives an indicator of amount of exposed leaf area. Enhanced PQA (Meyers and Vanden Heuvel 2008) allows for production of leaf exposure maps and may be useful to describe system differences in future training studies. LLN also correlates well with percent interior leaves and percent interior clusters in both VSP and non-VSP systems (Gladstone and Dokoozlian 2003, Vanden Heuvel et al. 2004b). The use of PQA for systems with no defined fruiting zone (e.g., vertikokordon) remains questionable (Vanden Heuvel et al. 2004b).

Generally, VSP canopies have increased LLN in the fruiting zone compared with non-VSP canopies. Low cordon and pendelbogen (Figure 1), for example, have been demonstrated to have high LLN in both Cabernet franc and Chardonnay (Vanden Heuvel et al. 2004b) compared with non-VSP systems such as four-arm Kniffin (4AK) and vertikokordon, although Scott Henry had a low LLN due to division of the canopy. Using contacts per insertion as a measure of canopy density, low cordon was also determined to be a dense canopy, with low levels of exposed or partially exposed cluster faces (Reynolds et al. 1996a). LLN can be twice as great in low cordon as in low head, high head, and high cordon (Howell et al. 1991). In British Columbia, Riesling on low cordon and Mosel loop (Figure 1) were determined to have the highest number of canopy contacts, compared to flächbogen and pendelbogen (Reynolds 1988b). Although low cordon had the highest number of canopy contacts in that experiment, it also had the highest cluster PAR compared with the other systems. VSP in conjunction with leaf removal can result in dense canopies that still have good fruit exposure; however, exposure of leaf area does not tend to be optimized.

Improving light exposure of leaves and clusters. Training systems should maximize the percentage of exposed leaves and minimize the percentage of leaves in the canopy interior. Shaded leaves of *V. vinifera* are able to enhance their ability to capture and use the light transmitted by external leaves (Cartechini and Palliotti 1995); however, specific leaf weight, volume, density, and thickness are reduced with increased shading, leading to reduced light compensation points and dark respiration rates (Vanden Heuvel et al. 2004a). A large proportion of interior leaves versus exterior leaves may be costly with respect to the carbohydrate budget of a vine, as photoassimilate from light-adapted shoots is translocated to shade-adapted shoots (Vanden Heuvel et al. 2002). Estimates of the contribution of interior grapevine leaves to vine carbon balance range from 22% (Williams 1996) to 30% of total CO_2 assimilation (Smart 1974).

Similarly, training systems must maximize fruit exposure in cool climates in order to optimize berry growth and composition. Fruit in exposed portions of the canopy generally exhibit higher concentrations of sugars, anthocyanins, and total phenolics, as well as lower levels of malic acid, potassium, and juice pH compared with shaded fruits (Smart and Robinson 1991). The strongest effects of light quantity on berry growth have been observed primarily when shading occurred early in berry development in warm climates (Dokoozlian 1990). Cluster temperature also significantly affects flavor and aroma development (Bergqvist et al. 2001, Lee et al. 2007), although light and temperature effects are difficult to separate in training studies.

In cool climates, increasing sun exposure to fruit through optimization of training system is typically positive. For red winegrape cultivars, for example, shaded fruit is generally associated with lower concentrations of both anthocyanins and phenols compared to exposed fruit (Crippen and Morrison 1986, Cortell and Kennedy 2006, Iacono et al. 1994, Ristic et al. 2007). Specific phenols such as quercetin appear to be particularly responsive to enhancement in cluster microclimate (Price et al. 1995). However, excessive fruit exposure in hot climates can be detrimental (Bergqvist et al. 2001, Mori et al. 2007). Sun exposure is of particular significance in hot climates because there are concomitant increases in berry temperature (Spayd et al. 2002) and linear increases with ambient temperature (Bergqvist et al. 2001). In warm regions, high levels of cluster exposure result in lower berry anthocyanin concentration (Dry et al. 1999, Haselgrove et al. 2000) and lower titratable acidity (Bergqvist et al. 2001). Increased fruit exposure in warmer vintages leads to either inhibition of anthocyanin synthesis or anthocyanin degradation (Haselgrove et al. 2000). In fact, high temperatures (>35°C) have been particularly inhibitory to anthocyanin synthesis (Kataoka et al. 1984, Kliewer 1970, 1977, Kliewer and Torres 1972, Spayd et al. 2002). Diurnal flux in temperature also affects fruit coloration. Day-night temperature differences >10°C were generally inhibitory to fruit coloration, above and beyond the detrimental effects of high temperature on coloration (Kliewer and Torres 1972). Many key fruit attributes such as soluble solids, color, and phenols can be optimized in warm sites by reducing berry temperature with moderate fruit exposure (Bergqvist et al. 2001).

Light microclimate of leaves and fruit in training systems have been quantified in many studies. One of the most thorough investigations into the effect of training on light in a canopy was performed with Chardonnay and Cabernet Sauvignon (Gladstone and Dokoozlian 2003). Investigating light microclimates in several trellis/training systems, which included both horizontally and vertically divided systems (single curtain, double curtain, VSP, lyre, Smart–Henry, and Smart–Dyson), researchers found that non-VSP positioned systems were characterized by a layer of relatively high leaf area density on the exterior of the vine, but had lower leaf area densities on the interior. In contrast, the VSP systems increased in leaf area density from the top of the canopy down toward the fruiting zone. However, the pattern of light attenuation did not change between systems. Fruit zone PAR was >10% in low-density canopies and <5% in high-density canopies. LLN was greater in nondivided systems compared with divided systems. Well-exposed fruit zones with higher leaf area densities but lower LLNs were achieved with shoot-positioned systems compared to non-positioned canopies, although higher LLNs have been demonstrated in VSP compared with nonpositioned canopies in other studies (Howell et al. 1991, Reynolds et al. 1996a, Vanden Heuvel et al. 2004b). This increase in leaf area density is a direct effect of VSP, which produces a single column of leaf area by restricting the volume of the canopy. In non-VSP systems, leaf area typically concentrates in the region adjacent to the fruit zone, since canopy volume and shoot orientation are unrestricted compared with VSP systems. Canopy division reduces leaf area density and improves sunlight exposure into the canopy interior by increasing the amount of space available for foliage distribution. Based on these results, the researchers concluded that trellis systems with canopy surface area:volume ratios >4 are best used for low to moderate canopies, ensuring that a high percentage of total vine leaf area is exposed to sunlight (Gladstone and Dokoozlian 2003). In contrast, systems with canopy surface area:volume ratios <4 are best suited for moderate to large canopies, so that the foliage can be distributed over a larger volume of space and shoot growth will be less restricted. As a result, leaf area density and shading in the canopy interior will be reduced.

For cultivars with an upright or a more procumbent growth habit, divided canopies have often increased both leaf and fruit exposure. With Riesling, the divided alternate double crossarm and VSP-trained low cordon were compared with respect to fruit temperature, cluster PAR, and leaf PAR; the divided canopies had higher cluster temperatures as well as higher leaf and cluster PAR (Reynolds et al. 1996a). In Chancellor, PAR was generally higher in the Hudson River umbrella (HRU) canopies regardless of position on the vine, but by late afternoon, GDC leaves were more exposed (Reynolds et al. 1995). Similar results have been reported (Poni et al. 1996).

In nondivided systems, increased training height resulted in improved light microclimate of the leaves and fruit. In work with six training systems on Seyval in New York, results showed that umbrella Kniffin (Figure 1) and HRU were superior in terms of percentage of clusters exposed (Reynolds et al. 1985). A midwire cordon system had a low percentage of exposed fruit. Increasing cane length, orienting canes toward the soil surface, high trunks, and more perennial wood improved the percentage of exposed clusters.

Influence of training on vine microclimate variables. *Air movement/diseases.* Surprisingly little attention has been focused on the effect of training on canopy leaf wetness and disease. Naturally, more open canopies with improved air flow will likely have reduced leaf wetness durations and hence reduced disease incidence; however, an array of additional factors also affect disease incidence, including fruit load/distribution, canopy temperature, and hormonal influences. In California, *Botrytis cinerea* was highest in clusters from a crossarm style trellis compared with a standard two-wire vertical trellis, but few differences in canopy microclimate could explain the results (Savage and Sall 1984). In Bulgaria, Guyot training encouraged *B. cinerea* infection because of poor air circulation and temperature inversion, while the high leaf temperatures of high-trained vines encouraged powdery mildew infection (Draganov and Draganov 1976a). Similar results were found with high-trained Grüner Veltliner vines in Austria (Redl 1988). Higher canopy temperature gradients and lower wind speeds were found within high-trained vines (Burckhardt 1958), and wide training has been noted to reduce canopy temperature (Becker 1966). Powdery mildew infection was higher in VSP compared to nonpositioned, topped vines in all years of a study on Cabernet Sauvignon and Chardonnay; researchers attributed this difference to light intensity inside the canopy (VSP vines having considerably lower light levels than free-positioned vines) as temperature and relative humidity did not differ, although air movement likely did (Zahavi et al. 2001). Training-pruning regimes that reduce wound numbers in order to reduce Eutypa infection have been recommended (Lake et al. 1996, Gu et al. 2005).

Canopy temperature. Much has been reported on the temperatures under different training systems of various vine organs and their implications for fruit composition, yield, and incidence of disease. Greatest heat loads of leaves and berries were accumulated by low-trained vines such as those trained to the Guyot system (Draganov et al. 1975). Night temperatures of leaves and berries of Guyot-trained Bolgar vines were also higher than those of high-trained vines (Draganov and Pandeliev 1976). In most cases, the west and south sides of vines are generally warmer than the east and north sides in terms of leaf and berry temperatures (Becker 1966, Bergqvist et al. 2001, Draganov and Pandeliev 1976, Draganov et al. 1975, Reynolds et al. 1986, Smart et al. 1982).

There have been significant contributions to the study of training effects on microclimatic variables (Carbonneau 1979, Carbonneau et al. 1978, 1981, Carbonneau and Huglin 1982, Castell 1982). In a comprehensive examination of 10 training systems for Cabernet Sauvignon (Carbonneau et al. 1978), numerous techniques were used to assess vine microclimate, including thermocouples, photocells, and fisheye photography. The systems varied greatly in the percent sky visible from underneath the canopy (as determined using hemispherical photography), the percentage of PAR reaching the leaves, the heat loads of the fruit and leaves, several photosynthetic variables, and total leaf area. Several components of yield, fruit composition, and wine quality also differed considerably among the many trellising systems. Results were complementary to a previous study (Shaulis et al. 1966), in that the divided-canopy systems (U and V configurations) provided the most optimal light exposure and vine temperature, which translated into higher Brix, anthocyanins, and tannins and lower TA, malic, and tartaric acids. Yield and fruitfulness of these systems were also superior. Experiments in California using a divided canopy similarly showed marked yield increases and improved fruit composition in terms of higher Brix (Kasimatis et al. 1982).

Microclimatic differences among four training systems were demonstrated in Chenin blanc vines in South Africa (van Zyl and van Huyssteen 1980b). More air movement and higher soil, air, and fruit temperatures were recorded for bush-trained (head-trained, spur-pruned) vines.

Carbon assimilation. Comparison of net carbon assimilation of vines among training systems has not been commonly studied, although amount and proportion of exposed leaf area in a training system differs among systems (Gladstone and Dokoozlian 2003) and likely impacts vine carbon assimilation. Vines trained to a single trunk have shown higher rates of assimilation when subjected to partial defoliation (~11.0 and 12.0 μmol•m^{-2}•s^{-1} for divided and single trunks, respectively, at 14 weeks following bloom); however, training system was reported to have only a minor influence on leaf carbon assimilation in the subsequent season (Candolfi-Vasconcelos et al. 1994), although the use of single-leaf rather than whole-vine measurements limited the usefulness of this data. Single-curtain-trained Cabernet Sauvignon vines demonstrated higher net photosynthesis values per leaf surface unit compared with lyre-trained vines; however, the existence of greater leaf surface per soil surface in the lyre system compensated for the reduction, resulting in similar yields for the two systems (Katerji et al. 1994). Erbaluce vines trained to an alternate curtain system had lower carbon assimilation per unit leaf area, per whole leaf, and per nitrogen content compared to leaves of vines trained to the Calusiese pergola system (Novello et al. 2001). Some of these results are likely due to reduced light interception by the canopy foliage (Poni et al. 2003).

Canopy restriction reduces total vine carbon assimilation in both potted natural bush-shaped Chardonnay vines and field-grown Sangiovese vines trained to spur-pruned cordons (Intrieri et al. 1997), suggesting that the reduction in canopy dimensions resulted in a limitation of overall foliage efficiency. The restricted canopies also differed in photosynthetic light response compared with the unrestricted canopies as evidenced by lower rates of carbon assimilation at PAR levels >500 μmol•m^{-2}•s^{-1}.

Vine water status. The quantity of intercepted light as determined by the canopy geometry is one of the more important determinants of vine water use in grapevine (Williams and Ayars 2005). Occasionally, water demands increase with relatively minor modifications such as increases in trellis height due to increased light interception. Decreased midday leaf water potential (ψ) was measured in Grüner Veltliner vines that were trained to 1.7-m-high trunks in comparison to those trained to 1.35-m trunks (Redl 1984). Pinot noir leaves on vines trained to a divided trunk had higher transpiration rates (as much as 12% higher) and had lower water use efficiency compared to vines with a single trunk, both in the year of defoliation and the year following (Candolfi-Vasconcelos et al. 1994). Chancellor on a nondivided canopy (HRU) and a divided canopy (GDC) were compared, and HRU leaves tended to transpire more than GDC (Reynolds et al. 1995). Midday leaf ψ was also strongly influenced by training system, with GDC ψ less negative throughout the sampling period compared with HRU. With Riesling, the divided alternate double crossarm and VSP-trained low cordon were compared with respect to transpiration and leaf ψ. Surprisingly, the two systems differed very little in terms of water relations (Reynolds et al. 1996a). On the contrary, bush vines, with their relatively low leaf area, had highest evapotranspiration as a consequence of their canopy microclimate (van Zyl and van Huyssteen 1980a). In general, training systems impact vine water status by changing the portion of total leaf area exposed to sunlight.

Vine winter hardiness. Few studies have quantified the effect of training system on bud survival; however, those that have indicate that percent of bud survival in cool climates can be significantly impacted by choice of training system, particularly if shoots are positioned in an opposite direction from their natural growth habit. Downward-trained *vinifera* vines may result in reduced bud survivability, as evidenced from the lower hardiness of buds in the Scott Henry system (Vanden Heuvel et al. 2004b), likely because of lower vigor. Vertically trained cordon Chardonnay and Cabernet franc (non-VSP) had the highest bud survivability of six systems compared in the Niagara Peninsula, Canada (Vanden Heuvel et al. 2004b), likely because of improved light environment in the canopy interior (Wolpert and Howell 1985). Following winter injury, training system had a strong influence on budbreak of the hybrid Seyval, with vines on a Y-trellis demonstrating reduced budbreak compared with non-VSP systems (Reynolds et al. 1994). High head-trained vines had less winter kill than high cordon for Vignoles in one of two years (Howell et al. 1991), although this difference was not seen in Vidal (Howell et al. 1987). Results for trellis height in Concord were inconclusive (Stergios and Howell 1977). In general, impacts of training on vine winter hardiness are likely a function of light penetration into the canopy resulting in good periderm formation and increased carbohydrate storage due to improved light interception.

Impacts on Yield and Yield Components

Yield. Training systems can have a significant impact on vine yield, although results are very site- and cultivar-dependent. Much of the training research has been focused in North America, particularly in the arid Okanagan region of British Columbia (Reynolds 1988a, 1988b, Reynolds and Wardle 1994, Reynolds et al. 1995, 1996a, 1996b, 2004a, 2004b) and the cool humid regions of New York (Reynolds et al. 1985, Shaulis et al. 1953, 1966) and Michigan (Howell et al. 1987, 1991). A summary of studies that have focused primarily on effects of training systems on yield and fruit composition is shown (Table 1), with the impacts of training system on bud fruitfulness, vine capacity (vine size), and Ravaz index noted where possible.

Vitis vinifera vines on divided canopies (either horizontal or vertical) tend to produce higher yields than those on nondivided canopies, generally because of improved exposed leaf area and hence light interception, as well as the greater number of buds that are retained per unit row length at pruning. Riesling vines on the alternate double crossarm system and the low-V, both of which were divided canopies, produced the highest yield compared to the Lenz Moser (Figure 1), low cordon, and pendelbogen systems because of more shoots per vine (Reynolds et al. 1996a, 2004a). Likewise, Scott Henry produced the greatest yield of six systems tested on Cabernet franc and the second greatest yield on Chardonnay with the same number of shoots per length of row compared with other systems (Vanden Heuvel et al. 2004b). In Italy, GDC produced greater yield than the arched cane system in a study with Trebbiano (Intrieri 1987).

French-American hybrids also tend to produce higher yields on divided canopies. When the divided systems of GDC and Y-trellis were compared to high cordon, six-arm Kniffin (6AK), and midwire cordon, divided canopies produced the highest yields in Chancellor (Reynolds et al. 1995, 2004a) and Seyval (Reynolds and Wardle 1994, Reynolds et al. 2004a) (Table 1), even though the midwire cordon had more shoots per vine than the divided canopies. GDC produced higher yield than bilateral cordon in Chancellor, Chelois, Villard noir, Seyval, and Verdelet, but not in Aurore (Morris et al. 1984). Seyval produced greater yields on upright-cordon training (both spur- and cane-pruned) than on Sylvoz training (but not bilateral cordon) in Ohio (Ferree et al. 2002). GDC has increased yield compared with vines trained to hedgerow and gobelet (Figure 1) in a number of Italian studies (summarized by Intrieri and Poni 1995). In eight of nine trials on French-American hybrids growing in Michigan as single-curtain canopies, the relationship was high cordon > low cordon > high head > low head with respect to vine size and yield (Howell 2001). GDC also produced the highest yield in own-rooted Concord and Concord/3309 when compared to umbrella Kniffin and single curtain (Shaulis et al. 1966), and Concord on GDC produced greater yield than single curtain in a more southerly climate (Cawthon and Morris 1977). A divided canopy also improved the yield of Sultana (Shaulis and May 1971). Generally improvements in yield in these studies were due to improved exposed leaf area and increased shoot numbers (and hence cluster numbers) per vine.

Vertical shoot-positioning of vines in training systems does not have a clear effect on the yield. The non-VSP systems of vertikokordon and 4AK produced equivalent yields in Chardonnay and Cabernet franc compared with systems that included VSP (Vanden Heuvel et al. 2004b). Similar results were seen in a study of Seyval (Reynolds et al. 1985).

Yield components. Generally, increases in yield due to training system tend to result from increases in cluster numbers per vine or per linear distance of row, particularly in French-American hybrid and *V. labruscana* vines. Among the myriad of training system studies, a few have investigated the impact of training on vine capacity (either as weight of cane pruning or trunk circumference) and even fewer have measured fruitfulness. Those studies that measured and reported fruitfulness typically found direct relationships between fruitfulness and trunk height (e.g., Alichev et al. 1973, Draganov and Dragonov 1976b, Howell et al. 1991), canopy division (Couvillon and Nakayama 1970, Shaulis and May 1971), or trellis widening (May et al. 1976). In many cases, however, increases in yield were simply due to the addition of more shoots per vine and per meter of row on high-capacity vines. For example, Chancellor grown on GDC and Y-trellis produced high yield because of increased clusters per meter of row (45 and 44, respectively) compared with 25, 36, and 24 from HRU, 6AK, and midwire cordon, respectively (Reynolds et al. 1994). Results with Seyval in the same study were similar, with GDC and Y-trellis each producing 42 clusters per meter of row, compared with 25, 34, and 23 in HRU, 6AK, and midwire cordon, respectively. In general, GDC and Y-trellis had increased node numbers; however, midwire cordon also had increased node numbers but decreased node fruitfulness. With Vignoles, the high-cordon system produced 111 clusters per vine, compared to 86, 67, and 75 clusters per vine for the low-cordon, low-head, and high-head systems, respectively (Howell et al. 1991), resulting in a substantially higher yield from the high-cordon vines because of improved node fruitfulness compared with the other training systems. Yield component path analysis of Okanagan Riesling vines subjected to pruning and training treatments revealed a large direct effect of clusters per vine and cluster weight on yield (Reynolds and Wardle 1993). Negative direct effects on yield came from berries per cluster and berry weight; however, in the two years of this study when path analysis was performed, training system had minimal effects on vine performance, although differences among training systems were found in the earlier years of the study (Reynolds 1988a). Yield increases because of increased clusters per vine were noted in additional studies for Seyval (Reynolds et al. 1985) and Concord (Shaulis et al. 1966).

In *V. vinifera*, higher yields have been linked to increased cluster numbers in Riesling where the divided canopy of alternate double crossarm produced the highest number of clusters per row due to increased shoot numbers, followed by V-trellis, another divided canopy (Reynolds et al. 1996a). In Shiraz, minimally pruned vines produced substantially greater yields through an increase in shoot numbers and hence cluster number per meter of canopy (Wolf et al. 2003). Studies reaching analogous conclusions include the cultivars Tempranillo (Baeza et al. 2005, Baigorri et al. 2001). However, yield increases of Chardonnay on pendelbogen were due to an increase in berry number per cluster leading to an increase in cluster weight (Vanden Heuvel et al. 2004b), and yield increases in Pinot noir were attributed to increases in cluster weight as well (Peterlunger et al. 2002).

Vine balance. Vine balance is defined as the appropriate relationship between vegetative growth and reproductive growth. A mathematical expression for vine balance was proposed as the ratio of yield to pruning weight (Bravdo et al. 1984, 1985). For *V. vinifera* vines, optimal values were suggested as 10 to 12 (Bravdo et al. 1985) or 5 to 10 (Smart and Robinson 1991). However, crop loads (i.e., Ravaz index; yield to pruning weight ratios) in the range of 12 to 22 did not appear to negatively impact yield the following year in young Cabernet franc vines grown on six training systems (Vanden Heuvel et al. 2004b). VSP systems such as 4AK, Scott Henry, and pendelbogen tended to have higher crop loads than the other systems; however, yield was not detrimentally affected in future years, although Brix was not as high as in other systems. Scott Henry, the only divided canopy in the study, had the highest crop load ratio because of increased node fruitfulness, particularly in Cabernet franc. Riesling had crop loads as high as 22.5 in the alternate double crossarm divided canopy and 18.2 in Lenz Moser (nondivided), while achieving 18.4 and 19.7 Brix, respectively (Reynolds et al. 1996a).

Higher crop loads in properly trained French-American hybrid vines do not necessarily have a negative impact on wine quality (Reynolds and Wardle 1994, Reynolds et al. 1985, 1995). Vines of Chancellor on GDC had a 5-year average crop load of 17.4 and an average Brix of 20.9 (Reynolds et al. 1995), while Seyval vines on GDC had an average crop load of 27.7 and Brix of 21.5 over a 5-year period (Reynolds and Wardle 1994). Crop loads of Seyval were affected by training system (Reynolds et al. 1985); however, vines trained to umbrella Kniffin, HRU, and cordon all produced crop loads above the recommended value in one year of the study (~12 to 16), but had fruit of 18.5, 19.2, and 18.0 Brix, respectively, while pendelbogen had a crop load ratio of 6.7 and produced fruit of 19.5 Brix. Crop loads higher than the recommended values of <12 may therefore be possible on both *V. vinifera* and hybrid vines if proper canopy microclimate is provided by the design of the training system and leaf exposure is optimized to support the fruit load. Divided canopies may provide the appropriate microclimate.

Impacts on Fruit Composition

The preceding sections have dealt with fruit quality as a variable responsive to leaf area, temperature, and light. Many investigators have found that these predominantly independent variables be made dependent on a single facet of management such as training. A number of noteworthy studies in addition to those cited have simply examined fruit compositional differences between different training and trellising systems (Table 1). Some of these works indicate that, with the appropriate choice of training system, yield can be increased (generally through an increase in exposed leaf area) with concomitant improvements in fruit composition and/or wine sensory (Bondzoukov et al. 1972, Carbonneau et al. 1978, Cawthon and Morris 1977, Couvillon and Nakayama 1970, Draganov and Draganov 1976b, Howell et al. 1991, Huglin 1977, Kasimatis et al. 1975, Morris and Cawthon 1980, Müllner 1951, Redl 1983, 1988, Reynolds et al. 1995, 1996a, Shaulis et al. 1966, Turkovic 1955, Weiss 1962, 1981).

Although there are many reports in the literature of training system affecting fruit composition, some show no effect on fruit and/or wine composition. In a comparison of four training systems (simple Guyot, double Guyot, horizontal spurred cordon, vertical spurred cordon), yields ranged among systems from 7.5 to 9.7 t/ha, but training system had little or no impact on grape or wine composition, with sensory analysis showing no difference among systems (Peterlunger et al. 2002). Microclimatic differences among four training systems were demonstrated in Chenin blanc vines in South Africa (van Zyl and van Huyssteen 1980b), but there were no differences in fruit composition. Similar experiments on divided canopies under Australian conditions failed to observe any compositional changes, although several yield components were increased (Shaulis and May 1971). These results were confirmed later (May et al. 1973). These studies indicate that, with the appropriate training system, yield can be increased with no detrimental impact on fruit quality.

Conclusions

The method by which a vine is trained impacts growth of the vine, including light interception and light microclimate of the leaves and fruit. Significant impacts of microclimate resulting from training have been demonstrated on fruit composition and on wine sensory analysis. Although not yet demonstrated conclusively, the reviewed literature indicates that a putative relationship exists among these aspects (e.g., training, vine microclimate, and fruit composition) and wine quality.

Table 1 Summary of training system effects on yield, fruitfulness, fruit composition, and canopy microclimate of grapevines (NM: not measured). Abbreviations: 4AK, 4-arm Kniffin; 6AK, 6-arm Kniffin; GDC, Geneva double curtain; HRU, Hudson River umbrella; MP, minimally pruned; RI, Ravaz index: SH, Scott Henry; UK, umbrella Kniffin; VSP, vertical shoot-positioned.

			Effects on			
Authors/region	**Cultivar(s)**	**Training systems**	**Yield**	**Fruitfulness and/or vine capacity**	**Fruit composition**	**Canopy microclimate**
Alichev et al. (1973); Bulgaria	Italian Riesling, Rkatsiteli, Ugni blanc	Guyot; three trunk heights	High trunks decreased yield in Italian Riesling	High trunks increased fruitfulness but reduced vine size	High trunks decreased Brix and TA	NM
Babrikov (1976); Bulgaria	Cardinal	Seven trunk heights	High trunks increased yields	High trunks increased fruitfulness	High trunks decreased Brix and TA	NM
Blaha (1966); Czechoslovakia	Gutedelweiss, Riesling, Gruner Veltliner, Welschriesling	Four different configurations: head training, Rheinhessiche, high training, Protinin palmette	Protinin palmette yielded highest	NM	Systems with highest leaf area had lowest Brix and TA	NM
Bondzoukov et al. (1972); Bulgaria	Bolgar	Several of different heights	Moser had highest sustainable yields	NM	High trellising allowed best fruit quality	Moser optimized sunlight interception
Cabras et al. (1981); Italy	Carignane	Albarello, spalliera	NM	NM	Albarello had highest Brix and lowest TA	NM
Carbonneau et al. (1978); Bordeaux, France	Cabernet Sauvignon	10 divided and undivided canopies	Divided had highest yields	Divided tended to have highest fruitfulness	Divided had highest Brix and wine quality, lowest TA	Divided increased leaf and cluster exposure
Cawthon and Morris (1977); Arkansas, US	Concord	Cordon, GDC	GDC increased yield and berries per cluster	No effects on vine size; fruitfulness NM	GDC increased Brix	NM
Clingeleffer and May (1981); Australia	Sultana	Swing-arm, T-trellis	Swing-arm increased most yield components	Swing-arm increased fruitfulness	Swing-arm decreased Brix and pH	Swing-arm shoots were more exposed
Couvillon and Nakayama (1970); Georgia, US	Concord	4AK, modified Munson	Munson increased yields, clusters per vine, cluster wt, berries per cluster, and berry wt	Modified Munson had more clusters per shoot and a greater percentage of fruitful shoots	Munson increased Brix, anthocyanins, and reduced asynchronous fruit maturity	NM
Draganov and Draganov (1976b); Bulgaria	Several *V. vinifera*	Guyot, high-training	High training increased yields and clusters per vine	Guyot increased trunk circumference; high training increased fruitfulness	Guyot increased Brix and reduced TA	High training increased sunlight interception
Ferree et al. (2002); Ohio, US	Seyval	Bilateral cordon, Sylvoz, upright cordon-spur pruned, upright cordon-cane pruned	Upright cordon yielded highest	Upright cordon had highest vine size	Sylvoz had highest Brix; no effects on wine quality	Sylvoz had highest % canopy gaps
Gladwin (1919); New York, US	Concord	Chautauqua; four-arm, single-stem, and two-stem Kniffin; HRU; Keuka high renewal; Munson; UK	Single-stem Kniffin yielded highest	Munson and Keuka high renewal had highest vine size	UK had best fruit quality	NM
Grösser (1964); Germany	Riesling, Ruländer, Weissburgunder	Normal, wide	Cane bending increased yield and berry wt	NM	Wide training decreased Brix and TA; cane bending increased Brix	NM
Haeseler and Green (1991); Penn., US	Vidal blanc	GDC, 6AK	GDC increased yield	GDC had lower vine size	No effects of training	NM
Hedberg and Raison (1982); Australia	Shiraz	Six trellis widths: two single wire and four T-trellis (0.9–2.25 m width)	T-trellis increased yield and clusters per vine	2.25 m T-trellis had highest trunk circumference and vine size and more fruitful shoots	T-trellis tended to have highest Brix and lowest pH	T-trellis had lowest light penetration
Howell et al. (1987); Michigan, US	Vidal blanc	High cordon, high head, low cordon, low head	Cordon systems yielded highest	Cordon systems generally had highest vine size; fruitfulness highest in high cordon	No consistent effects	NM

Howell et al. (1991); Michigan, US	Vignoles	High cordon, high head, low cordon, low head	High cordon yielded highest	No effects on vine size; high cordon had highest fruitfulness	High cordon was equal or superior to other systems in Brix	High-trained systems had most open canopies
Huglin (1977); Alsace, France	Chasselas, Gamay	Cordon, Guyot	Cordon yielded highest	NM	Cordon increased Brix; TA increased in cordon-trained Gamay	NM
Kasimatis et al. (1975); Calif, US	Thompson Seedless	One-wire vertical, two-wire T, four-wire double T	Yield was highest in four-wire double T	Four-wire had highest vine size; fruitfulness not consistently affected	Brix highest in four-wire	NM
Katerji et al. (1994); France	Cabernet Sauvignon	Single-curtain VSP, lyre	No effects	NM	Higher anthocyanin concentration in wines from lyre	NM; transpiration and net carbon assimilation per unit leaf area higher in single-curtain
Kiefer (1979); Germany	Several *V. vinifera*	Flächbogen, halbbogen, pendelbogen, Sylvoz	Yield differences; cultivar-dependent	Halbbogen had highest vine size; pendelbogen least	Brix and TA differences; cultivar-dependent	NM
Konlechner and Mayer (1961); Austria	14 *V. vinifera* cultivars	High, low trunks	High-training decreased yield	High-training increased leaf area per vine	High-training decreased Brix and TA	NM
May et al. (1976); Australia	Crouchen	Six combinations in a factorialized arrangement of three widths and two heights, cane- or spur-pruned	Trellis widening and spur-pruning increased yields	Yield increases attributed mainly to improved budburst; trellis widening increased fruitfulness	No effects	NM
May et al. (1973); Australia	Sultana	Two undivided and one divided canopy	Divided canopy yielded highest	Wide and high trellis had highest vine size	No effects	NM
Matevska and Kondarev (1973); Bulgaria	Cabernet Sauvignon	Three trunk heights; lowest was Guyot-trained	High trellises yielded highest; Guyot yielded lowest	High trunks increased fruitfulness	High trellising reduced Brix and TA	NM
Mihailov (1980); Bulgaria	Rkatsiteli	Midwire, Moser, modified Moser, umbrella	Increased trunk height increased yields	High trunks increased fruitfulness; Moser increased vine size	Moser hastened veraison; results correlated with trunk height	NM
Morris and Cawthon (1980); Arkansas, US	Concord	GDC, HRU, UK	GDC increased yield	GDC had highest node fruitfulness; UK had highest vine size	GDC increased color and decreased TA without affecting Brix	NM
Morris et al. (1984); Arkansas, US	Chelois, Chancellor, Villard noir, Verdelet, Seyval, Aurore	GDC, bilateral single cordon	GDC increased yield in all cultivars except Aurore	No impact on vine size; fruitfulness NM	GDC fruit had lower Brix, did not affect pH and TA	NM
Müllner (1951); Austria	Grüner Veltliner, Neuberger, St. Laurent, Weissburgunder	High and low cordon	High training increased yield	NM	High training increased Brix and TA	NM
Pandeliev et al. (1980); Bulgaria	Afuz-Ali	Guyot, high training	High training increased yields 45%	High trunks increased fruitfulness	High-trained vines had slightly reduced Brix	NM
Peterlunger et al. (2002); Italy	Pinot noir	Simple Guyot, double Guyot, horizontal spurred cordon, vertical spurred cordon	Double Guyot and vertically spurred cordon produced highest yields	Simple Guyot had highest vine size and spurred cordon the lowest; both had lowest RI (4.7), double Guyot was highest (6.0)	Horizontal-spurred cordon and simple Guyot increased Brix; no impact on wine sensory analysis	NM
Peterson et al. (1974); Australia	Semillon, Shiraz	Single wire; 37 cm-wide T-trellis	T-trellis increased yield in Shiraz and decreased cluster and berry wt and clusters per node (both cultivars)	Single wire had highest vine size; no impact on fruitfulness	T-trellis decreased Brix	NM

Table 1 (cont.) Summary of training system effects on yield, fruitfulness, fruit composition, and canopy microclimate of grapevines (NM: not measured). Abbreviations: 4AK, 4-arm Kniffin; 6AK, 6-arm Kniffin; GDC, Geneva double curtain; HRU, Hudson River umbrella; MP, minimally pruned; RI, Ravaz index: SH, Scott Henry; UK, umbrella Kniffin; VSP, vertical shoot-positioned.

			Effects on			
Authors/region	**Cultivar(s)**	**Training systems**	**Yield**	**Fruitfulness and/or vine capacity**	**Fruit composition**	**Canopy microclimate**
Redl (1980); Austria	Grüner Veltliner	Moser (1.3 m trunk height), free-growing high trunk (1.7 m)	Moser increased yield	Free-growing had less vegetative growth	Moser reduced Brix and TA	NM
Redl (1983); Austria	Grüner Veltliner	Bründlmayer, Klosterneuberg, Metternich (all 1.7 m trunk ht), Moser (1.3 m trunk ht)	Moser increased yield	Moser had the most vegetative growth	Moser had highest Brix and lowest TA	Moser had lowest mildew and bunch rot
Redl (1988); Austria	Grüner Veltliner	High cordon (1.7 m trunk ht), Moser (1.3 m trunk ht)	Moser yielded higher	Moser had the most vegetative growth	Moser had higher Brix and lower TA	Moser had higher leaf area per vine but better light microclimate and less disease
Reynolds (1988a); BC, Canada	Okanagan Riesling	HRU, midwire cordon, Moser manually or mechanically pruned	Midwire cordon had highest yields	No effects on vine size; midwire cordon had highest shoot number	Midwire cordon had lowest Brix and highest TA, pH, and bunch rot; HRU had best wines	Midwire cordon had densest canopies and lowest exposed fruit
Reynolds (1988b); BC, Canada	Riesling	Two-tier flächbogen, low cordon, Mosel loop, pendelbogen	Low cordon increased yields	Vine size not affected but low cordon had more shoots per vine	Flächbogen had most intense wine aroma; low cordon least	Low cordon had densest canopies
Reynolds et al. (1985); New York, US	Seyval	Seven nondivided systems	Kniffin had highest yield	6AK had highest vine size and HRU lowest; fruitfulness was not affected	HRU had highest Brix and pH, and lowest TA and malate	HRU had highest fruit exposure
Reynolds and Wardle (1994); BC, Canada	Seyval	HRU, GDC, 6AK, midwire cordon, Y-trellis	GDC and Y-trellis had highest yields but smallest berries	GDC had lowest vine size	GDC had lowest Brix, TA, bunch rot	NM
Reynolds et al. (1994); BC, Canada	Pinot noir	Low cordon (10 and 20 shoots/m row), SH	20 shoots/m and SH had highest yields	10 shoots/m had highest vine size and lowest RI (5.9); SH had highest RI (11.1)	20 shoots/m and SH had lowest Brix, pH, anthocyanins; SH had lowest TA	10 shoots/m and SH had lowest canopy density
Reynolds et al. (1995); BC, Canada	Chancellor	HRU, GDC, 6AK, midwire cordon, Y-trellis	GDC and Y-trellis had highest yields but smallest berries	Y-trellis had highest vine size; other systems similar	GDC had lowest Brix, TA; highest anthocyanins	GDC had higher cluster exposure, leaf water potential, transpiration; HRU had higher berry temperatures
Reynolds et al. (1996a); BC, Canada	Riesling	Double crossarm, low cordon, Moser, pendelbogen, V-trellis	Double crossarm yielded highest	Double crossarm had highest RI (10.2); low cordon had lowest (5.9). V-trellis had highest vine size	Double crossarm had lowest Brix but highest free and bound terpenes	Double crossarm had higher leaf and cluster exposure, and berry temperatures; lowest leaf water potential
Reynolds et al. (1996b); BC, Canada; Oregon, US	Pinot noir	Low cordon (10 and 20 shoots/m row), SH	NM	NM; see Reynolds et al. (1994)	SH increased anthocyanins and several sensory descriptors	NM; see Reynolds et al. (1994)
Reynolds et al. (2004a); BC, Canada	Seyval, Chancellor	HRU, GDC, 6AK, midwire cordon, Y-trellis	GDC and Y-trellis had highest yields but smallest berries	Seyval: GDC had lowest cane prunings/m canopy (0.19 kg/m), RI ranged from 21.1 (HRU) to 56.7 (6AK). Chancellor: GDC had most ideal cane prunings/m (0.40 kg/m), RI ranged from 13.1 (HRU) to 27.7 (6AK)	GDC Seyval had lowest Brix and HRU highest; 6AK Chancellor had lowest Brix and HRU highest	NM; see Reynolds et al. (1995)

Reynolds et al. (2004b); BC, Canada	Riesling	Double crossarm, low cordon, Moser, pendelbogen, V-trellis	Double crossarm yielded highest	V-trellis had highest vine size; double crossarm, Moser, and V-trellis had highest RI (13.0–14.2)	Double crossarm had lowest Brix; low cordon and low-V were highest	NM; see Reynolds et al. (1996a)
Shaulis and May (1971); Australia	Sultana	Several divided and nondivided canopies	Canopy division increased yield and cluster wt	Canopy division increased node fruitfulness	No effects on Brix	NM
Shaulis and Robinson (1953); New York, US	Concord, Fredonia	1.2, 1.7, 2.1 m trellis heights	NM	NM	1.7 m high-trellis had lowest TA and highest methyl anthranilate; no effects on color	NM
Shaulis et al. (1966); New York, US	Concord	GDC, UK	GDC yielded higher	GDC tended to have ~20% lower vine size but did not have higher fruitfulness (1.3 vs 2.8 clusters /shoot)	GDC had higher Brix	GDC had more external shoots, hence higher leaf and cluster exposure
Slesinger (1965); Czechoslovakia	Welschriesling	Six systems	High training had highest yield	NM	High training decreased Brix	NM
Slesinger (1969); Czechoslovakia	Grüner Veltliner	Six systems	High training had highest yield	NM	Low training increased Brix and lowered TA; high training had lowest quality	NM
Smart et al. (1985a,b); Australia	Shiraz	0.4-m wide T-trellis (control, hedged to 9 nodes); GDC	No effects on yield	No effects on vine size; fruitfulness NM	GDC had lowest berry and wine K, highest wine TA, and lowest wine pH	GDC improved most aspects of canopy microclimate
Todorov and Petrova (1980); Bulgaria	Bolgar	Guyot and tendone with two trunk heights	Guyot produced most marketable clusters	NM	NM	NM
Turkington et al. (1980); Australia	Muscat Gordo Blanco	Single-wire, T-trellis	T-trellis increased yield and clusters per vine	T-trellis had lower vine size; fruitfulness not measured	Single-wire increased Brix	NM
Turkovic (1955); Yugoslavia	Blauer Portugieser, Gütedelweiss, Traminer, Welschriesling	Bockschnitt, cordon, doppelschenkel	Cordon and doppelschenkel had highest yields	Cordon and doppelschenkel had highest vine size	Cordon and doppelschenkel had highest Brix	NM
Vanden Heuvel et al. (2004b); ON, Canada	Chardonnay, Cabernet franc	Low cordon, pendelbogen, 2-tier flatbow, 4AK, SH, vertikokordon	Pendelbogen had highest yields; low cordon and vertikokordon had lowest	4AK and SH had lowest vine size and highest RI; fruitfulness NM	Low cordon and vertikokordon had highest Brix	Low cordon was most dense canopy (highest LLN); SH had lowest LLN
Van Zyl and van Huyssteen (1980a,b); South Africa	Steen (Chenin blanc)	Bush, Perold, lengthened Perold, slanting trellis	Slanting trellis had highest yields	Slanting trellis had highest vine size; RI highest (8.8) in Perold and lowest (3.5) in slanting	Bush training increased pH and decreased Brix and TA	Bush vines had highest cluster, leaf, and canopy temperatures
Weaver and Kasimatis (1975); Calif, US	Thompson Seedless	1.4, 1.7, and 2.0 m trellises with and without crossarms	2.0 m trellis increased yield	Increasing trellis height increased vine size	No trellis height effects; crossarms increased Brix	NM
Weiss (1962); Germany	Gütedelweiss, Müller-Thurgau	Flächbogen, halbbogen, weitraum (cordon with crossarms)	Halbbogen had highest yield	NM	Halbbogen had highest Brix, and reduced TA in Gütedelweiss	NM
Weiss (1981); Germany	Several *V. vinifera*	Flächbogen, halbbogen, umkehr (unilateral cordon with long spurs)	Flächbogen had highest yield	NM	Flächbogen had highest Brix; umkehr had highest TA	NM
Wolf et al. (2003); Australia	Shiraz	Low bilateral cordon, high bilateral cordon, VSP, SH upward, SH downward, MP (low bilateral cordon)	MP vines had highest yield, bilateral cordons had lowest yields	MP and SH upward had highest fruitfulness; SH downward and low bilateral cordon had lowest fruitfulness	MP had lowest Brix and anthocyanins	VSP had lowest fruit zone PAR
Wolpert et al. (1983); Michigan, US	Vidal blanc	High-cordon, high-head, low-cordon, low-head	No effects on yield	Vine size measured but data not reported	No effects on fruit composition	NM
Yonev (1976); Bulgaria	Rkatsiteli	Guyot, high training	High training increased yield	High trunks increased fruitfulness	No effects on fruit composition	NM

Although a few investigations have produced some rather confusing and contradictory results, the basic tenet that providing the maximum amount of exposed leaf area per meter of row will optimize yield and quality cannot be disputed. As demonstrated in this review, both higher yield and improved fruit composition can be realized with some training systems in some circumstances.

While much literature details the effect of training on yield components and basic fruit composition, few studies have included an in-depth analysis of training impacts on additional flavor and aroma compounds and/or sensory analysis. Future studies should focus in these areas so that the potential of training systems for optimizing yield and fruit quality are fully investigated.

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