Training System choice as relate to genotype, site vigour and grape quality targets

Stefano Poni; Lorenzo Casalin

1. Introduction

Due to its long flexible canes, the grapevine is especially suitable to be trained to a multitude of canopy forms and more than 40 of them are named in viticulture textbooks (Eynard and Dalmasso, 1990). Yet, grapevine training systems can be more simply categorized according to canopy division (single versus split canopies), growth habit (vertically shoot-positioned or free growing) and growth orientation (upward versus sloped or horizontal).

The aim of the next paragraphs is to analyze which factors are more tightly bound to the trellis system choice in wine grape growing.

2. Training System Vs. Cultivar-Rootstock Combination

Training system choice is influenced by the genotype through effects related to growth habit, fruitfulness of the basal buds and degree of mechanization. The advent of trellises like the GDC and the single high-wire cordon featuring the unique trait of absence of foliage wires has let to investigate the natural growing pattern of different varieties which can be classified as naturally upright (e.g. Cabernet S.), intermediate (e.g. Chardonnay) or downward (e.g. Ugni blanc). The challenging issue is to assess, at the same leaf area level, if a free-growing habit is physiologically more efficient than a traditional vertically-shoot positioned (VSP) growth pattern. Results (Poni and Intrieri, 2001) indicate that a canopy squeezed between catch wires can suffer a decrease in total net photosynthesis by more than 25% as compared to a nicely managed, upright free canopy (Figure 1). Moreover, findings from Bergqvist et al. 2001 have shown that such canopies create a mostly diffuse light micro-environment around the clusters enriched with occasional sun-flecks which, especially in warm climates, is conducive to high-quality grapes.

A tool which can be used to “induce” a more erect canopy growth in cultivars having a natural downward direction of growth is an early shoot trimming which reinforces the basal part of the cane and temporarily arrests shoot growth. However, this technique is biased towards the unpredictable dynamic of lateral re-growth which is often a primary factor for reaching adequate maturity; while a weak regrowth can be adjusted through supplemental irrigation, an excessive vigour of laterals invariably requires repeated trimming leading to prolonged vegetative growth and increased canopy density which, in turn, might spoil final grape quality.

Genotype affects training system choice also through the genetic fruitfulness of basal buds. While it is clear that a cultivar having a high fruitfulness of the basal buds allows any type of pruning (spur vs. long canes), a cultivar showing a very low degree of fruitfulness is bound to a long pruning type. The most interesting case arises with cultivars having a low-to-intermediate level of fruitfulness which often puzzles the growers whether or not using a short pruning.

Here we shall summarize a specific experience (Poni et al., 2004) involving ‘Croatina’ (Vitis vinifera L.), a cultivar marked by a low fruitfulness of basal buds (varying between 0.3 – 0.6 inflorescence/shoot within the 1-to-4 basal nodes). Four pruning treatments—hand pruning (HP), short mechanical pruning followed by severe or light manual follow-up (SMP-SF; SMP-LF) and medium mechanical pruning followed by light manual follow-up (MMP-LF)—were compared in a 10-year-old "Croatina" vineyard trained to high free cordon and planted at 1.1m x 2.5 m. "Severe" and "light" follow-up were defined as number of machine runs per row (two and one, respectively), thereby allowing the crew more or less time for shortening and/or thinning of machine pruned wood. "Short" mechanical pruning was defined as cuts made as close as possible to the cordons; MMP-LF was set by maintaining the cutter bars at approximately 10 cm above and sideways the cordon.

A summary of the main results recorded over 2000-2003 is reported in Table 1 and can be discussed as it follows:

a) SMP + hand finishing retaining 50-60 nodes/vine achieved about 25% higher yield than HP at similar quality and 50% time saving;
b) yield compensation was manifested here primarily as reduced bud-break beyond the threshold of 60 nodes/vine and was indeed aided by the natural low fruitfulness of the basal nodes of this cultivar;
c) the breakpoint in this study was represented by MMP-LF (> 60 nodes/vine) which started to show a depressant effect on vine capacity paralleled by a contraction of soluble solids and anthocyanins.
d) These data show that mechanical pruning can be an excellent tool to bring low fruitful cultivar to a level of acceptable yield without detriment for grape quality.

3. Training System Vs. Vine Vigour

The training system is a tool for vigour control itself. Expanded training systems featuring large, lightly pruned vines (e.g. the group of the "pergola" trellises) reduce individual shoot vigor while retaining a high vine capacity. However, these "large" trellises have several weaknesses: high planting costs, low susceptibility to mechanization, and the tendency to produce low quality grapes especially when the inherent high cropping per vine is associated to un-favorable weather climate or poor canopy management. Therefore, a training system which can still retain the capacity to reduce site vigor (if needed) while allowing a high degree of mechanization would represent a good compromise.

Under such circumstances, trellises such as GDC (Geneva Double Curtain) and Lyra have represented a benchmark. In particular, the GDC, proposed by N. Shaulis et al. in 1966, besides having structural features suitable to full mechanization of pruning and harvesting, presents two revolutionary traits which are key-factors for vigour control: canopy splitting and a free- growing growth habit. Splitting the canopy means that, at the same vine spacing in the row, node number per vine doubles therefore accommodating cases of high vigour. Then, the literature is rich of contributes showing that the vigour of downward growing shoots is lower than that of upright shoots. This is also confirmed by a long term trial carried out in Italy (Intrieri et al., 1992) on an array of training systems, clearly indicating that the GDC was by far the most weakening trellis in terms of pruning weight per meter of canopy length (Figure 2).

Another factor which impacts on the decision for the more suitable training system in a given environment is the vine distance along the row. It is still a quite accepted postulate that, in a vigorous environment, narrowing the vine in the row would eventually trigger some root competition which, in turn, can limit shoot growth. This might be true under specific cases (shallow soils) or for soils where factors such as water table, calcareous layers, ecc. limit root growth; however, as it is shown in figure 3, several studies carried out in different environments and for varying cultivars clearly show that pruning weight per meter of row length decreases at increasing in the row vine spacing. This is because, without any effective root competition taking place, node number per vine increases with spacing leading to higher crop and, in turn, attenuated shoot vigor. Therefore, especially if training systems which inherently promote vegetative growth (e.g. a VSP, spur-pruned cordon) are planted at a too narrow spacing, vines can become unbalanced for excessive vigor and, as a paradox, the low yield per vine (caused by the low node number) sometimes is also associated with incomplete ripening due to un-favorable cluster microclimate and too competitive shoot growth.

Grape growers would also need user-friendly tools to assess if the chosen training system leads the vine to equilibrium. The most popular indices of vine balance (yield-to-pruning weight ratio, leaf area-to-fruit ratio, pruning weight and leaf area per unit of length, and leaf area to canopy volume) as well as their optimal range for both single and divided canopies have been recently reviewed by Kliewer and Dokoozlian (2005, table 2).

The usefulness of these indices as gauges of severe vine unbalances (either over cropping status or excessive vigour) is ascertained; yet they are static (i.e. usually calculated at harvest) and their representativeness of the actual source (effective leaf area) characterizing a given canopy is still debated. As a matter of fact, pruning weight is not necessarily a good predictor of leaf area, hence "source" potential (Palliotti et al., 2004). The best example here is provided by minimally pruned vines where the one-year old cane pruning weight can be considerably lower than that formed by conventionally pruned vines, yet their leaf area is usually larger (Clingeleffer, 1993).

Undoubtedly, the leaf area-to-fruit ratio can better represent the source potential of a given canopy, but total leaf area is still quite difficult to be determined without adopting time consuming methods and a paper by Mabrouk and Sinoquet (1998) has highlighted that while this index is well correlated with sugar concentration (Table 3), it shows no correlation with other important grape quality traits (TA, colour and phenolics). The same paper also points out that the indices having a closer correlation with parameters of grape quality are the fraction of foliage gaps (FG) and the ratio of sunlit leaf area to yield; at the same time it is shown that a range of 1.21-3.35 m^2/kg for "total" leaf area to yield is reduced by 33% when the "exterior" leaf area is estimated and by 77% if the "sunlit" leaf area is computed through a sophisticated method of 3D canopy sampling. These findings underpin the importance of better assessing the "quality" of the foliage especially as related to light exposure.

4. Training System Vs. Grape Quality Targets

It is generally accepted that the training system represents a primary factor influencing canopy efficiency. Yet, determining if and when a canopy is "efficient" is a tremendous endeavour since this trait is a complex interaction of terroir, cultivar-genotype combination and vineyard management. However, focusing on radiation as being the most influencing environmental parameter and given a site location having a defined radiation availability, a grapevine canopy becomes efficient when it compromises between high light interception, adequate light distribution within canopy and effective dry matter partitioning to cluster and next year's renewal wood.

A key factor to reach such equilibrium is canopy density which, according to well known principles dictated by the relationship between leaf net photosynthesis and incident light should result in a leaf layer number comprised between 2 and 3. Studying "when" this happens is made especially troublesome by the multitude of canopy forms and geometries to which this species can be adapted. Therefore, a common problem is to extrapolate at the whole-canopy level the photosynthesis readings taken at the single-leaf level. In many cases, these are obtained on healthy leaves under optimal environmental conditions (full light, maximum boundary layer conductance) which represent one case-study; yet, the population of leaves composing the canopy experiences various degrees of exposure, ageing and healthiness which even the largest single-leaf sampling would hardly take into account.

Therefore, over the last 15 years, several working groups have set up and evaluated custom-built tree-enclosure systems which are able to wrap the entire canopy or portion thereof and provide, often under an automated and unattended fashion, direct evaluation of CO_2 and H_2O gas exchanges (Poni et al., 1997). The major drawback of this approach is that the system needs to be very well designed and the flow fed through the chambers carefully adjusted to reach the minimum alteration of the micro-environment inside the envelops (i.e. overheating and "pockets" with altered CO_2 concentration need to be avoided).

While the direct assessment of whole-canopy gas exchange cannot be certainly proposed as a user-friendly method for evaluation of grapevine canopy efficiency, it has to be recognized its value for studying basic principles of canopy physiology. The simplest approach would be to provide, for a series of training systems, a paralleled comparison of single leaf vs. whole-canopy derived gas exchange rates. Once the data are expressed on a per leaf area basis (i.e. μmol CO_2 m^{-2} s^{-1}), it is conceivable that the calculated differential represent "how much" the "whole canopy" is less efficient as compared to the ideal situation of a healthy leaf. In other words, the difference between the two calculated rates accounts for effects due to mutual shading, exposure and any factor influencing leaf function. The higher this differential the less efficient is the canopy.

Another worth-noting example is shown in Figure 4 where the pattern of canopy NCER is plotted against leaf area per vine. In that particular study, variability in vine leaf area was obtained by progressively removing internal leaves according to a decreasing level of shade (i.e. the most shaded were removed first). The left graph shows that beginning from the initial level of about 13 m^2 leaf area per vine, removing about 3.5 m^2 of foliage did not produce any significant lessening of NCER. Beyond the threshold of 9 m^2 leaf area per vine, NCER started to decline sharply suggesting that such level of vigour represented, for the specific site and vineyard condition, the optimal canopy filling (i.e. enough leaf area to fill the canopy volume and reach maximum photosynthesis with minimal effects of mutual shading).

The type of pruning (length, position and number of bearing units) can greatly influence the physiological performance of a training system. In fact, the same bud load per vine can be composed by changing one or more of the above factors and the effects on grape quality can be substantial. In a study conducted on cv. "Albana" trained to an arched-cane system, Baldini et al. (1974) recorded the growth of individual shoots from different buds along the cane at bloom and veraison (Figure 5). The findings showed a non-uniform leaf area of fruiting shoots at bloom, the variation coefficient (CV) being 33%, which was caused by the reduced growth in the mid-cane area. This non-uniformity of growth was even more pronounced at veraison, the CV being 37%. The content in soluble solids of clusters stemming from basal and apical shoots was comparable and higher than that of bunches that had developed from median shoots.

Subsequent trials (Poni and Volpelli, 1988) involving canes that were less-markedly bent or kept horizontally (e.g. Guyot) showed, especially in the latter case, a more uniform shoot growth at veraison (8% CV). Even better results were recorded with short-pruning systems (two-bud spurs), in which fruiting-shoot leaf area registered a mere 3% CV and soluble solids content was particularly uniform at harvest (Filippetti et al., 1991).

It is known that shortening of pruning mitigates the effects of apical dominance and promotes uniformity within the population of shoots forming a canopy. A noteworthy side-effect of short pruning is that mean fruitfulness of the shoot population decreases as a consequence of selection of less fruitful basal nodes and this usually makes less frequent the need for manual cluster thinning.

Overall, long-cane pruning has the advantage to be easy to perform, it overcomes the problem of low fruitfulness and, under this last connection, long pruning is psychologically more accepted since "cropping" is generally assured. On the other hand, cane pruning hinders full vineyard mechanization and aggravates physiological unbalances as compared to short pruning. Short (spur) pruning facilitates mechanization and builds over time larger carbohydrates reserves; moreover, if well conducted, it should lead to more uniform shoot growth, hence ripening. Yet, spur pruning needs more skilled workers and is mentally less accepted due to the feeling that cordons may suffer lack of vigor and productivity over time and will have to be renewed.

Berry composition is influenced by both the direct (light quantity and quality) and the indirect (temperature mediated) effects of sunlight exposure. Cluster location within the canopy and leaf density and arrangements around the fruiting area are the primary determinant of cluster exposure and indeed influenced also by the training system. Previous studies (Smart et al., 1985; Crippen and Morrison, 1986; Reynolds et al., 1986; Dokoozlian and Kliewer, 1996) have found that sunlight exposed fruits are generally greater in soluble solids, anthocyanins and phenolics and lower in titratable acidity, malate, juice pH and berry weight as compared to non-exposed or canopy shaded fruits. However, more recent findings have better clarified the effects of shade and exposure to light. For example, in a paper by Downey et al. (2004) where opaque boxes were applied to clusters of Shiraz grapes prior to flowering, shading did not affect berry weight, sugar, anthocyanin and condensed tannin concentration as compared to uncovered clusters. However, shaded clusters had a significantly reduced level of flavonols in the berry skin and a decreased proportion of malvidin, petunidin and delphinidin glucosides relative to peonidin and cyaniding glucosides.

The same paper along with others previously published (Bergqvist et al., 2001, Mabrouq and Sinoquet, 1998) then raises questions about the optimum range or amount of cluster exposure. Generally, the indication is that high temperatures rather than high light results in decreased total anthocyanins supporting the notion of inhibition of anthocyanin biosynthesis at high temperature. Moreover, high berry temperatures promote a shift from non-acylated glycosides and acetyl-glucosides towards coumaroylated anthocyanins which are known to be less readily extractable from the skin during fermentation (Leone et al., 1984). Therefore, an increasing number of studies are concluding that canopy management practices that provide high amounts of diffuse light in the fruiting zone rather then direct sunlight exposure, are best suited to warm regions.

To achieve such pattern, training system and canopy management need to be considered quite carefully. If the aim is to create a cluster microclimate mainly characterized by diffuse light enriched with sun-flecks, a upright growing, free canopy is probably the best suited. It should also be kept in mind that adequate air circulation around clusters not only diminishes the hazard for rot but, according to Rebucci et al, 1997, increases cluster transpiration which, to a certain extent, is positively correlated with the daily net sugar import by the berry.

In VSP trained canopies, the type of cluster microclimate from fruit-set onward is largely decided by timing and modalities of leaf removal. The choice is between a manual leaf removal, usually aimed at eliminating all the basal leaves around the cluster area and a mechanical leaf removal which typically strips off only a fraction of the leaves.

There are several reasons for which a severe manual leaf removal should be cautiously considered especially in warm climates: a recent study by Petrie et al. (2003) reported that leaf removal from the lower quarter of the canopy during the lag-phase of berry growth caused a significant reduction in whole-vine photosynthesis, even when expressed on a per unit leaf area basis, indicating that the lower portion of the canopy contributed more than the upper portion to the whole-vine carbon budget. Furthermore, removing all the leaves would cause an over-exposure of the clusters which can be detrimental to quality for the reasons named above. On the other hand, a mechanical leaf defoliation which typically retains some leaves or portion thereof would attenuate the drawbacks listed above.

The relationships between training system and grape quality can be clarified if methods become available to define the supply (leaf area, photosynthesis, light availability, light interception, reserves) and demand (maintenance of structures, crop-shoot-root-wood growth, and accumulate reserves) functions. Under such perspective, modeling represents the major resource, although the model should not be either too simple to avoid unrealistic behavior or too complex to become incomprehensible to users.

Quite recently a simplified grapevine model for prediction of daily carbon balance based on the user-friendly STELLA auto-programming software has been successfully validated for both Vitis labrusca and vinifera versus actual data of whole canopy net carbon exchange rates. The modeling approach and the required inputs are reported in Poni et al., 2004, 2005. In general, a model as such can be used as a tool for dynamic (seasonal) estimation of the CO_2 canopy balance as a function of training system (e.g. hedgerow or pergola) and/or pruning techniques. Moreover, due to the very friendly interface of the model, sensitivity analyses can be run by changing specific inputs and the resulting outputs can be attained in real time. For example, the model can aid training and pruning strategies in vineyard planning by simulating how daily and seasonal carbon fixation could be affected by an increased light interception achieved by modifying row spacing, canopy height or canopy thickness.

A more specific example of the model output in shown in figure 6 where the simulated carbon supply minus demand (shoot + fruit) is shown for conventionally (32 buds/m) vs. minimally-pruned "Concord" grapevines in New York. From the supply-demand functions comparison (top frame) it appears that there is an excess in the carbohydrate supply in the period around bloom (usually greater in MP vines due to the early canopy development and the earlier decline in shoot demand compared to the heavier pruning that stimulates longer shoot growth periods) and that MP vines are not able to meet the large demand of the ripening crop. Yet, it should be emphasized that these simulations were for a quite heavy crop of 27 tons/ha in the short, cool season in New York. In the bottom frame on the same graph, the two periods of positive carbohydrate supply (around bloom and pre-veraison) coincide with the main periods of fine root production observed in the field in NY. Thus, root growth may be limited by competition for carbohydrates by the shoots and crop, although early season root production from bud-break through bloom is likely supported also by root carbohydrate reserves. The pre-veraison peak of root growth does appear to be related to the current season carbohydrate supply availability with a rapid drop in root production after veraison when the crop demand peaks.

All in all, we feel that thinking that "good" and "bad" training system do exist is, physiologically speaking, quite wrong. Good results can be achieved with a variety of training systems provided that they are correctly integrated to the environment and well trained and managed. Yet, a tendency towards highly-mechanized spur pruned systems is manifested in several viticulture countries and more efforts will be needed in the future to achieve a better interaction between mechanization and "terroir".

Literature cited

Baldini E., Intrieri C., Marangoni B., Toscano A. 1974. Primi rilievi fenologici e produttivi su vigneti trasformati per la raccolta meccanica con vendemmiatrici non scavallatrici. Atti Acc. It. Vite e Vino, Vol. XXVI, 191-204.

Bergqvist J., Dokoozlian N., Ebisuda N. 2001. Sunlight exposure and temperature effects on berry growth and composition of Cabernet Sauvignon and Grenache in the Central San Joaquin valley of California. Amer. J. Enol. Vitic. 52: 1-7.

Clingeleffer, P.R. 1993. Vine response to modified pruning practices. Proc. 2nd N. Shaulis Grape Symp. on Pruning mechanization and crop control, Fredonia, NY, July 13-14, USA, p.20-30.

Crippen D.D., Morrison J.C. 1986. The effects of sun exposure on the compositional development of Cabernet Sauvignon berries. Amer. J. Enol. Vitic. 37:243-247.

Dookozlian H.K., Kliewer W. M. 1996. Influence of light on grape berry growth and composition varies during fruit development. J. Amer. Soc. Hortic. Sci. 121: 869-874.

Downey M., Harvey J.S., Robinson S. 2004. The effect of bunch shading in berry development and flavonoid accumulation in Shiraz grapes. Austr. J. Grape Wine Res. 10:55-73.

Eynard, I. and Dalmasso, G. 1990. Viticoltura moderna. Ulrico Hoepli, Milano.

Filippetti I., Intrieri C., Silvestroni P., Poni S. 1991. Effetti sulla potatura corta e lunga sulla sincronizzazione fenologica e sul comportamento vegetativo e produttivo della Cv. Sangiovese (V. vinifera L.). Vignevini 12: 41-46.

Kliewer, W. M. and Dokoozlian, N.K. 2005. Leaf area/crop weight ratios of grapevines: Influence on fruit composition and wine quality. Am. J. Enol. Vitic. 56: 170-181.

Intrieri C., Poni S., Filippetti I., Silvestroni O., Colucci E. 1992. Indagini poliennali su forme di allevamento della vite tradizionali e innovative in Emilia-Romagna. Vignevini 10: 29-35.

Lakso A.N., Poni S. 2005. "Vitisim" – a simplified carbon bilance model of a grapevine. Proc. 14th Gesco, 23-28 August, Geisenheim, p. 478-484.

Leone A.M., la Notte E., Gambacorta G. 1984. Gli antociani nelle fasi di macerazione ed elaborazione del vino. L'influenza della tecnica diffusiva sulla loro estrazione. Vignevini 4: 17-31.

Mabrouk, H. and Sinoquet, H. 1998. Indices of light microclimate and canopy structure of grapevines by 3D digitising and image analysis, and their relationship to grape quality. Austr. J. Grape and Wine Res. 4: 2-13.

Palliotti, A., Silvestroni, O., Cartechini, A., Neri, D., Mattioli, S. and Nasini, L. 2004. Seasonal carbon bilance of Sangiovese grown in two different central-Italy enivironments. Acta Hortic. 662: 183-190.

Petrie, P.R., Trough, M.C.T., Howell, G.S. and Buchan, G.D. 2003. The effect of leaf removal and canopy height on whole-vine gas exchange and fruit development of Vitis vinifera L. Sauvignon blanc. Func. Plant Biol. 30: 711-717.

Poni S., Volpelli P. 1988. Gradienti vegetativi dei germogli di vite in rapporto alla posizione dei capi a frutto. Vignevini 1-2: 59-64.

Poni, S., Intrieri, C. and Magnanini, E. 1997. An automated chamber system for measurements of whole-vine gas exchange. HortScience 32 : 64-67.

Poni, S. and Intrieri C. 2001. Grapevine photosynthesis: effects linked to light radiation and leaf age. Adv. Hort. Sci. 15: 5-15.

Poni S., Bernizzoni F., Presutto P., Rebucci B. 2004. Performance of Croatina to Short Mechanical Hedging: A Successful Case of Adaptation. Am. J. Enol. Vitic. 4, 379-387.

Poni, S., Paliotti, A., Silvestroni, O., Mattii, G.B., Intrieri, C. and Nuzzo, V. 2004. Validazione e applicazioni del modello Stella per l'analisi dell'efficienza del vigneto. L'Inf. Agrario 43: 101-111.

Poni, S., Palliotti, A. and Bernizzoni F. 2005. Calibration and evaluation of a STELLA-software based daily CO2 balance model inVitis vinifera L. J. Amer. Soc. Hort. Sci., accepted.

Rebucci B., Poni S., Intrieri C.. Magnanimi E., Lakso A.N. 1997. Effects of manipulated grape berry transpiration on post-veraison sugar accumulation. Austr. J. Grape Wine Res. 2: 57-65.

Reynolds A.G., Pool R.M., Mattick L. 1986. Influence of cluster exposure on fruit composition and wine quality of Seyval blanc grapes. Vitis 25: 85-95.

Shaulis N., Amberg H., Crowe D. 1966. Response of Concord grapes to light, exposure and Geneva Double Curtain. Proc. Amer. Soc. Hortic. Sci., 89: 268-280.

Silvestroni O., Palliotti A. 2005. Distanze di Impianto. In: Manuale di viticoltura: impianto, gestione e difesa del vigneto. Ed agricole, Bologna, p.135-154.

Smart R.E., Robinson J.B., Due G.R., Brien C.J. 1985. Canopy microclimate modification for the cultivar Shiraz II. Effects on must and wine composition. Vitis 24: 119-128.

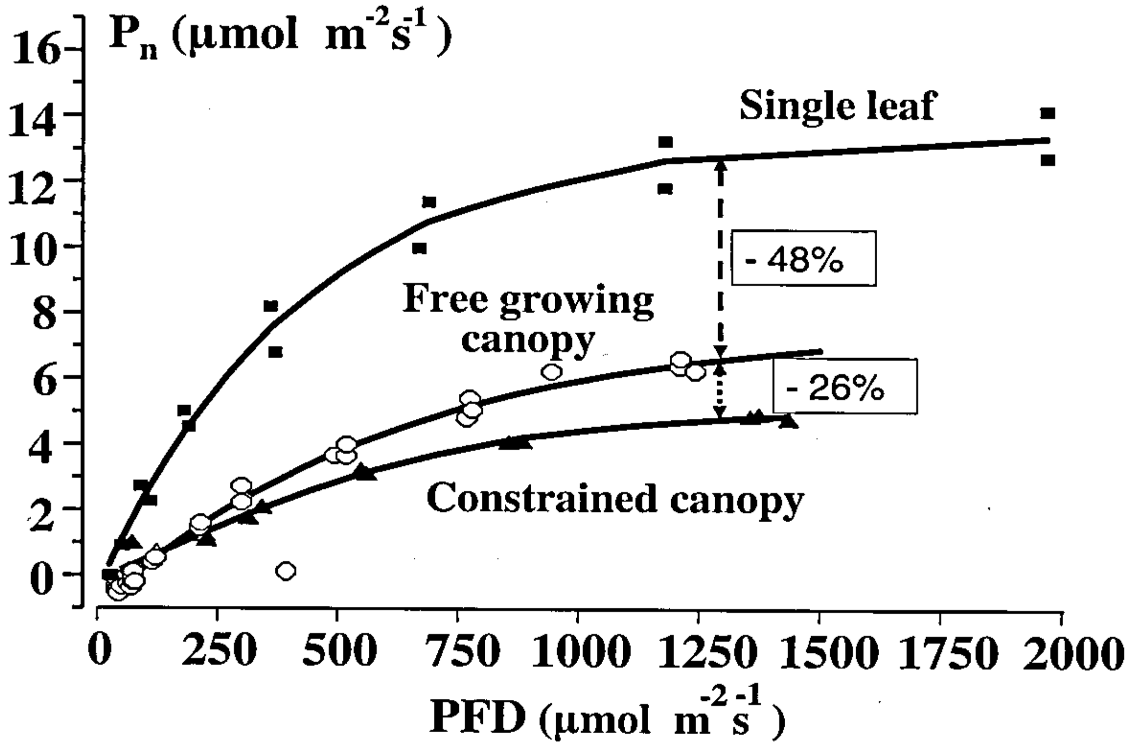


Fig. 1. Light response curves for a single leaf and two canopy types (free growing and constrained). Source: Poni and Intrieri, 2001.

Table 1. Influence of manual (HP) and mechanical pruning treatments on growth, yield and grape quality of "Croatina" vines. TLA = total leaf area per vine. From Poni et al. 2004.

Source of variation	Nodes/vine	Budbreak (shoots/node)	TLA/vine (m^2)	Yield/vine (kg)	TLA/yield (m^2/kg)	Soluble solids (°Brix)	Anthocyanins (mg/g FW)	Phenolics (mg/g FW)
Pruning								
HP	37.5 d	0.91 a	4.79 b	2.82 c	1.70	20.7 a	1.34 a	2.96 a
SMP-SF	50.5 c	0.89 a	5.02 b	3.48 b	1.44	20.4 ab	1.34 a	2.93 a
SMP-LF	60.0 b	0.81 b	5.88 a	3.67 ab	1.60	20.4 ab	1.28 a	2.95 a
MMP-LF	75.2 a	0.74 c	5.10 b	4.19 a	1.22	19.7 b	1.18 b	2.79 b
Significance	**	**	*	*	ns	*	*	*
Pruning x year interaction	ns	**	*	*	ns	ns	ns	ns

Mean separation within columns by Duncan's test. ns = non significant; *,** significant at 5% and 1%, respectively.

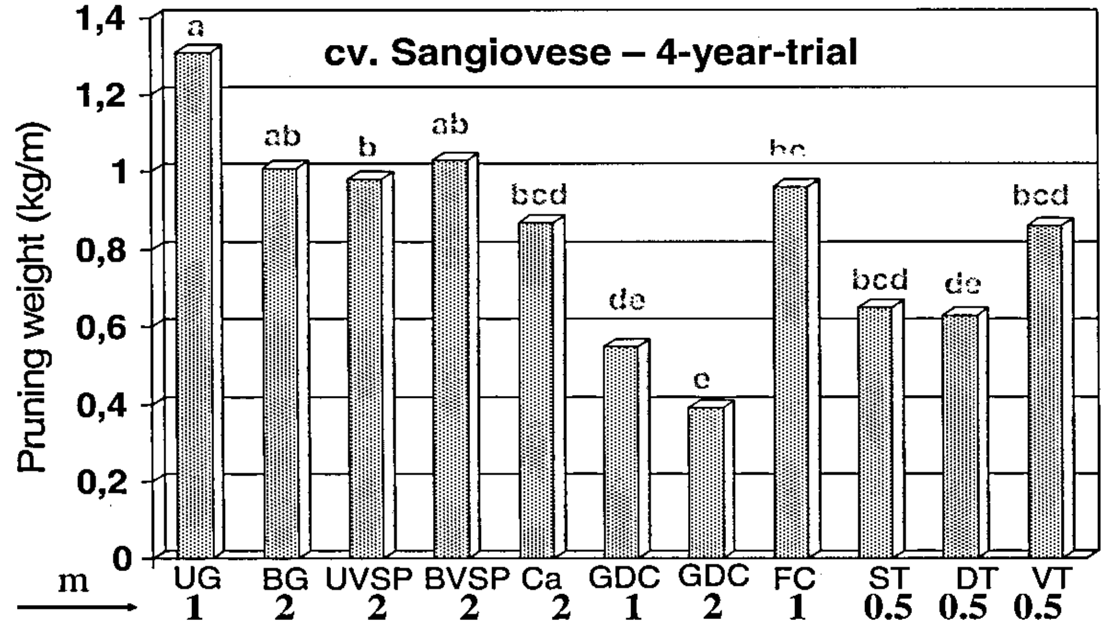


Fig. 2. The effect of different training systems on pruning weight per meter of canopy. UG = unilateral Guyot; BG = bilateral Guyot; UVSP and BVSP = unilateral and bilateral vertically shoot positioned; Ca = Casarsa; GDC = Geneva Double Curtain; FC = free cordon; T = narrow T trellis; CV = vertical cordon. Vine spacing in the row is indicated below x-axis. Mean separation by SNK test, 5% level. Source: Intrieri et al., 1992.

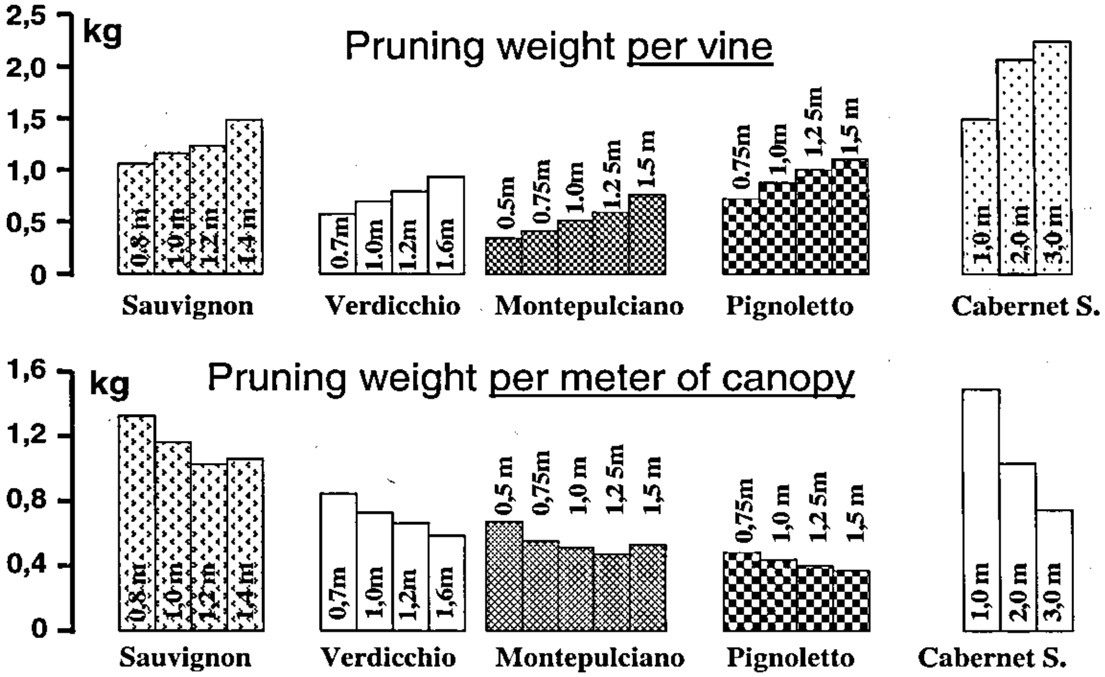
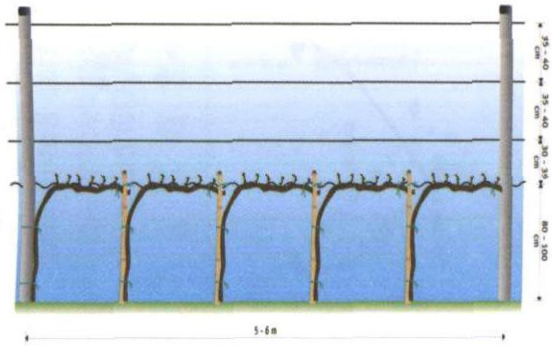


Fig. 3. Pruning weight per vine and meter of cordon recorded in different trellises and locations. Vine spacing in the row is specified in the histograms. For details see Silvestroni and Palliotti, 2005.

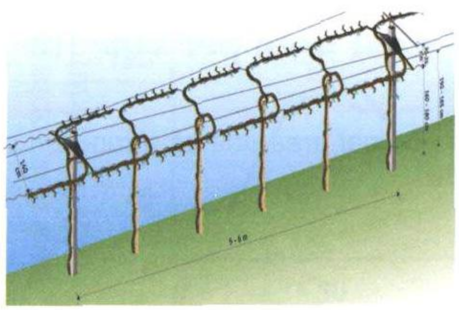
Table 2. Vine balance indices and their optimal range for single and divided canopies. From Kiewer and Dokoozlian, 2005

Single-canopy



Index	*Optimal range*
Y/PW (kg/kg)	4-10
LA/Y (m^2/kg)	0.8-1.2
PW/m (kg)	0.5-1.0
LA/m (m^2)	2-5
LAD (m^2/m^3)	3-7

Divided-canopy



Index	*Optimal range*
Y/PW (kg/kg)	5-10
LA/Y (m^2/kg)	0.5-0.8
PW/m (kg)	0.4-0.8
LA/m (m^2)	2-4
LAD (m^2/m^3)	3-6

Table 3. Correlation coefficients of grape quality parameters with various canopy structure indices. Cv. Merlot. ***From Mabrouq and Sinoquet, 1998***

Index	**°Brix**	**TA**	**Color**	**Phenolics**
LA_v/Y	**0.85**	**ns**	**ns**	**ns**
SfA_c/Y	**0.94**	**ns**	**ns**	**ns**
LA_{ext}/Y	**0.91**	**ns**	**ns**	**ns**
$FSfA_{exp}/Y$	**0.94**	**ns**	**ns**	**ns**
SD/m	**-.75**	**ns**	**-0.83**	**-0.72**
LA/m^3	**ns**	**ns**	**-0.74**	**ns**
FG	**0.76**	**-0.74**	**0.87**	**0.85**
LA_v/SfA_c	**ns**	**-0.75**	**ns**	**ns**
LA_{ext}/LA_v	**ns**	**ns**	**0.76**	**ns**
LA_{sl}/Y	**0.95**	**ns**	**0.72**	**0.75**

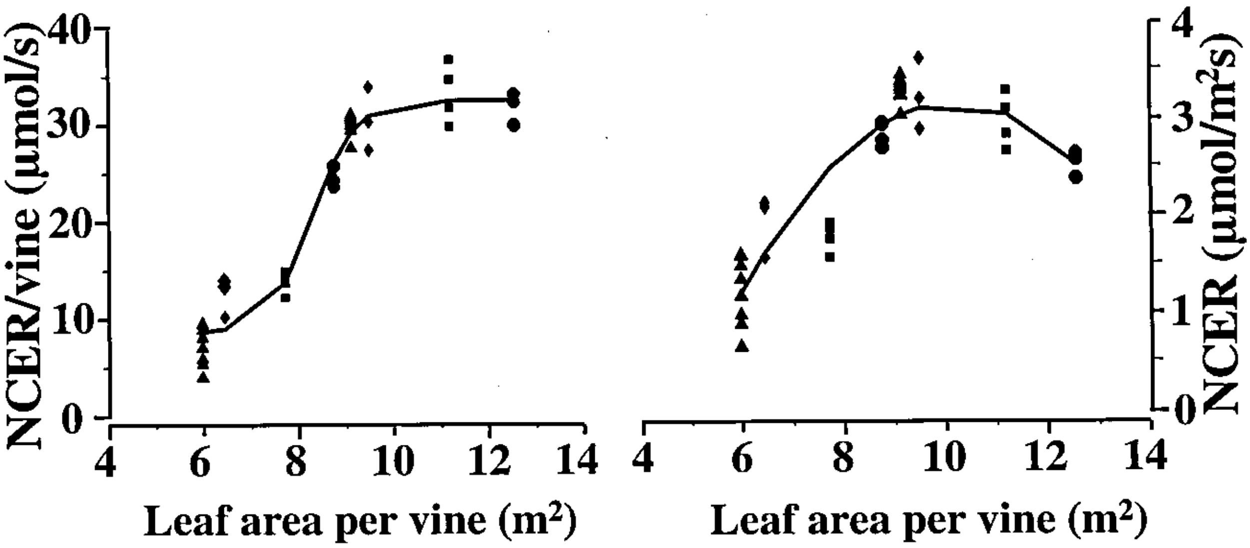


Fig. 4. Net CO_2 exchange rate (NCER) per vine and per leaf area unit as a function of leaf area per vine. Source: Poni and Intrieri, 2001.

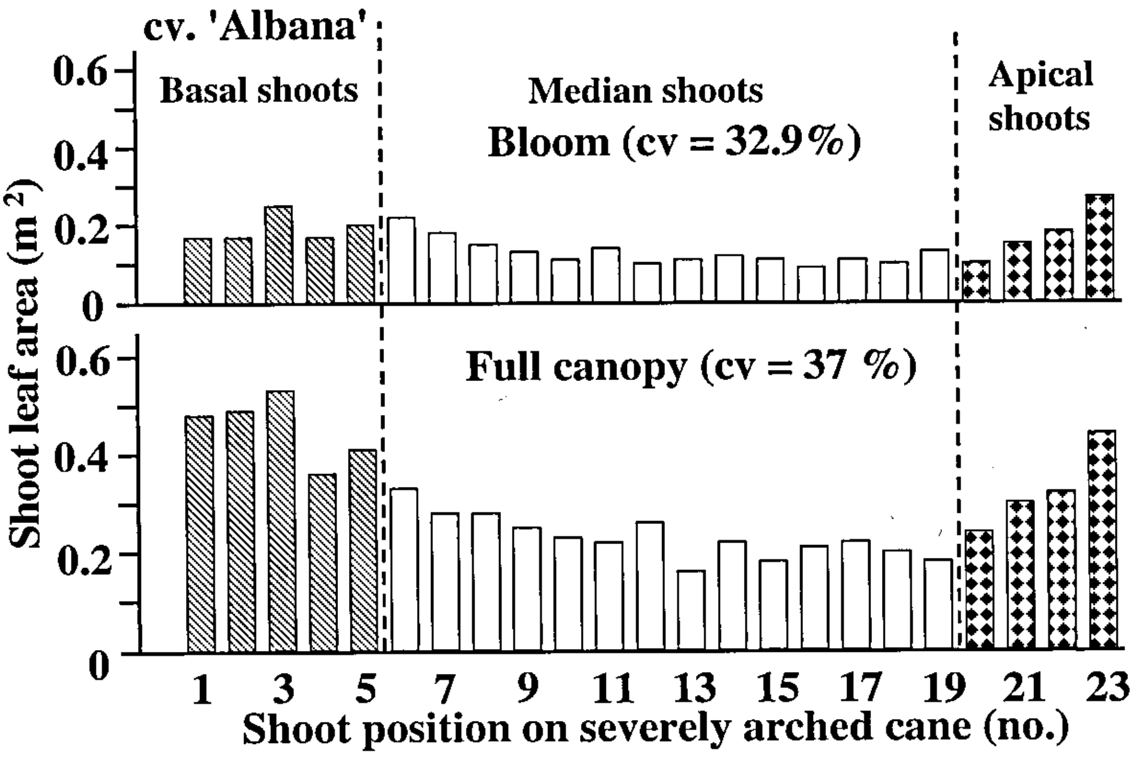


Fig. 5. Variation of shoot leaf area according to shoot insertion on the cane. CV = variation coefficient. Source: Baldini et al., 1974.

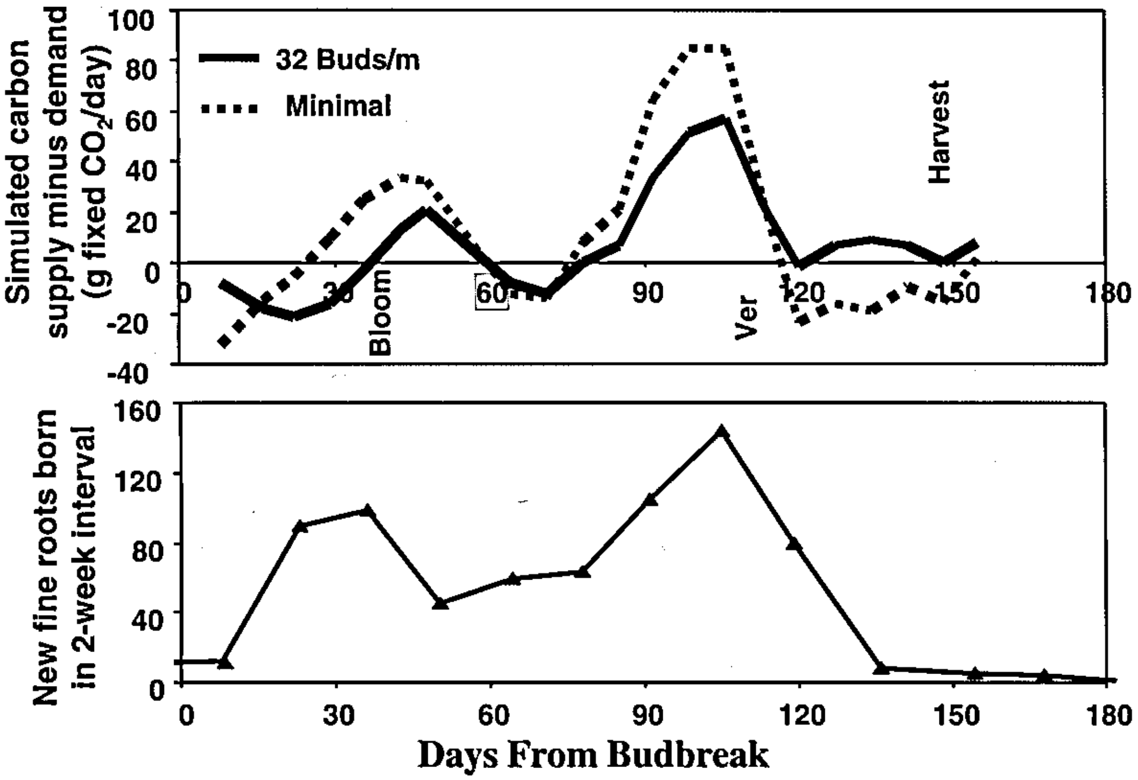


Fig. 6. Comparison of simulated carbon balances to observed patterns of fine root production. Source: Lakso and Poni, 2005.