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*Review Article*

# Climate Change Affects Choice and Management of Training Systems in the Grapevine

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Although vertical shoot positioned (VSP) training systems, either cane- or spur-pruned, are adopted in the great majority of the vineyards worldwide, the lianas nature of the grapevine and the presence of long and flexible canes confer high plasticity and render structural and pruning changes quite easy. The focus of this review is if, in light of the most consistent features triggered by global warming (e.g., longer growing season, earlier phenology, faster ripening, higher incidence of overheating stress and sunburn, higher frequency of extreme weather events), the type and management of training systems should also be reconsidered. We surveyed the main methods to assess training system efficiency and the current attempts and outlook toward exploiting the training system as an adaptation tool to climate change. For the latter, we considered 12 main trellis types and scored them based on climate-related features and general traits such as vigor, yield control, susceptibility to fungal diseases, and suitability according to wine types (still or sparkling). The resulting balance of positive and negative recommendations leads to a re-evaluation of either old, nonmechanizable trellis types (e.g., Raggi-Bellussi and pergola types), divided canopy systems (e.g., GDC and Scott Henry) or, among the single canopy types, of the single high wire (SHW) trellis. However, historical systems traditionally used by best regions and producers (e.g., goblet and VSP either cane- or spur-pruned) overall show less adherence to the chosen evaluation criteria. To direct future evolution of training systems, regardless of the broadly shared need for suitability to partial or full mechanization, the scenario looks different depending on cool and temperate (warm) areas. The former experiences an outburst of interest as warming is broadening growing areas and affordable genotypes. Under such circumstances, training systems should help accelerate or favor the ripening process through vigor control and lower yield, better cluster exposure, and nonlimiting leaf area-to-fruit ratio. Whereas, in warm areas that are now becoming sub-tropical areas in the worst cases, the SHW gains credit as compared to goblet and traditional VSP. The latter requires an increasing number of canopy manipulations and a rethinking of some planting choices to accommodate the needs of slower and more delayed ripening, more cluster shading, and higher cordons, the latter reducing the probability of incurring significant frost damage.

## 1. Introduction

The last published review on grapevine training systems dates back to 2009 [1]. Since then, the number of papers devoted to the topic has been limited. The general perception is that themes such as training systems and related items (e.g., vine spacing and pruning methods) fall within a sort of traditional viticulture which attracts less funding than other areas of research, which raises less interest than better-funded areas of research (e.g., smart or precision viticulture). However, with the harmful effects of global warming increasing in severity and frequency—observed more in Mediterranean areas [2] and in some other warm districts of the New World viticulture [3]—the role of a training system as an adaptation tool to climate change is gaining importance. In the grapevine, this role is facilitated by the astonishing plasticity of the plant to be modeled into many different shapes and geometries, mostly due to its lianas nature and the presence of long, flexible, and malleable canes.

Moreover, recent work conducted on grapevine training systems [4] using an untargeted metabolomic approach has interestingly shown that three main groups encompassing vertical shoot positioned (VSP) canopies, hanging shoot (sprawl) canopies, and minimally pruned canopies generate a metabolic signature, which can be consistently found in the final wines. These findings seem to reposition training systems to a higher level suggesting that preferring one category over another may already hint at a given compositional target.

This review will use VSP vs sprawl canopy types as the main categorizations of grapevine training systems and will aim to (i) summarize the most recent findings in terms of physiological efficiency and vine performance; (ii) deepen the role of the training system as an adaptation tool to climate change; (iii) determine if the training system itself has an impact on the incidence and severity of some serious grapevine diseases; and (iv) provide an outlook to probable future orientations for training system choices.

## 2. Vertical Shoot Positioned (VSP) vs Spreading Type

There is some logic in assuming that VSP vs. free growing canopy types (Figure 1) are the most meaningful comparisons. Although reliable data are difficult to obtain, both of them belong to the hedgerow training system category, which likely encompasses nearly 70% of the current world vineyard acreage. Moreover, while VSP training perfectly represents the natural status of a liana plant eager to climb onto trees or any other possible support, its conversion into spreading ("sprawl") is somewhat revolutionary. The concept of vegetative habitus [5], common in other fruit tree crops, has now been introduced and, with it, the importance of having a mostly upright or downward growth is now well perceived. Before attempting any direct comparison of VSP and spreading canopy efficiency and vine performance, several authors [1, 6, 7] have stressed the importance of a correct supporting frame for each type of vine training and pruning. This is well coded in VSP where a key factor is having a narrow, vertical canopy extension which, in regard to other site factors, will avoid the main source limitation for ripening while assuring optimal light interception and minimizing mutual row shading. At the most common latitudes for wine grape growing, the latter goal is achieved by attaining a close to 1 : 1 ratio between maximum canopy height and between-row spacing [8].

In case of spreading types, the optimal canopy arrangement is more debated. In humid cool climates, especially when big leaf size cultivars such as Concord or Isabella (*Vitis labrusca B. x Vitis vinifera* L.) are grown, a downward habit is preferred [9, 10], whereas, in most Mediterranean areas, the interest is around single-high wire (SHW) cordon trellis. By maintaining a mostly upright canopy, it assures better cluster protection against berry dehydration and sunburn [11]. Technically speaking, while a downward habitus is rather easy to obtain—growers just need to wait until the shoots start to bend and eventually, a close-to-the ground trimming can be mechanically performed—promoting and/or maintaining an upright growth in a relatively narrow form is anything but obvious. In fact, the pattern of growth is primarily cultivar-dependent (i.e., Cabernet Sauvignon and Franc usually maintain a beautiful upright growth) and grower-dependent (e.g., a prebloom light shoot trimming is very useful to ameliorate the habit of reluctant varieties such Pinots). On the other hand, increasing the length of the pruning bearers at more than three count nodes will unavoidably favor a procumbent canopy.

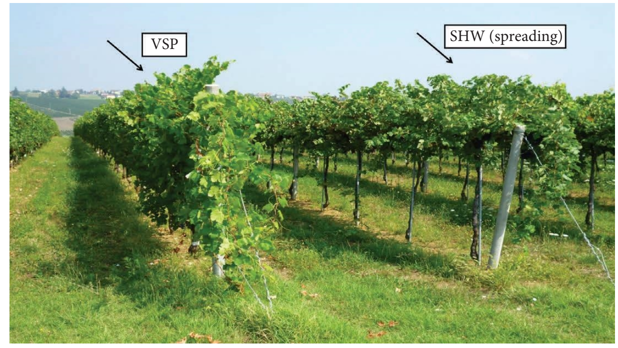


Figure 1: Left: a typically vertically shoot positioned (VSP) row of Barbera managed with spur pruning. Right: a single high wire (SHW) row with spur pruning showing a mostly erect free shoot growth (sprawl canopy).

In terms of planting, training, and management costs [7, 12, 13], the SHW cordon is a winner as compared to VSP due to less foliage wires and accessories, faster winter pruning regardless of the mechanization used, minimal need for shoot thinning, shoot positioning, and leaf removal, etc. However, the agronomic superiority of either canopy type has not been ascertained in full. A few long-term comparisons between different training systems [13–19] have supported the conclusion that if a given training system is correctly established and managed, major differences in yield and grape composition might not occur.

The above statement does not imply that assessing physiological performance of VSP as compared to spreading is unnecessary. A recent review paper by Yu et al. [20] indicated that, as compared to traditional VSPs, sprawl trellis systems could increase the efficiency of grapevine canopies at promoting total soluble solids (TSSs) accumulation, yield, and the capacity for flavonols and anthocyanins' accumulation in berry skins with less chemical degradation. However, this comparison faces a classic methodological problem. The superiority of one canopy structure over another is likely to depend on how the extraordinarily complex population of leaves forming a canopy interacts with environmental and endogenous factors, which, in association with the scion/rootstock combination, determines the ripening and wood maturation potential.

So far, the most common approach has been to take the risk of upscaling single leaf responses to the whole canopy level. Functional structural plant models [21–23] have been published that integrate different models that calculate intercepted radiation, leaf traits (e.g., nitrogen content), and gas exchange for each leaf in the canopy. The results have been encouraging yet inconclusive. The 3D canopy modeling approach to simulate canopy structure presented in Louarn et al. [21] concluded that nonpositioned (spreading) canopies enable the possibility to associate high light interception, more favorable cluster microclimate, and reduced labor-intensive practices for moderate vigor vineyards as compared to VSP. When the same model was coupled with photosynthesis and canopy conductance models that consider light-driven variations in N distribution, the modeled whole-canopy gas exchange values were successfully validated for each canopy type against measured rates assessed via an enclosure system (error was less than 10%). However, gas exchange data were on either a vine or soil surface basis and no expression was available per unit of leaf area. Therefore, actual differences between training systems were undetermined.

An alternative approach is to directly measure whole canopy net $CO_2$ rates (NCER) using a vine enclosure system ([24]) which, however, still has to deal with variability in total leaf area and, with it, different patterns of light exposure, aging, etc. Such factors were cleverly evaluated in the work done by Poni et al. [25, 26] where whole-canopy NCER exchange was monitored on the same vines manipulated to two different forms. Initially, NCER measurements were done under a sprawl habitus and then constrained between catch wires to simulate the structure of a traditional VSP training system (Figure 2). Results showed that the free-growing canopy achieved 26% higher whole-canopy photosynthetic rates, very likely due to better light penetration into the inner canopy layers. A VSP configuration also achieves lower mid-day total vine light interception. This conclusion is strongly supported by the work from Louarn et al. [21] that showed that light interception efficiencies and proportions of sunlit leaf area (SLA) were 25–30% lower for a VSP canopy with two catch wires as compared to a bilateral free cordon for intermediate Leaf Area Index (LAI) values.

Another very good reason to favor an upright-spreading shoot growth in a SHW system is that any winter mechanical pruning is greatly facilitated, and hence, is faster, as compared to a procumbent canopy [27]. Obviously, having the great majority of the pruning wood located in the upper 180° of the canopy volume (Figures 3(a)–3(c)) makes it very easy to be intercepted by a reverse C cutter bar profile. Even in a single passage, it can assure removal of not less than 90% of the pending wood. This eases follow-up by hand for quick finishing [28, 29]. On the contrary, as long as the growing habit becomes more procumbent, an increasing number of canes will escape the cutting profile, especially those inserted on a ventral position to the cordon while posts will become increasingly obstructed worsening visibility of the machine driver. Therefore, it will require more accurate and time-consuming hand finishing (Figures 3(d)–3(f)).

## 3. Divided Canopies and Other Variants

It is known worldwide that the pioneer of a divided canopy training system was Shaulis et al. [30], who proposed the Geneva Double Curtain (GDC) system adapted on procumbent Concord vines. The initial goal of the GDC was to essentially replicate close row spacing and its greater light interception and yield potential by having close canopy spacing but wide trunk spacing. This gave higher yields of acceptable sugar concentration but allowed the larger tractors and sprayers to have access by pushing the hanging canopies aside. High yields were critical for low-value varieties such as Concord. Also, GDC reduced canopy density in high pruning weight vines but was not suitable for weaker vines.

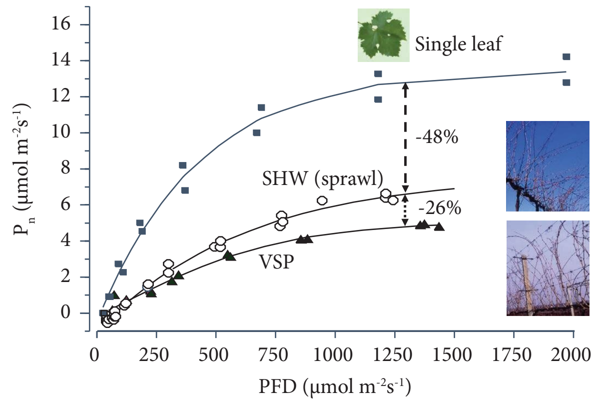


Figure 2: Light saturation curves that correlate the intensity of the incident radiation (PDF) to the net photosynthesis ($P_n$) in Sangiovese leaves and in two training systems, SHW and VSP. The percentages indicate, in correspondence with the light saturation point, the extent of the reduction in $P_n$ with respect to free canopy vs. single leaf (−48%) and palisade canopy wall vs free canopy (−26%). Different PFD levels were obtained by superimposing on the leaf or the whole canopy chamber a different number of layers of black mesh (45% light transmission). Redrawn from [26].

Further elaboration of how the original system was adapted to *Vitis vinifera* cvs. and integrated better with pruning and harvesting machinery has been provided afterward [7, 31] (Figures 4(a) and 4(b)). The introduction of the horizontally split GDC canopy has been revolutionary under two primary perspectives. First, aside from the peculiar case of low-trained bush vines (alberello type) not needing any support and, therefore, presenting a natural spreading canopy, the GDC is the first to bring the concept of free growing shoots on a fairly large and expanded trellis as no foliage wires were foreseen. Second, the horizontal canopy split allowed by the GDC also shed new light and possibilities in terms of yield-quality relationship in the vineyard. Here is a numerical example: a comparison between a standard spur-pruned VSP system planted at 1.20 m spacing in a row and a GDC system planted at 60 cm in a row. Each vine will have the same bud load (e.g., 12 count nodes per vine) and we assume that grape quality will not change much since yield per vine or per meter of canopy length is very similar. However, when this is taken to a hectare basis, the balance is in favor of the GDC system. At an average row spacing of 4 m, the GDC system develops 5,000 m of productive cordon against the 4,000 m that a VSP trellis planted at 2.5 m between rows can empower. Thus, the GDC system might achieve higher yield levels at similar grape quality by simply exploiting higher cordon investment per surface area.

Instead, if vine spacing in the row is not changed as compared to a single canopy, then regardless of the type of canopy splitting—Smart Dyson and Scott Henry for

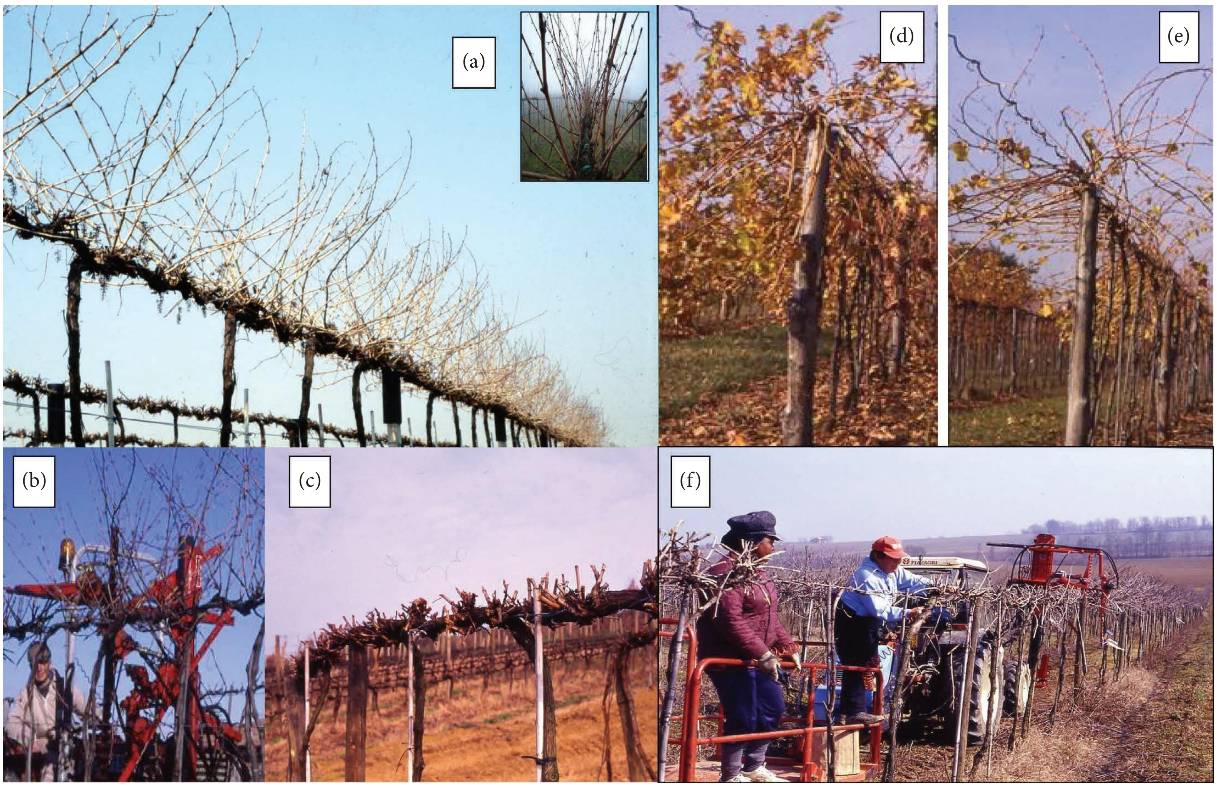


Figure 3: (a) Structure of a SHW-trained Cabernet sauvignon row showing a beautifully erect canopy pattern. In the inset, it can be better appreciated how all canes are framed within the upper 180° of the canopies. (b) A pruner machine with cutter bars performing an easy mechanical pruning which, due to the ideal canes position, does not require any hand follow-up. Final view after the machine work is shown in panel (c). (d, e) Two SHW trained rows showing a definitely downward growing canopy (Trebbiano Romagnolo in (d)) or intermediate canopy (Chardonnay in (e)). In both cases, manual follow-up (f) becomes mandatory to lower total nodes per vine and remove canes inserted in ventral cordon positions.

a vertical splitting, GDC and Lyra for horizontal splitting—the expected effect is canopy weakening based on the largely different bud loads per vine [1, 8]. So, it is no surprise that the GDC system is a good fit for the vigorous Lambrusco family grown in the fertile Po Valley in Italy; similarly, Scott Henry is gaining popularity in the Finger Lakes region in the US under wet conditions. Likewise, some recent work confirms that, once the chosen divided canopy fits well with the objective need of controlling excessive vigor, higher yields associated with unaltered or even improved quality are possible [32–39].

Overall, the adoption of divided canopy trellis system models is still very limited on a worldwide basis. Especially for the GDC system, it has significantly shrunk over the last decade (i.e., Northern and Central Italy, Upstate NY, etc.). This is due to two main reasons. First, as originally postulated by Nelson Shaulis, the GDC trellis is valid if physical separation is maintained between the two parallel curtains (Figure 4(b)). If they start to overlap, the inner trellis space will progressively fill and the canopy will be transformed into an umbrella or pergola type [1]. As the GDC system is suited to high vigor environments per se, curtain separation over time must be assured through hand shoot positioning, which has a narrow time window for optimal execution and is also time-consuming (not less than 25–40 h/ha needed). In most cases, growers drop the operation and, with that, most of the advantages pertinent to a split canopy are lost. A clever solution proposed to alleviate the labor burden for hand shoot positioning on the GDC system [7] has been sporadically adopted, which consists of mounting swinging arms along a row so that a quick opening would create a physical barrier that prevents shoots from growing inward (Figure 4(c)). Second, and most importantly, due to its supporting structure, the GDC system requires vertical mechanical harvesters. However, their production and improvements have been progressively abandoned by the industry due to the very limited planted acreage [7].

Over the years, some modifications of the more traditional divided canopy systems (i.e., GDC, Scott Henry, and Lyra) have been proposed to preserve high or full suitability to mechanization, reduce the tendency to overcrop, and improve final grape composition through ameliorated leaf area-to-fruit ratio or improved cluster morphology and microclimate [31, 40]. Among these, the most pertinent seems to be the COMBI [41] and the SAYM training systems [42]; the latter inspired by a foldable Lyra system ([43]). The former was designed to incorporate the advantages inherent in the GDC system and California U-trellis [44]. The vines are spaced 50–70 cm along the row and every other cordon is deployed on the outside wires about 110–120 cm from the

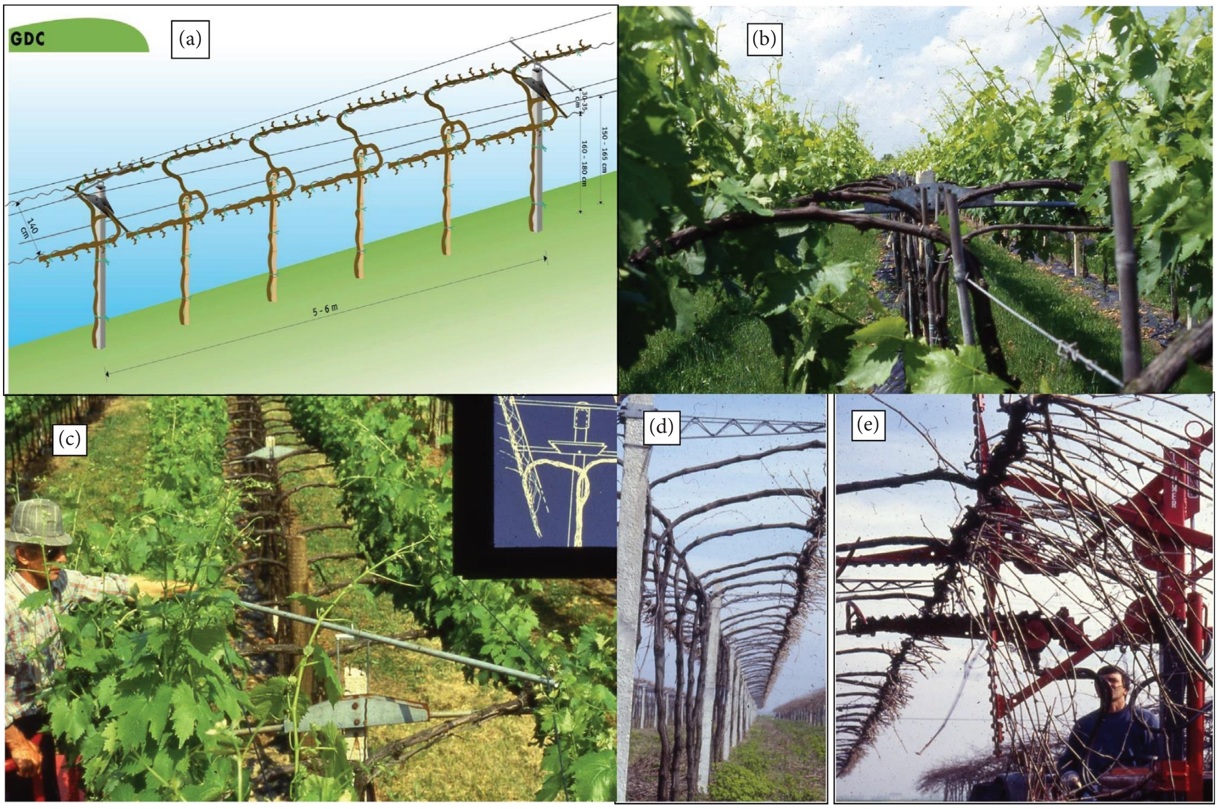


Figure 4: (a) A diagram of a modern version of a Geneva Double Curtain (GDC) trained row also featuring a device for semi-automated shoot positioning. When shoots start showing the tendency to grow inward (b), a metal T bar is rotated to position two extra wires above the main wires to avoid overlapping between the two adjacent canopies (c). A positive consequence of this operation is that, at the timing of winter pruning, the largest majority of canes are directed outward (d), thus facilitating any mechanical pruning approach (e).

ground to create two parallel VSP walls by paired foliar wires, with the U-trellis at every three to four posts. The main support wires are strung through brackets to enable vertical shaking of each wall. The COMBI can be mechanically pruned in summer and winter with the same multiple-bar unit regularly used for GDC winter pruning [7]. While the COMBI cleverly resolves the issue of hand shoot positioning and assures physical separation of the two canopy walls over the season, the high planting costs and the need for mechanical harvesting using a vertical pivot have contributed to its limited adoption.

The SAYM training system [42] is a dynamic version of a Y or traditional Lyra system [45] and employs a 1.1 m, V-shaped galvanized iron frame with an overall aperture angle of 50°, which is used to keep the canopy in two sloping walls until, just before harvest, the two wings are lifted to form a single canopy that facilitates both mechanical harvest and winter pruning. According to the five-year evaluation, as compared to a standard VSP trellis, the SAYM was able to reduce the incidence of bunch rot and improve grape and wine quality (alcohol, anthocyanins, phenolics, tannins, and color intensity), while maintaining an adequate yield (about 13 t/ha) without significantly increasing the management operations of the vineyard.

## 4. Efficiency of Diverse Training Systems: Still an Open Issue

A challenging task is to define when and why a given training system can be deemed efficient. This is due to the complexity and variability of the grapevine training systems [1], which also link to the lianas characteristics of the species and its adaptability to be directed toward various forms and geometries. The first milestone was set by Nelson Shaulis who recommended optimization of the light available in the fruiting zone for desired fruit microclimate and quality and for flower bud development [46]. Then, it can be added that an efficient training system finds the best compromise between light interception and light distribution within the canopy while also assuring balanced dry matter partitioning to clusters and renewal wood. Moreover, efficiency should also encompass suitability to at least partial or full mechanization. Figure 5 shows 12 out of the many training forms possible [1] and renders an idea of how methodologically hard it is to provide fair comparisons. Besides the varying geometries, the complexity primarily arises from the interacting factors coming into play when the population of leaves and clusters composing the canopy is taken into consideration. Among them, patterns in age, light exposure,

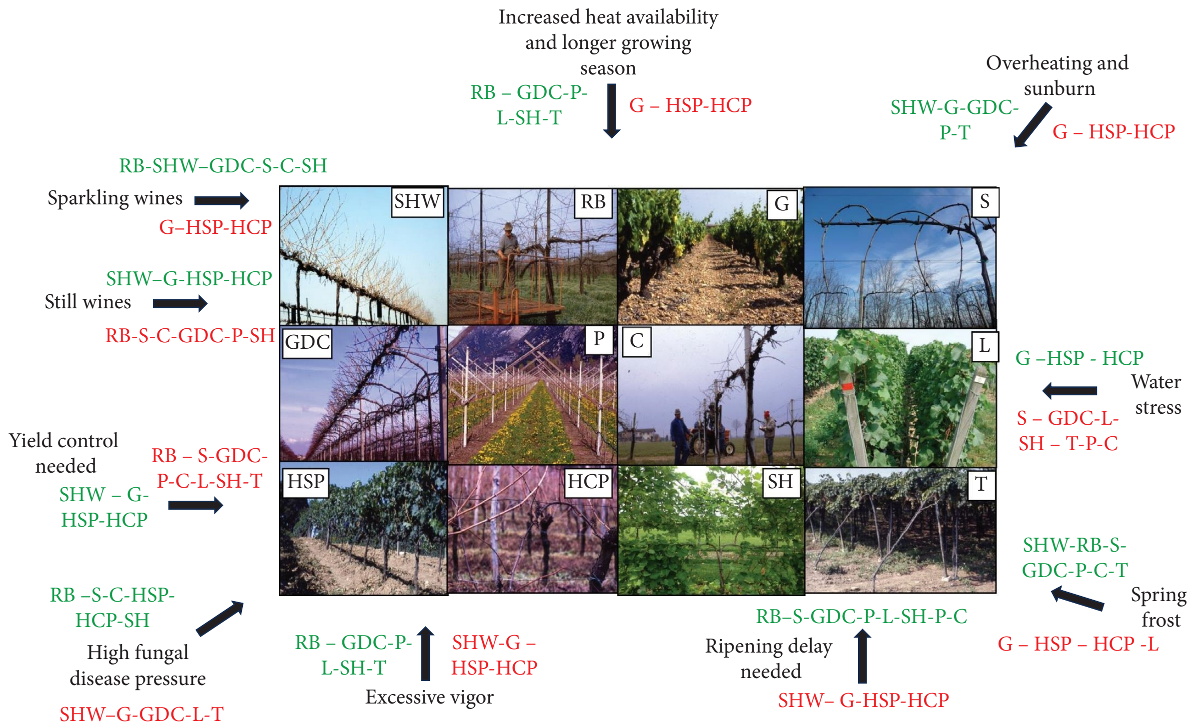


Figure 5: Internal panel shows portrait pictures of twelve grapevine training systems and, in clockwise, ten features are indicated: five of them link to climate change; three are more general, and two deal with attitude to produce still or sparkling wines. For each of them, “recommended” training systems are reported in green, whereas “nonrecommended” training systems are shown in red. Not necessarily, all training systems have been scored for each feature as some of them have been deemed to be rather neutral. The summary of these data is reported in Table 2. SHW = single high wire; RB = Raggi-Bellussi; *G* = goblet; *S* = Sylvoz; GDC = Geneva Double Curtain; *P* = pergola (sloped roof); *C* = Casarsa; *L* = Lyra; HSP = hedgerow spur-pruned; HCP = hedgerow cane pruned; SH = Scott-Henry; *T* = tendone (horizontal roof).

water, nutrients, and health status represent a very complex system. In Figure S1, a scheme of each training system is reported, whereas in Table S1, a short description of each of them with main features is provided.

In Table 1, we have summarized, according to a top-bottom gradient of increasing complexity, the main methodologies available to assess the efficiency and performances of different grapevine training systems. The basic step is that of computing simple geometrical calculations leading to, for instance, the exposed or external canopy area per meter of row or per hectare. This is useful information for a preliminary check about the potential for light interception and correctness of canopy size as compared to between-row spacing. However, these parameters usually consider a solid canopy wall and do not take into account, for instance, the contribution of the diffuse and direct light. Therefore, variable correlations with yield and grape quality traits originate [61].

A consistent step forward has been made with the increasing popularity of the so-called vine balance indices, pioneered by the yield-to-pruning weight ratio, otherwise known as the Ravaz Index [76]. Despite being created long ago, this index is still attractive and used due to the simplicity of its calculations. Since it is a ratio, it considers the demand (yield) and supply (pruning weight) functions. Although it has been shown that the Ravaz Index is an acceptable predictor of the desired quality level [77], it is considered to be a bit rough. In fact, pruning weight, which is a well-accepted parameter to express vigor, is not necessarily a good expression of vine capacity [27]. A case in point is the minimal pruning technique where, due to self-pruning induced by the growth of several immature main canes and laterals, the winter pruning weight can be very low, yet vine capacity given as total leaf area is very high [78–80]. Nevertheless, the Ravaz Index retains validity as a general warning because too low (<than 3 kg/kg) or too high< (>10 kg/kg) ratios suggest excessive vigor and excessive cropping, respectively. Therefore, it provides useful hints about corrections that a training system might need unless the extreme solution of retrofitting to a different one is considered.

No doubt that, as an index, the leaf area-to-yield ratio ($m^2$/kg) has received the greatest attention. The reason is easy to understand. Despite a multitude of studies conducted on an array of different cultivars, sites, and cultural practices, the relationship between a given ripening parameter (most commonly TSS or total anthocyanins or phenols) and the LA/Y ratio fits to a negative exponential model that shows the start of a saturation phase over 1-2-1.5 $m^2$/kg [40, 81–85]. It is also true that total LA does not necessarily equal vine capacity and spreading a given leaf area can ripen more fruit than the same clumped leaf area. Indeed, the need to

Table 1: Survey on the methods used or currently available to determine and compare efficiency of different grapevine training systems.

| Method | Examples | Advantages | Disadvantages | Notes | References |
|---|---|---|---|---|---|
| Geometrical features | External or exposed canopy surface; canopy height to between rows spacing | Direct, simple, no complex inputs, or calculations needed | Limited comparative value; difficult to find correlation with yields and ripening parameters; often canopy gaps are not accounted | Sometimes *exposed* and *external* are erroneously used as synonyms | [47–49] |
| Indices | Y/PW (kg/kg); LA/Y ($m^2$/kg); PW/m (kg); LA/m ($m^2$); LAD ($m^2/m^3$); LLN (n), LAI ($m^2/m^2$) | Some very simple to be measured. Those expressing a ratio usually lead to a good general estimate of vine balance | Source-sink vine balance not taken into account by the one-variable expressions; need of measuring or estimating LA is a deter for the using | Recent apps have facilitated nondestructive LA estimates | [40, 50–55] |
| Amount and quality of light interception | $I_g/I_o$ (%); fractions of exposed organs; gap fractions (%) | Good potential to differentiate training systems; in low to medium vigor conditions, good correlation with canopy photosynthesis | Time-consuming; it usually requires diurnal trends; becoming less accurate with increasing LAI values | Minimal equipment needed is a light bar with multiple sensors for rapid canopy scanning | [56–60] |
| Canopy reconstruction (2D or 3D) and inference of physiology performance | Fractions of external/sunlit LA; spatial distribution of light interception; estimates of canopy water use efficiency (WUE) | Flexibility; helpful to amend and optimize canopy management practices | Parametrization might be time consuming; light interception underestimated at the single organ level; assumption of independence between leaf orientation and 3D leaf positioning might be wrong | | [61–67] |
| Direct measurements of canopy gas exchanges | Canopy net $CO_2$ exchange rate, transpiration. Calculated canopy water use efficiency (WUE) | It solves the problem of upscaling from leaf/shoot to canopy; long-term 24 h monitoring is possible | Commercial versions are still unavailable, and setting requires a custom made approach; viable for experimental purposes only | Air flow setting and degree of chamber perturbance must be carefully addressed | [24, 56, 68, 69] |
| Modeling | Simulated leaf area, photosynthesis, transpiration, respiration and dry matter accumulation, and partitioning trends and patterns | Flexibility; dynamic trends of usually static variable or indices (e.g., leaf-to-fruit ratio) | Independent outputs calibration required; several allometric relationships are usually required | Balance between reasonably simple inputs and accurate enough outputs always difficult to find | [47, 70–75] |

LA = leaf area; *Y* = yield; PW = pruning weight; LAD = leaf area density; LAI = Leaf Area Index; LLN = leaf layer number; $I_o$ = incoming radiation intensity; $I_g$ = ground radiation intensity.

estimate the total leaf area is a burden which is being progressively relieved by new digital, nondestructive methods of leaf area assessment [50, 51, 86, 87].

An outstanding contribution toward studying the physiology of canopies pertaining to different training systems in more detail was brought by the advent of 3D reconstruction models. These models inferred canopy structure indices from basic field measurements (e.g., leaf azimuth and inclination, leaf number, average shoot leaf area, and length) and dissected the ability of a training system to capture light efficiently [62].

This approach brought two major improvements. The first was that the total leaf area could also be assessed as subcomponents such as external, sunlit, and shaded. Recalculating indices on such bases resulted in surprising yet significant results. Across a comparison involving four training systems, each of them separated into two vigor classes (medium and high) to provide a total of eight treatment combinations [61]; it was found that the traditional total LA/Y ratio ranged between 1.21 and 3.35 $m^2$/kg. Using external leaf area resulted in an interval of 0.70–2.27 $m^2$/kg, whereas expressing sunlit leaf area resulted in an interval of 0.3–0.7 $m^2$/kg. These remarkable differences emphasize the importance of determining the quality of the foliage because, depending upon canopy size, density, and structure, several leaf layers might have low functionality as related to, for instance, sugar accumulation.

A second notable finding from the same paper was a significant curvilinear relationship between the amount of light reaching the fruiting zone and the concentration of total anthocyanins in Merlot. The fitted trend indicates that maximum berry pigmentation is reached at about 10–12% of transmitted light to the clusters, and higher or lower values can lead to a decrease in berry color though these values may vary with cultivar. Values achieving the best performance pertained to the following combinations: open Lyra system–medium vigor, GDC–medium and high vigor, and single high wire–medium vigor. This outcome stresses the importance of assessing the local canopy microclimate at the cluster level which, in a given training system, is a function of multiple factors such as the cordon height, upright or downward spreading canopy, shoot density, recourse to shoot thinning, and/or leaf removal. Subsequent 3D reconstruction of grapevine canopies has allowed a better understanding of cultivar behavior (e.g., Syrah vs. Grenache) once trained on a VSP or sprawl fashion [21]. Whereas, using the plant architecture model YPLANT based on resampled allometric parameters, approximately, 80% of intercepted light by VSP-trained canopies was shown to be captured by 20–30% of the leaves, with deficit-irrigated and N-stressed plants having a greater proportion of leaf area exposed to high and moderate light intensity throughout the day as compared to that of nonstressed vines [63].

Among other approaches followed in the past to address the issue of light interception from specific organs or portions of the canopy, the work done by Poni et al. [58] that used an over-row solar arc positioning device equipped with a laser to simulate the position of sunbeams and angle at any latitude and time of the day is worth mentioning. This device was used to describe light availability in the fruiting area (nodes 1–6) that is also the cane portion where, in the case of spur pruning, nodes are retained in winter for next season cropping. The comparison was between GDC, VSP, and SHW, and the canopy laser scanning showed that the relative amount of light captured at full canopy by the renewal-fruiting area (nodes 1 to 6) of SHW and GDC was considerably higher (43% and 59%, respectively) than that of VSP (31%), whose vegetative area (distal to node 6) received about two-thirds of the incoming light. Quantifying such amounts is practically meaningful because, for instance, the probabilities of a developing dormant bud to complete floral induction is closely relative to the amount of light available at those specific nodes [88, 89].

A method that inherently solves the issue of canopy complexity in any given training system is that which affords a direct assessment of whole-canopy gas exchange using an enclosure system (Table 1) [90–93]. The entire canopy is enclosed in a chamber made of different materials (polyethylene, mylar, polycarbonate, etc.), which is flushed by a continuous air flow adjusted to control overheating and, at the same time, allows some gas exchange differential to develop. $CO_2$ and $H_2O$ measured at the inlets and outlets of the chambers then allow a calculation of the net $CO_2$ exchange rate (NCER), transpiration (T), and canopy water use efficiency as NCER/T. As these systems are essentially custom-built, there might be a great diversity in terms of complexity, portability, degree of automation, attendance need, etc. Indeed, several merits can be attributed to this approach when the efficiency of different training systems is the challenge. As it was shown in the work by Intrieri et al. [26], parallel readings taken of single leaf and whole canopy gas exchange rates for different training systems are inherently a method for comparison. If readings taken on healthy mature single leaves under nonlimiting light and VPD conditions represent the optimal (read maximum) rate, values derived from the whole canopy assessment, once normalized according to a shared unit (for instance, $\mu mol \cdot m^{-2} s^{-1}$ for the photosynthetic rate), will be lower depending upon the incidence of any factor that limits leaf function (too young, too old, pale green or yellow, unhealthy). The larger this gap, presumably the less efficient the training system.

Specific work employing a whole canopy approach has greatly contributed to clarify several responses related to different canopy size, density, orientation, and manipulation within a given trellis or between trellises. To name a few, by mounting chambers on VSP-trained field-grown Sauvignon Blanc grapevines with NS-oriented rows, Petrie et al. [68] found that the expected bimodal diurnal patterns found in clear days was not evident on cloudy days when, interestingly, the vines appeared to be more efficient, photosynthesizing at a higher rate per calculated unit of light intercepted. Also, a whole canopy approach has been profitably used to assess, mostly under VSP training, the complex changes that summer pruning is causing on a seasonal basis and that a single leaf approach would be unlikely to represent effectively [11]. Thus, responses have been clarified for traditional leaf removal and shoot topping

[94], early leaf removal [95], apical to the cluster leaf removal [96], shoot thinning [97], row orientation [98], and conventional vs minimal pruning [80].

Fewer examples are available where whole vine chambers have been mounted to include different training systems within the same experiment. The comparison is still limited to VSP vs. SHW [21, 23, 26]. A common trait to these studies, albeit conducted with different cultivars and growing conditions, is that if the SHW is a mostly erect canopy that is eventually trimmed to prevent downward growing, sunlit leaf area might be 25–30% higher than in a VSP.

Finally, the modeling approach (Table 1) links to the 3D canopy reconstruction techniques that have been previously addressed. However, model outputs can easily be extended to other variables such as leaf area, yield, and seasonal dry matter partitioning. A good example on how modeling can truly improve speed and flexibility of training systems assessment is when it makes feasible accurate seasonal estimates of crop load given as leaf area-to-yield ratios. We have previously discussed the physiological reliability of such indexes as a predictor of grape quality (at least sugar and berry pigmentation) and some inherent limitations. A major bias of LA as proxy for vine capacity is the assumption of the same Pn rates in all cases and assumption of the same light interception/unit leaf area, or extinction coefficient. Moreover, leaf area-to-yield ratios calculations are usually performed at harvest only. Whereas, the same has a dynamic change over the season depending upon growth models pertaining to shoot and berry growth. An ideal outcome is that depicted in Figure 6 [47] where, for a VSP trellis presenting variability in terms of low and high shoot and cluster density, seasonal variations of the leaf area-to-fruit ratio are shown from prebloom until harvest. While the reported seasonal trends show that there is a decreasing pattern due to higher cluster sink strength as we proceed toward harvest, and the model is sensitive to variations brought about by a canopy manipulation event such as shoot trimming, the most important information is that the user can, at any given time during the season, verify if a source limitation occurs. A good example is cluster thinning that is needed when, around the time it is usually performed (e.g., veraison), an excessive crop load burdens the vines. In the example provided in Figure 6, regardless of the canopy density and year, this does not seem the case as, at veraison, the model estimates at least two $m^2$ of leaf area available per kg of crop, which is a likely sign that a major source limitation is not occurring. This approach will benefit in the future from novel methodologies of crop load mapping that exploit proximal or remote sensing technologies [85].

Another good example of how modeling can help in training system assessment is the VITISIM application [70, 99, 100], and the case study described in Figure 7 is significant. The graph shows simulations of the balance of canopy net $CO_2$ fixation minus the combined demand of crop and the shoots of Concord (*Vitis labruscana B* x *Vitis vinifera* L.) vines trained to Umbrella Kniffin [101], a high wire cordon, and subjected to two different pruning regimes to correspond to conventional pruning (about 32 buds/m) and minimal pruning [100]. With arrows indicating the estimated dates of flowering and veraison, and the actual date of harvest, the model can effectively describe when a source limitation is occurring or when the carbon demand is fully met. The early-season period of relatively positive carbon balance around and after bloom is greater in the minimally pruned vines due to the early canopy development for supply. This is combined with the earlier decline in shoot demand as compared to the heavier pruning that stimulates longer shoot growth duration. In both pruning regimes, the greatest potential carbohydrate supply for growth processes is just before veraison when crop and shoot demands are low and canopy supply is high. Between veraison and harvest, it appears that normal pruning was in balance with the crop demand, while the minimal pruning was not able to meet the larger demand of the ripening crop. These analyses provide a plausible explanation of why minimally pruned vines had higher but more stable year-to-year yields, yet could not ripen those larger crops as compared to the balance-pruned vines [102]. If a similar analysis is run for other training systems, it could be possible to diagnose when, over the annual growing cycle, a significant supply deficit might occur and then offer possible solutions or amendments.

## 5. Training System as an Adaptation Tool to Climate Change

The main climate changes that impact viticulture worldwide have been covered in some recent comprehensive reviews [103–106]. It is reasonable to ask if the climate change issue has so much impact that the training systems that historically pertain to certain districts should be reconsidered. We have endeavored to summarize the problem in Figure 5. Around the central panel containing 12 different training systems, we have chosen to embrace the most represented ones in viticulture worldwide. These are surrounded by different items often specifically linked to climate change. We have also reported both recommended and less recommended training systems. Please note that, for a given item, all the training systems were not necessarily scored. Rather, some were neutral for specific traits.

Moving clockwise around Figure 5, we find five items that are somewhat directly linked to global warming (increased heat availability and longer growing season, overheating and sunburn, water stress, spring frost, and a desirable delayed harvest). Then, three other criteria follow (yield potential, vigor control, and interaction with diseases) while the last two refer to attitude toward still or sparkling wines. The latter requirement would identify training systems assuring medium-to-high yield associated to significant leaf cover around clusters as most suited for sparkling wine making. While keeping these three groups separated, it would be interesting to identify those training systems that might achieve the highest number of positive or negative recommendations.

Table 2 summarizes the previous approach in terms of frequency of positive or negative recommendations for each

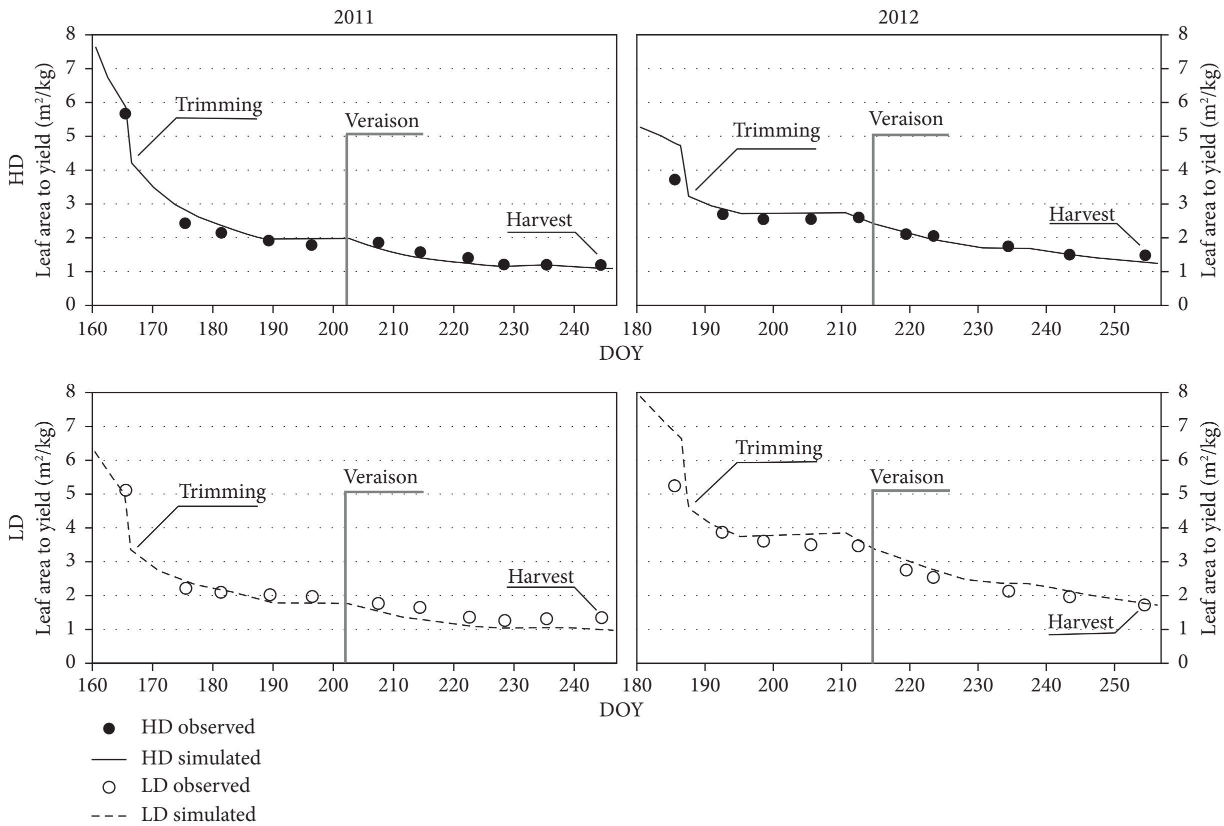


FIGURE 6: Simulation of source-sink ratio expressed as leaf area-to-yield ratios ($m^2 \cdot kg^{-1}$) in seasons 2011 and 2012 for high density (shoot number per meter of cordon = 20) and low density (shoot number per meter of cordon = 10) in VSP-trained Barbera canopies. Taken from [47].

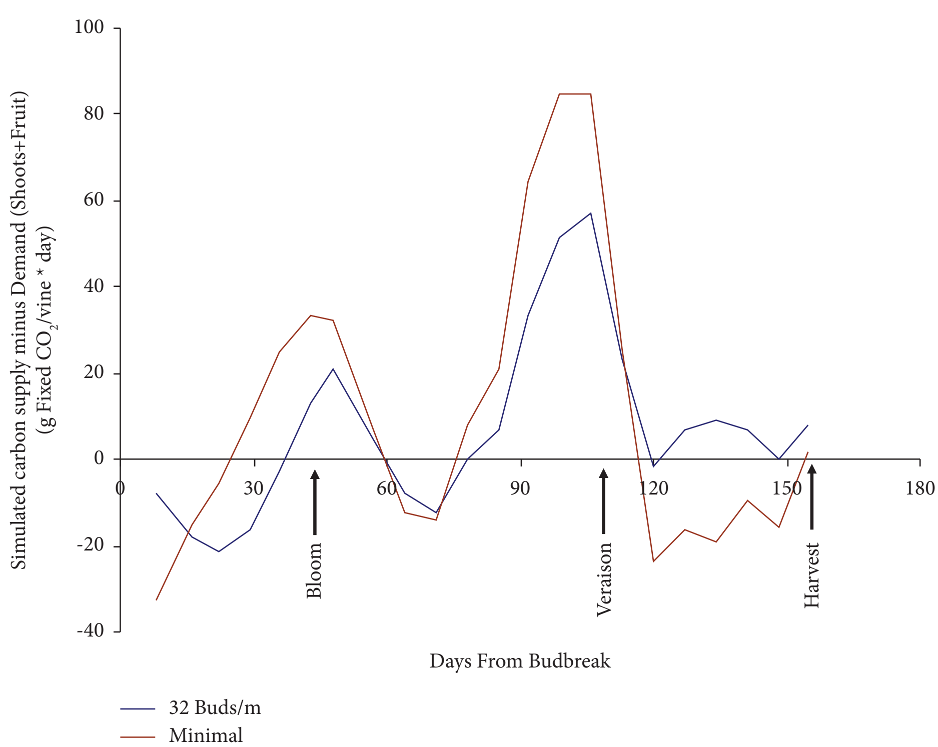


FIGURE 7: Season-simulated carbon supply minus demand (shoots + fruit) run for Concord (*Vitis vinifera x Vitis labrusca*) vines trained as conventional Umbrella Kniffin training system (32 buds per vine left) and to minimal pruning. Redrawn from [100].

Table 2: Number and balance of positive or negative recommendations for climate-related, general, and wine type-related features for the 12 grapevine training systems shown in Figure 5.

| Training system | Climate-related | | General | | Wine type | | Grand total | | Balance |
|---|---|---|---|---|---|---|---|---|---|
| | Positive | Negative | Positive | Negative | Positive | Negative | Positive | Negative | |
| SHW | 2 | 1 | 1 | 2 | 2 | 0 | 5 | 3 | +2 |
| RB | 3 | 1 | 2 | 1 | 1 | 1 | 6 | 3 | +3 |
| *G* | 2 | 3 | 1 | 2 | 1 | 1 | 4 | 6 | −2 |
| *S* | 2 | 1 | 1 | 1 | 1 | 1 | 4 | 3 | +1 |
| GDC | 4 | 1 | 1 | 2 | 1 | 1 | 6 | 4 | +2 |
| *P* | 4 | 1 | 1 | 2 | 0 | 0 | 5 | 3 | +2 |
| *C* | 2 | 1 | 1 | 1 | 1 | 1 | 4 | 3 | +1 |
| *L* | 2 | 2 | 1 | 2 | 0 | 0 | 3 | 4 | −1 |
| HSP | 1 | 4 | 2 | 1 | 1 | 1 | 4 | 6 | −2 |
| HCP | 1 | 4 | 2 | 1 | 1 | 1 | 4 | 6 | −2 |
| SH | 2 | 1 | 2 | 1 | 0 | 0 | 4 | 2 | +2 |
| *T* | 3 | 1 | 1 | 2 | 0 | 0 | 4 | 3 | +1 |

SHW = single high wire; RB = Raggi-Bellussi; *G* = goblet; *S* = Sylvoz; GDC = Geneva Double Curtain; *P* = pergola (sloped roof); *C* = Casarsa; *L* = Lyra; HSP = hedgerow spur-pruned; HCP = hedgerow cane pruned; SH = Scott-Henry; *T* = tendone (horizontal roof).

training system within each group and as a grand total. Although the outcome has a provocative value, it should be a matter of consideration that our analysis ranks first on the old Raggi-Bellussi (RG) training system, which has historically been used in the Lambrusco area in Northern Central Italy. RG reunites six positives represented by (i) good potential to exploit an unusually longer growing season, mostly related to its high-yielding attitude; (ii) good tolerance to overheating and sunburn as clusters are always variably shaded; (iii) excellent behavior toward spring frost as cordons are trained at even more than two meters from the ground; (iv) proneness to postpone a too early harvest again mostly due to the high cropping; (v) good vigor control due to the high bud load per vine and space available for vegetative growth and good tolerance to fungal disease as severe leaf clumping around the cluster area is almost impossible, and (vi) high attitude to the production of sparkling wine types. However, such a positive scenario clashes with the reality as the adoption of the system is impeded by laborious and expensive planting, which demands management and almost no susceptibility to mechanization.

Under a balance of two positive recommendations, the second place is taken by a group including SHW, GDC, P, and Scott Henry. They all share high cordons (useful in case of frost and winter injury events), good potential to control vigor and, concurrently, warrant some leaf cover to clusters to prevent or mitigate overheating and sunburn. Moreover, they do have a generally good attitude toward sparkling wine-making, which is also related to their high-yielding attitude that can better exploit a longer growing season and have a better ripening potential.

Then, a third group includes all the remaining training systems that have an overall negative balance. This group comprises traditional, renowned training systems such as goblet and VSP. The latter is considered in its short and long pruning management. Indeed, they maintain a leading role when premium still wines are the main target. Yet, mostly due to the impact of climate change, they are showing increasing weaknesses, which often require modifications in canopy management [11] or retrofitting to other trellises. The typically featured low cordons increase the risk of frost damage, whereas the low yield levels (especially in *G*) contribute to earlier ripening under the risk of untypical traits, while showing little or no potential to exploit a longer growing season. In VSP canopies such as hedgerow trained spur-pruned (HSP) and hedgerow trained cane pruned (HCP), a given row side will be exposed in summer, sooner or later, to the issues of overheating and/or sunburn, regardless of row orientation.

All contributions which we will mention therein aim at suitable modifications of a traditional trellis to increase its adaptation to climate change. Some adjustments are transversal to a number of training systems and a good case is the recourse to basal leaf removal which, especially in VSP-trained vines, is now more cautiously regarded as compared to the past [11].

Although the ideotype of a quality vineyard would emphasize the positive role of trunk height (the lower, the better), there is no scientific evidence that trunk height variation can heavily impact vigor, yield, and grape composition [107]. Van Leeuwen et al. [106] measured canopy temperature at 30, 60, 90, and 120 cm from the ground and calculated that the Winkler Index [108] was 60°C lower at 120 cm vs. 30 cm. Therefore, increasing cordon height, while obviously diminishing the risk for frost damage, might also help at slightly postponing ripening. It might represent a future trend when the training system must be chosen. Another study [109] investigated whether trunk height could be a viable option for manipulating microclimate in the fruiting area and measured air T at 30, 60, 90, and 120 cm above ground in two parcels, one cover-cropped and the other tilled. Close to the ground (30 and 60 cm heights), the cover crop parcel generally had lower minimum temperatures and higher maximum temperatures in comparison to the tilled parcel, exposing the vine to an increased risk of both frost and heat wave damage.

Moreover, kinematic analysis found that vineyard workers spent more than 50% of their time with the trunk flexed greater than 30° and more than 20% with the trunk rotated greater than 10° [110]. These results show that pruning activity led to forward bending and rotated trunk postures that could significantly increase the risk of work-related musculoskeletal disorders in the lower back. An intriguing work has also been conducted about ergonomic evaluations referred to simulation trellis systems: VSP 4 × 4, Smart Dyson, Scott Henry, VSP, and Lyre. The cutting heights were based on average vineyard standards and are as follows: 61.0 cm VSP 4 × 4, 86.4 cm Smart Dyson, 99.1 cm Scott Henry, 106.7 cm VSP, and 122 cm Lyre. The row length for all trellis systems was approximately 9.1 m [111]. Not surprisingly, results showed that the Lyre and VSP 4 × 4, both of which encompass relatively extreme trunk postures, caused the largest wrist flexion angles compared to other trellis systems. Conversely, the VSP system (106.7 cm working height) resulted in the most time spent in a neutral trunk posture combined with acceptable wrist postures.

An issue that deserves more in-depth studies is how the training system affects, per se, the vineyard water use. Here, a confounding effect is contributed by the unit used to express water use: either unit of row length or hectare bases. Indeed, the latter considers the effect due to between-row spacing which, especially in VSP, plays a major role. Under the validated assumption that seasonal grapevine crop coefficients ($K_c$) can be estimated from the shaded area (SA) beneath grapevine canopies at solar noon in vineyards with different trellises and row spacings, Williams et al. [112] have reported mid-season $K_c$ estimated for the Lyre and VSP trellises on a common 2.74 m between-row spacing to be 0.96 and 0.49, respectively. In addition, $K_{c\,\mathrm{mid}}$ was inversely correlated with vineyard row spacing. The closer the row spacing for a particular trellis, the greater the $K_{c\,\mathrm{mid}}$. The $K_{c\,\mathrm{mid}}$ for a VSP trellis on 1.83 and 3.05 m row spacings were 0.87 and 0.52, respectively. This example clarifies that, with everything else kept constant, canopy division or progressive reduction of row spacing significantly increase vineyard water use. Indirect confirmation derives also from a comparison made between a VSP trellis and a vertically split canopy (Scott Henry) planted at the same row spacing (1.83 m) [113]. There were only minor differences in midday leaf water potential between the two trellises for a specific irrigation treatment throughout the season. In addition [114], measured stem water potential at various dates under well-watered or water-restricted conditions in Sangiovese vines spaced 1 m apart in the row and trained as VSP and SHW showed minor differences, suggesting a V-shaped sprawl canopy might have a diurnal water use fairly similar to a VSP canopy, as it was also found by Intrieri et al. [26]. The same conclusion was reached in a trial on Albariño [15] where VSP and a downward growing SHW trellis were compared.

Likewise, it is well established that when the water use comparison deals with training systems having large differences in total leaf area per vine or per meter of row length, canopy transpiration is affected accordingly [115]. A good example has been provided for Sylvoz (average LA/vine = 4.5 $m^2$) vs minimally pruned SHW trained vines (average LA/vine = 10.0 $m^2$) conducted in Germany on White Riesling [116] and using a modified Granier system to derive canopy transpiration [117]. During a period of 130 days, the total water consumption of Sylvoz-trained vines was 282 liters per vine, i.e., 24.2% less than the water use recorded in the minimally pruned vines (372 liters per vine).

Based on the assumption that an NS-oriented row has its highest evaporative demand midafternoon when the sun shines on the west-exposed row side, Intrigliolo et al. [118] tested if a canopy leaning 30° toward the west (WSP) could reduce transpiration due to a likely diminished light interception when VPD is at the peak. Apparently, canopy transpiration rates per leaf area bases were very similar between NS and WSP, suggesting that the high VPD was an overwhelming factor. Slightly different results were obtained in the Central Valley of Chile [119] when, again for a SHW vs. VSP comparison, it was found that when water supply was not limiting, the SHW trellis had 12% higher seasonal cumulative actual evapotranspiration than VSP and, consequently, SHW was more affected by water stress than VSP during the water-limited season.

A further question deals with differential canopy water use efficiency pertaining to different training systems. It is a difficult task as canopy photosynthesis and transpiration need to be measured or estimated first and the methodological issue of single leaf-based vs whole canopy-based readings pops up again. Therefore, it is no surprise that while the possible mismatch between water use efficiency (WUE) assessment based on single leaf or whole canopy approaches has been investigated in some detail [120–122], scant information has been provided across different training systems. Within head-trained vs. VSP-trained vines, Patakas et al. [123] have shown that for leaf water potential values higher than −0.9 MPa, the VSP canopies had higher WUE. Differences vanished at more stressful water potential levels.

## 6. Training Systems, Grapevine Health, and Disease Incidence

It is surprising that most of the work published on comparisons of training systems have considered physiological and agronomic performance, while much less attention has been devoted to the interaction between a training system and the incidence of major pests and disease. Even less attention has been paid to how operations made during the young vine training phase can affect the performance of the mature vineyard.

In the latter connection, an excellent example is provided in the work by O'Brien et al. [124] and Tomás et al. [122] who tackled an issue whose importance is underestimated. When the establishment of a permanent cordon is needed, the common choice is to use a good cane at the end of the second year after planting and fill the space on the wire. However, if such canes lack vigor and varietal sensitivity varies, shoots arising from the mid-portions of the trained canes can be stunted or even absent. This, in turn, will unavoidably lead to weak or missing spur positions along the cordon. The authors tested the benefits of adjusting the length of newly trained canes intended as permanent cordon arms to limit their bud number and guide new growth. Short-term results were positive as the treatment for cordon lengthening had higher pruning weight, cane number, and cane weight in the intermediate section of cordon arms during the first season of growth. However, such a difference was not conformed over the next three seasons.

A correlated issue is how different techniques in cordon training might impact longer-term xylem hydraulic conductivity and vulnerability to drought-induced cavitation, which, in turn, might also be conducive to varying susceptibility to wood diseases. This field is still surrounded by a great deal of uncertainty. Studying the Esca complex, Pouzoulet et al. [125] found that vines carrying vessels of small diameter such as Merlot might be able to restrict the spread of toxins and bud cells in a quicker and more efficient manner than vines carrying wider vessels such as Cabernet Sauvignon and Thompson Seedless. Conversely, Stevenson et al. [126] were unable to establish a correlation between xylem hydraulic architecture and the incidence of Pierce's diseases in Chardonnay vines. Backing up to cordon training, methods which constrict the vasculature of the cordons, in particular tightly wrapping the cordon around the main wire, might have negative effects on cordon health and vine productivity [127, 128]. However, a bit surprisingly, rather than finding evidence of cordon strangulation being a driving force behind cordon decline, there was actually a trend of lower severity of dieback observed with cordons displaying the greatest degree of strangulation in a trial conducted on Sirah grown in South Australia [129].

More attention has also been recently devoted on how, in spur pruning, wood necrosis is affected by the type of winter pruning cuts. Bruez et al. [130] have shown that, when applying cordon spur pruning, a woody stub of at least 3 cm left above the diaphragm vs an above-node cut is useful to limit colonization by grapevine trunk disease pathogens. However, the same authors observed a large variability according to cultivar as Ugni Blanc was highly responsive and Sauvignon Blanc the least responsive.

A trial carried out in Germany on Chardonnay and Reberger [131] has compared susceptibility to main fungal diseases in vines trained to VSP (control) or semi-minimal-pruning hedge (SMPH), a recent development from a minimal pruning system [132]. This work demonstrated that SMPH-trained vines can be more susceptible to downy mildew, powdery mildew, and Botrytis bunch rot than VSP-trained vines. However, another trial conducted in Italy on Sangiovese for three seasons and comparing traditionally pruned SHW vines vs minimally pruned vines [27] has shown that, while minimal pruning led to substantial overcropping and impaired final grape quality, the development of smaller and looser clusters with smaller berries had a positive effect on rot reduction. Other works involving the same trellis comparison (VSP vs. minimal pruning) have investigated their effect on predatory mite densities, an interesting approach for biolimitation of pest mites (e.g., Eriophyidae, Tetranychidae) and other arthropod taxa that can cause serious damage to vineyards [133]. Very interestingly, predatory mites were significantly more abundant in both minimal pruning and under reduced plant protection. Increases in predatory mites appeared to be independent of fungal infection, suggesting mostly direct effects of reduced fungicides and minimal pruning.

When the Four Arm Kniffin training system [134] was compared in a wet region of China with single Guyot and spur-pruned VSP, it was apparent that the latter had lower leaf and cluster infection rates, especially toward the end of the season [135]. A similar outcome was seen in work done in Brazil about the effect of VSP, GDC, SHW, and tendone (overhead pergola) on temporal dynamics and the incidence of a downy mildew epidemic showing a sort of outstanding behavior of the VSP-trained vine compare to the others [136]. A comprehensive five-year trial was carried out on VSP and early-topped SHW to evaluate the development of powdery mildew in Chardonnay and Cabernet Sauvignon vines under a no-fungicide application regime [137]. The same research group also investigated a fungal disease incidence that was consistently lower in SHW across the years with larger relative differences in seasons having an overall mild disease pressure (e.g., 30% of the clusters in VSP vines infected compared to 5% only in the SHW vines). Finally, the impact of the timing of basal leaf removal on fungal diseases should not be underestimated. When VSP training was combined with early leaf removal in the absence of fungicide sprays, it reduced the mean disease severity by 32% relative to untreated clusters on Umbrella Kniffen-trained vines [138].

## 7. Conclusions and Outlook

A close view at the interaction between the types and structure of current training systems used in viticulture and the main effects brought in by climate change suggest that training systems should go through an adaptation process, implying alternate trellises or modification of the current ones through differential canopy manipulations or structural changes.

The issue, however, becomes more complicated if projected over the scenario of cool vs. warm viticulture. In cool climate viticulture, climate change is opening more opportunities than problems and the rapid increase in land suitability for grape growing and the related marketing perspective are very tempting. In such a context, training systems should be targeted to help or even further improve capacity to bring to full ripening varieties that, just a few decades ago, were ill adapted and unaffordable. Therefore, where water availability is usually nonlimiting and excessive radiation loads and high temperatures are still a fairly minor problem, the training system should be able to strengthen the already enhanced climate-related ripening potential by leading a higher fraction of exposed/sunlit leaf area to total leaf area and better cluster microclimate (i.e., with more frequent adoption of leaf removal including early leaf removal). On the other side, vigor control function is needed (hence the emphasis on divided canopy types) to avoid major problems in disease occurrence and very delayed or incomplete ripening.

If the viticulture model of the Mediterranean area is considered instead, the overall impact of climate change on viticulture is deemed to be negative, mostly due to the higher frequency of meteorological drought (often a combination of soil and atmospheric water stress), hot spells leading to severe and rapid dehydration and sunburn, and compressed and fast ripening dynamics leading to serious severe grape composition unbalances. Under these circumstances, the evolution of training systems should be the opposite of what we stated previously. Canopies should be reduced in size and extension to limit transpiration and between-row spacing should be adjusted accordingly. Clusters should benefit from at least some leaf cover until ripening, which means that training systems favoring this condition will have to be preferred (i.e., upright SHW, pergola types, etc.). Moreover, training systems allowing a high bud load per vine and enhancing yield potential might come back as interesting alternatives since the high crop level can postpone ripening while also better exploiting a longer growing season. Lastly, higher cordons seem to be preferred, especially due to less susceptibility in spring frost.

We conclude that some items pertaining to “old, expanded training systems” should be recovered and transferred into the mostly used hedgerow (VSP) type, either cane- or spur-pruned. This might theoretically clash against a need that is currently independent of the changing climate, i.e., suitability to some degree of mechanization (primary needs to be directed to pruning and harvest) and, maybe in a not too far future, to robotics.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Supplementary Materials

Figure S1: Schematic representation of the twelve training systems also shown in real view in Figure 5. A brief description of each of them is provided in Table S1. (*Supplementary Materials*)

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