Planting Density and Physiological Balance: Comparing Approaches to European Viticulture in the 21st Century

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Abstract: The downturn over the past decade in Europe's leading viticulture and wine-producing countries has led to a rethinking of conventional vineyard viability and the criteria for establishing new plantations in areas of *Dénomination d'Origine Controllée* (DOC). It is not uncommon to hear that enhancing grape quality in new vineyards requires, at the very least, planting densities as high as 5000 to 6000 vines and more per hectare. The underlying idea appears to assume that high density improves quality *per se,* raising it to an almost absolute concept. Yet density is the result of intrarow and interrow vine spacings—neither an absolute. Indeed, the data being amassed in literature tend to assign priority status to a given planting's 'physiological balance', which depends on environment and implies varying densities. Intrarow spacing effects are first investigated by positing a model vineyard consisting of a single row in a non-limiting environment at wide, medium, and narrow vine spacings. The medium, postulated in physiological balance with the projected environmental conditions, outperforms the others as to vegetative and yield ratios, leading to both optimum yield per row meter and grape quality: intrarow spacing and hence yield per row meter is thus the key factor in berry quality. The interrow effects are then modeled in a vineyard featuring the balanced intrarow medium and interrow spacing varying from 3.5 to 2.5 m, the standard practical range, in the same environment. Decreasing interrow from 3.5 m means increasing row length, yield, and planting density per unit of area without altering quality. Interrow spacing is thus the chief factor in establishing total crop, indicating yield and vine number/hectare as nonabsolute concepts in enhancing quality. The models underscore that any given viticultural ecosystem tends toward a physiological balance that cannot be established *a priori* in relation to high planting density. Worldwide data indicate best quality performance when vine number ranges from 2500 to 4000 per hectare.

Key words: vine balance, planting density, yield, ecosystem

The Issue and Its Origins

Whither the vineyards of Europe's winegrape industry at the turn of the third millennium? If the signals being picked up from the traditional districts — beset by the need for a thorough revamping — are any indication, there would seem to be more confusion than concerted planning in the state of the art. At the root of the problem lies the crisis that has been afflicting 'Vineyard Europe' (France, Italy, Spain, and Portugal) since the early 1980s, a downturn determined at the outset by a lengthy period of surplus wine production and thereafter the loss of over a million hectares of vineyard acreage. This reduction, the outcome of a deliberate European Union policy to restabilize the market, was driven on the one hand by incentives granted to growers who permanently took non-premium acreage out of production and on the other by prohibiting new plantations in premium districts unless as replacements on the same acreage. The upshot of this policy was twofold: whereas it eliminated old vineyards marked by low quality product, outdated management systems, and high overhead outlays, it also created a market vacuum that soon attracted foreign exporters, including emergent producers like Australia, Chile, and Argentina.

Stimulated by these pressures, Europe's industry has begun to review the viability of traditional vineyard models in the premium growing districts and how best to replace obsolete vineyards. The message most often being propounded by certain 'experts' is that a return to market competitiveness and the advancement of crop quality can only be achieved by replacing traditional vineyards with new high-density plantings (6000 - 8000 vines/ha) along the lines of the paradigm offered by France's classic viticulture (Fig. 1). Yet the real, underlying issue here is to promote the idea that only a vineyard at high-density planting is capable of attaining these goals.

A categorical conviction such as this is very often grounded in a basic misconception, one presumably engendered by the fact that until the mid-1980s the planting systems in many fertile districts, as for example in north-central Italy, had been modeled on those developed during the previous decade when favorable market prospects had led to an unrestrained growth of vineyard acreage. These systems almost invariably featured medium-wide spacing at medium-low density (1500–2500 vines/ha), with massive energy inputs needed to maintain the high expected cropping—a strategy designed to ensure good returns even for medium-grade crop (Fig. 2).

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Figure 1 A high-density vineyard in the Champagne district: plantings like this are suited to rather limiting environmental conditions such as result in low vegetative vigor.

Figure 2 A low-density vineyard in Italy's north-central lowlands: the pronounced vigor of such plantings depends on favorable environmental conditions and nutrient inputs.

Yet this approach suffered from a technical flaw in that, lacking the market incentives to modernize vineyard systems, it paid scant attention to the findings of researchers, for by then a number of studies had already raised doubts about the 'absolute' nature of such concepts as 'high-density planting' and 'low-yield level' in the pursuit of quality. Indeed, the data then being amassed assigned priority status to the vineyard's inherent 'physiological balance' through the core concept of 'equilibrium indexes' and how best to control them. Independent of spacing and cropping, these indicators yielded an optimum value based on grape and wine characteristics which proved to be all but invariable, no matter what the growing environment.

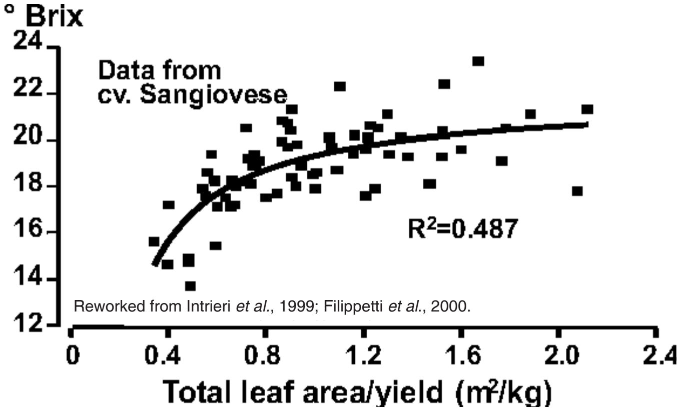
At least three of these indexes, readily measurable in any hedgerow system, could have been taken at the time as particularly significant in assessing the quality potential of a given vineyard.

(i) The ratio (m^2 to m^2) of total leaf area (TLA) to external leaf area directly exposed to sunlight (ELA) results in an optimum value ranging between 1.5 and 2.5, or basically about half the number of leaf layers making up the hedgerow [5,21,35,38,41,75,76,77].

(ii) The ratio of TLA (in m^2) to weight (kg) of harvested grapes (G) gives an optimum ranging between 1 and 1.5 [27,29,33,34,36,39,46,47,48,56,63,64] (Fig. 3).

(iii) The ratio (kg to kg) of G to weight of the year's wood (W) pruned the subsequent winter yields an optimum ranging between 6 and 10 [9,10,11,12,22,40,41] (Fig. 4).

These indexes in turn provided the basis for a new management approach aimed at maintaining the balance between the plant's vegetative and reproductive growth habits by relying on the given ecosystem's resource potentials with minimum recourse to outside inputs. The



Reworked from Intrieri *et al*., 1999; Filippetti *et al*., 2000.

Figure 3 Regression of juice soluble solids concentration (°Brix) on total leaf area/yield ratio (m^2/kg). Data taken at harvest from cv. Sangiovese vines trained to GDC, Free Cordon and Spur-Pruned Cordon.

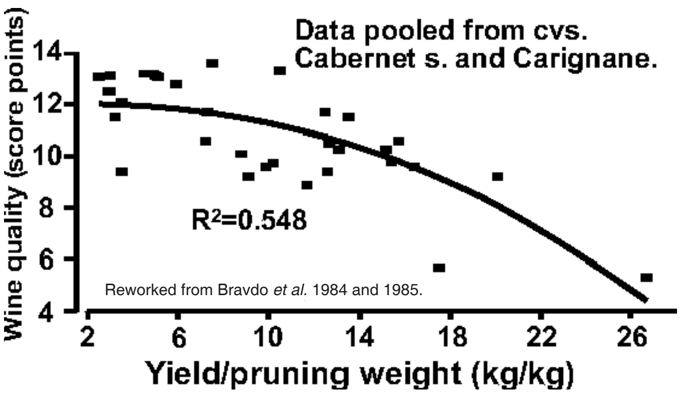


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Figure 4 Regression of wine quality (score points) on yield/pruning weight ratio (kg/kg) for cvs. Cabernet Sauvignon and Carignane.

result was that soil and climate, the chief environmental resources, gained in stature, and emphasis was clearly placed on the need to plan spacing and management practices so as to ensure maximum vine performance and crop quality via the exploitation of natural energy supplies. This means in effect that the level of quality achieved determines the admissible level of yield—a complete reversal of traditional thinking. The adopting of these principles therefore led to the 'physiological equilibrium' becoming the primary objective of planning, and accordingly, the planting density of new vineyards differed depending on the given environment.

The Effects of Planting Density

The literature on planting density is lengthy and includes contributions from grapegrowing countries the world over. The overall data make possible a brief *catalogue raisonné* of the effects determined by variations to planting density in a hypothetical vineyard, a stable soil-climate context being assumed as given. The key factors to distinguish are the effects of vine intrarow and interrow spacing, two variables that seldom interfere with each other in routine management conditions and can therefore be evaluated separately.

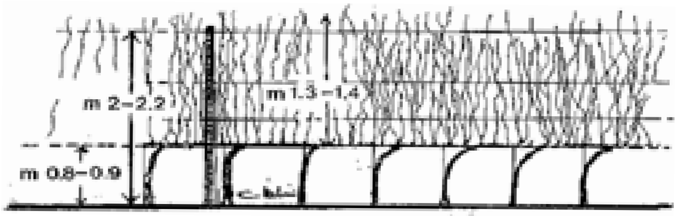

Figure 5 The effects of planting density can be analyzed correctly by defining the essential parameters of a "model" vineyard in an ecosystem with sufficient soil fertility and non-limiting seasonal rainfall and temperature range. If a textbook, spur-pruned cordon training system is assumed, the permanent cordon should be set 0.8 to 0.9 m from the ground with a maximum trellis height of 2 to 2.2 m above ground for proper shoot-system development.

Before setting up spacings and analyzing their effects, it would be a good idea to provide precise physiological and structural specifications for a preliminary definition of a 'model' vineyard (Fig. 5). So let us imagine a variety having sufficient fertility at cane basal buds (1 - 1.5 cluster per year's shoot) in a hedgerow layout featuring N-S oriented rows with vines grafted to a medium-vigor rootstock and trained to the 'textbook' spur-pruned cordon. Let us next assume that each vineyard is situated in an average ecosystem as to soil fertility, rainfall, and seasonal temperature range. Let us further posit that vineyard management is designed simply to maintain the original conditions and that the permanent cordon is trellised 80 to 90 cm above, with the support poles 2 to 2.2 meters from the ground.

These 'model' parameters are drawn from field management data reported for like vineyards in the best-suited European growing districts [28,35,36,38, 40,41,42,50,51,62,63,74]. They provide certain key factors everyone can agree on so as to keep attention focused only on the effects of intra- and interrow spacing.

The 80- to 90-cm cordon height confines the cropping zone to an area that facilitates manual and mechanical pruning and harvesting. The 2- to 2.2-m pole height is both compatible with the use of available pruners and harvesters and, most important, leaves adequate room for shoot growth above the permanent cordon (at least 1.3 m) so as to ensure the development of a leaf area that does not pose a limit to assimilation processes. With the layout and management parameters of our 'model' vineyard thus defined, we can now turn our attention to analyzing, separately, the effects of intra- and interrow spacing.

Intrarow Spacing

It is worth noting that most of the reported data indicate intrarow vine spacing as the chief factor in achieving high berry quality [1,2,15,16,17,18,23,32,35,43,44,45,55, 72,73]. To check the reliability of these findings and to exclude possible interferences, imagine a vineyard featuring a single continuous row (Fig. 6) with vines at 'optimum', 'wide', and 'narrow' intra-spacings.

Optimum intrarow spacing (OIS): This layout assumes that OIS is in perfect equilibrium with the posited

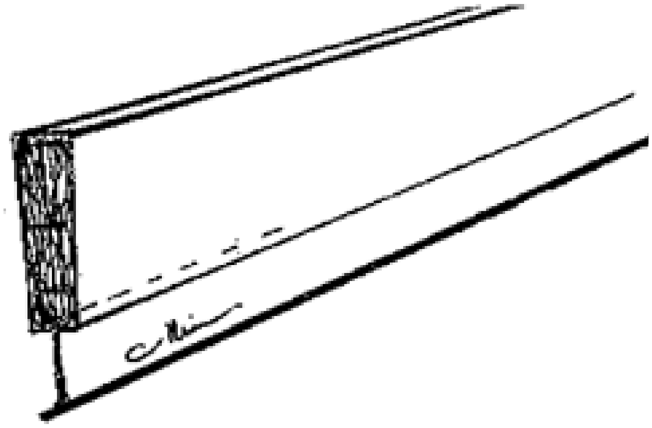

Figure 6 Most of the data reported in literature imply that intrarow spacing is the key factor determining crop quality. To assay the importance of this criterion to the exclusion of other factors, a "model" vineyard can be posited featuring a single continuous hedgerow whose only structural variable is intrarow spacing. The following models analyze hypothetical optimum (OIS), wide (WIS), and narrow (NIS) intra-vine spacings.

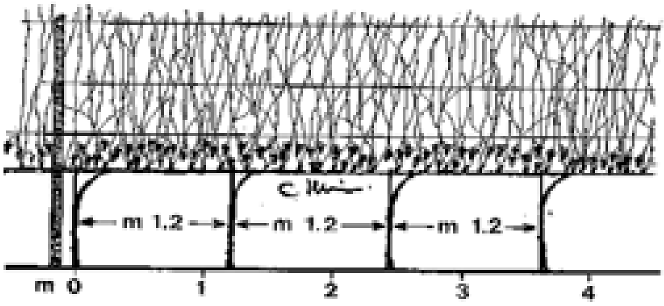

Figure 7 OIS hedgerow at 1.2-m intrarow vine spacing. If this spacing proves to be the optimum in the postulated ecosystem, the vines will be in physiological equilibrium and generate high, constant yield per linear unit of hedgerow and maximum crop quality.

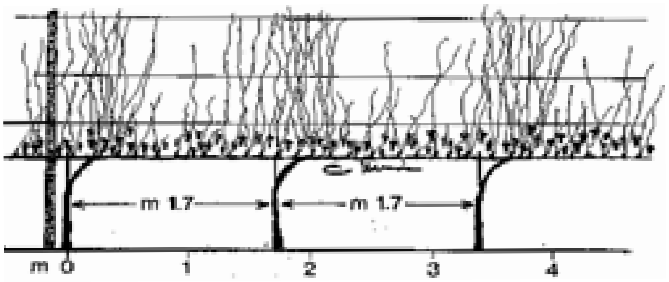

Figure 8 WIS hedgerow at 1.7-m intrarow vine spacing. With respect to the OIS, vine development should be marked by evident weakness, a lower yield per linear unit of hedgerow and poorer crop quality.

ecosystem, which, given the medium-vigor rootstocks, is 1.2-m intrarow spacing (Fig. 7), approximately the same as that found in the best managed vineyards in Europe's premium growing districts. Moreover, pruning must be planned for uniform spatial arrangement of spurs — about 15 cm one from the other, or about eight spurs with two basal buds per vine (about 16 buds). This array yields on average about six to seven spurs and 12-14 buds per hedgerow meter.

Given the assumed balance of vines, the number of seasonal shoots should be slightly higher than the number of post-pruning count nodes because only a few secondary shoots are able to develop [77]. This means that only 18 to 20 shoots and, given the average fertility assumed (just over 1), about 20 to 22 bunches can grow per vine, or about 16 shoots and 18 clusters per hedgerow meter [66,67,77,78]. These are the optimum conditions for assuring initially rapid shoot growth, which for physiological reasons later slows down naturally at bloom once each shoot has developed 18 to 20 leaves [65,80]. The lowest shoot nodes also feature a certain number of medium-sized laterals whose leaf system positively integrates the vine's assimilation capacity, especially late in the season [37,49].

The pace of post-bloom growth continues to slacken until ceasing altogether because of cluster competition, which more or less coincides with veraison when overall leaf number per shoot and its laterals is about 30. Ripening is thus proceeding regularly, being sustained by an assimilating leaf area, at once efficient and sufficient, which has also been able to occupy all the space available above the permanent cordon. As post-veraison growth is practically nil, the need for topping is reduced to minimum and the useful leaf area is kept to a maximum.

Plant and berry development is well matched under these conditions, and this balance translates into the optimum values yielded by the equilibrium indexes. The grapes attain full maturity and the best taste and flavor traits compatible with the cultivar and site. Our imaginary vineyard thus fully matches the ideal 'development model' found in many studies, and if we assume an average size for clusters with a weight of about 200 g each (*e.g.,* typical for certain cultivars like Sangiovese or Merlot), the yield per vine is about 4 kg, or about 3.5 kg per meter of hedgerow.

Wide intrarow spacing (WIS): Let us now look at vineyard performance in the same environmental, management, and structural conditions, but at 1.7 m intrarow spacing (Fig. 8). To retain the same 15-cm spur array along the row, pruning will have to leave about 11 two-bud spurs, or 22 buds per vine, to keep the same 6 to 7 spurs and 12 to 14 buds per meter of hedgerow.

The WIS means a lengthening of the permanent cordon and more buds per vine, *i.e.,* from about 16 at OIS to 22. The vines will likely respond to this overload by triggering a self-regulatory mechanism to reduce vegetative growth potential, the effects being an increase in the number of buds, which even on the spurs are likely to remain latent, and the failure to burst of the non-count and secondary buds [43,78]. Yet given the greater length of the permanent cordons, each vine will develop more shoots and clusters than its counterpart in the OIS vineyard [15,16,17,18].

A check of the WIS's canopy structure several years later will reveal a drop in shoot and cluster number per meter of hedgerow, noticeably bare patches of cordon, and an evident, though not widespread, drop in vigor with consequently excessive canopy gaps [2,30,43,77,78]. The shoot growth rate will have slackened and become irregular, even ceasing altogether for some shoots before bloom [31,43,77,78]. This means under-exploitation of full trellis height, ensuing diminution of leaf area per cluster and a retarded ripening process destined to end before achieving full potential. While crop load per vine may even reach 5 kg, it will drop to about 3 kg per meter of hedgerow, *i.e.,* below the optimum 3.5 kg/m at OISs 1.2 m spacing.

The WIS equilibrium values will obviously be different from OISs. The TLA/ELA and TLA/G ratios will be lower (below 1.5 and 1, respectively) because of the insufficient leaf area, whereas the G/W index will rise (over 10) as crop development rate is greater than that for same-year wood.

Attempting to bring such a vineyard more into line with OIS will necessarily entail shortening some cordons, though this will create empty spaces along the hedgerow, and resorting to heavy inputs of nutrients, though their proper amounts are difficult to ascertain and their result is almost always short of the mark. Rehabilitating a weak vine is no simple task because the irregular shoot growth and stunted berry maturity tend to persist over the years, while the increased vigor attained by cordon back-pruning and nutrient inputs by no means ensures a regaining of crop quality. Indeed, the latter objective can only be achieved by eliminating or thinning the clusters from the weaker shoots and vines—a practice involving a further drop in yield and a marked rise in management outlays.

Narrow intrarow spacing (NIS): Let us now turn to a vineyard under all the usual model conditions but with a 0.7-m intrarow spacing (Fig. 9). Keeping the usual 15-cm spur array here means each permanent cordon will have 4 to 5 spurs with two count buds, for an average 9 buds per vine, or six spurs and 12 buds per hedgerow meter. The tighter spacing with respect to OIS calls for shorter cordons and a bud load per vine that drops from 16 to 9.

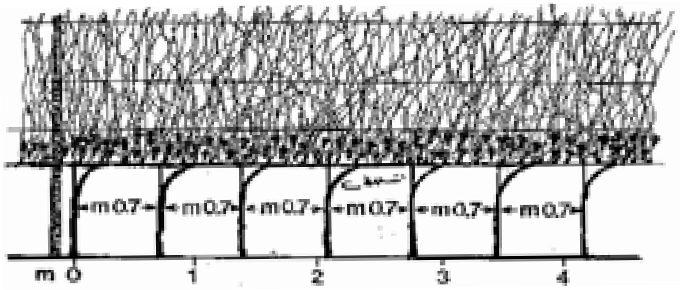

Figure 9 NIS hedgerow at 0.7-m intrarow spacing. With respect to OIS, vine development should be marked by excess vigor, higher yield per linear unit of hedgerow and lower crop quality.

The more limited bud number per vine here will again trigger a self-regulating physiological mechanism, this time to boost shooting [43,79]. As not only the count but also a certain number of non-count, secondary, and latent buds, some with clusters, will burst, shoot number and potential yield per vine will be higher than expected from estimates using the count bud-load per cordon [30,31,43]. Yet with respect to OIS, while the closer intrarow spacing and the shorter cordons will result in a lower shoot and cluster number per plant [15,16,17,18], shoot and cluster number per meter of hedgerow will be higher [43].

The lower bud number of NIS vines will generate faster growing shoots whose vigor will promote the development of a marked number of laterals [44,54,78]. The seasonal growth rate will slacken but slightly at bloom and then resume a rapid pace until after veraison, thereby determining competition with the ripening clusters.

The increased canopy density along the hedgerow [7,25,32,44,54,69] means heightened shading of the innermost leaves and the cropping zone. The shoots, in fully exploiting trellis space, will extend above and beyond it into the interrow alley, thereby casting further shade over the bottom parts of the hedge and the bunches [2].

Figure 10 A high-density vineyard in the Bordeaux district: note that the excessively narrow intrarow spacing (left) with respect to environmental potential leads to pronounced vegetative vigor and shading. The result is the need for radical topping (right) to enhance light penetration and canopy air circulation but adversely affects leaf area, yielding in turn to slower berry ripening.

Repeated topping above and on the sides of the hedge will be needed to enhance light interception and promote air circulation inside the canopy (Fig. 10), steps that will also stimulate the development of laterals, which in turn will result in greater competition with clusters and a more compact canopy.

Even the NIS vineyard, then, with its overly low bud load, deviates from the OIS model because of its excessive vigor and longer growth cycle [23], the result being a retarded accumulation of carbohydrates in the berries and poor wood hardening. Even cluster thinning is useless in such circumstances as it merely increases the risk of promoting shoot growth and further retarding maturation. Yield in the NIS will likely be about 3 kg per vine, or approximately 4.5 kg/m—far above the OISs 3.5 kg/m. The marked vine vigor will also affect the equilibrium indexes. While the ratio of TLA to ELA and that of TLA to G will increase (over 2.5 and 1.5, respectively), because of the greater density and foliage per hedge wall, the ratio of G to W will diminish to very low values (3 - 4) as the amount of wood will grow disproportionately to yield.

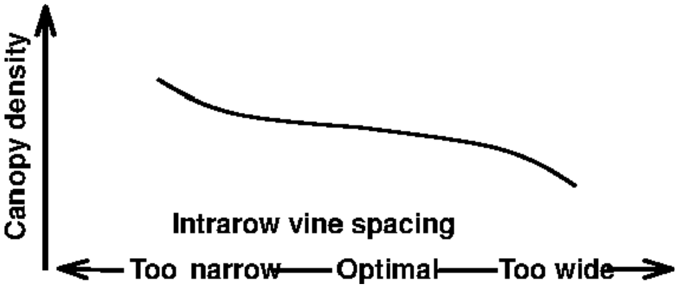

Figure 11 Projected variation in canopy density along the hedgerow in a given environment as a function of changes in intrarow vine spacing.

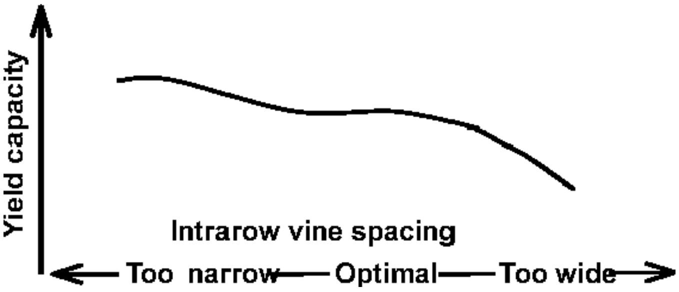

Figure 12 Projected variation in yield capacity along the hedgerow in a given environment as a function of changes in intrarow vine spacing.

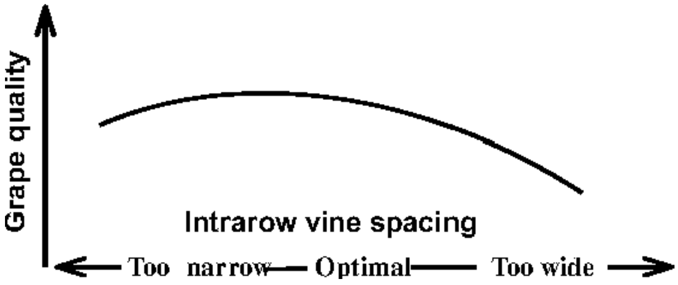

Figure 13 Projected variation in grape quality in a given environment as a function of changes in intrarow vine spacing.

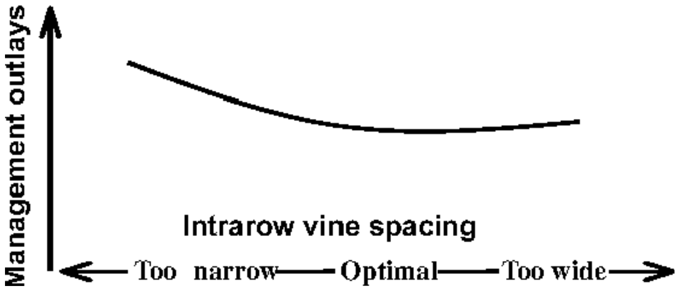

Figure 14 Projected variation in management outlays in a given environment as a function of changes in intrarow vine spacing.

Intrarow spacing. ***Remarks:*** These models indicate that in the same given conditions even a relatively moderate change in intrarow spacing (*e.g.,* 1.2 in OIS as opposed to 1.7 in WIS and 0.7 in NIS, which in fact amounts to about 40% either way) can shift the vines from a stable state of 'physiological equilibrium' to an unstable one at odds with the ecosystem. Imbalanced soil-climate conditions with respect to planting density require corrective action (*e.g.,* back-pruning, topping, nutrient inputs, cluster thinning), but this merely increases management outlays without necessarily achieving the desired results.

Clearly, as many researchers have pointed out, proper intrarow spacing of vines in a given environment is the primary factor in keeping such steps to a minimum and in achieving quality grapes; improper spacing spells lower returns and lower crop quality [2,15,16,17,18,23,44,79]. Thus, tentative models embodying the variations towards either end of the OIS range can be postulated for canopy density (Fig. 11), yield capacity (Fig. 12), grape quality (Fig. 13) and management inputs (Fig. 14).

In practice, appropriate decision-making should focus on intrarow spacing as the key parameter against which the others must be measured if costly management outlays to bring the vineyard back into equilibrium are to be avoided. It should be noted too that, quite apart from the question of crop quality, and contrary to what is often thought, WIS almost always tends to diminish and NIS to increase yield, except in the latter when spacing becomes so narrow as to induce excessive root competition and/or canopy density [24,43,45,57].

Interrow Spacing

Most of the data in the literature suggest that interrow spacing is the key variable to increasing or diminishing a vineyard's yield capacity per unit of acreage without altering berry quality [45,72,73]. At constant intrarow density, the fact that interrow spacing induces no effects on crop quality is corroborated whenever that spacing is sufficient to prevent both reciprocal interference by roots of contiguous vine rows and excessive interrow shading [2,3,68]. In a low-vigor vineyard [61], berry quality is not affected at interrow spacings from 1.6 meters on (Fig. 15). In soil of average fertility [4], it can be assumed that shading and root interference by contiguous vine rows ceases

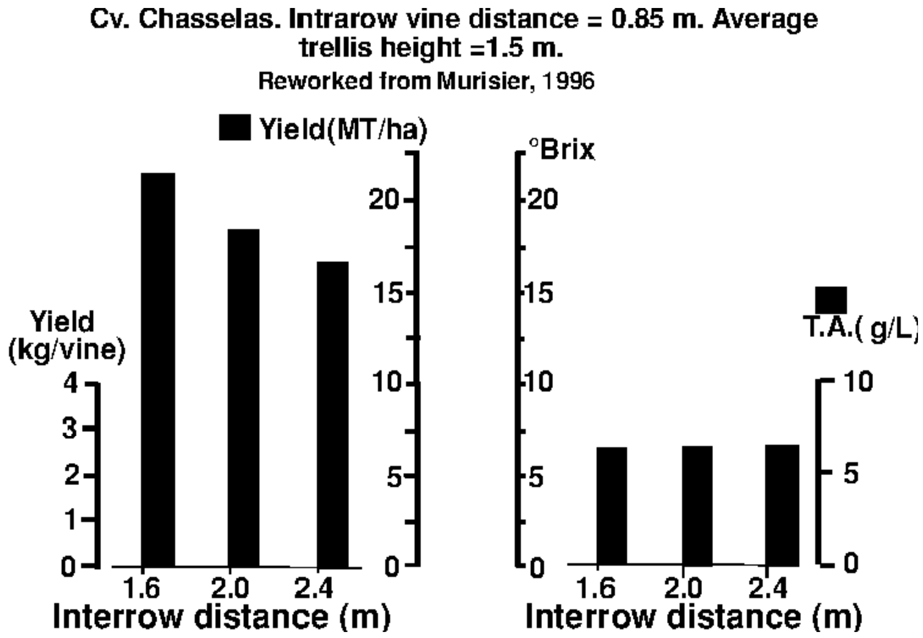

Figure 15 Most of the findings reported in literature suggest that interrow spacing is the primary variable in determining an increase or drop in a vineyard's yield capacity per unit of acreage without altering crop quality. This assumption is corroborated wherever interrow spacing is such as to eliminate root interference between contiguous rows and excessive, reciprocal shading. In a low vigor vineyard berry quality was not affected at interrow spacings from 1.6 meters on.

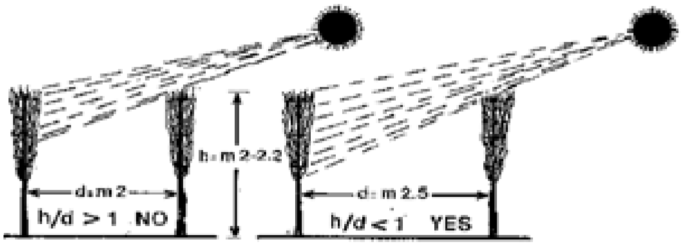

Figure 16 In soil of average fertility, it can be assumed that root interference by contiguous vine rows ceases altogether starting at interrow spacing from two meters on. However, considering the trellis height and the hedge thickness of our posited "model" vineyard the minimum interrow spacing to eliminate shading in the paradigm shown here cannot be less than 2.5 m.

Table 1 Effects determined by variations in interrow spacing on row number and total hedgerow length in a 100 m^2 "model" vineyard trained to spur-pruned cordon as in Figure 3.

Interrow spacing (m)	Attainable rows (no/ha)	Cropping wall length (m/ha)
2.5	40	4000
2.7	37	3700
2.9	34	3400
3.1	32	3200
3.3	30	3000
3.5	28	2800

altogether starting at interrow spacing from two meters on. Accordingly, if we were to take the single hedgerow of our posited model above, we could add others next to it at, say, a two-meter interrow spacing (Fig. 16).

Yet such a spacing narrows as the hedges grow thicker and would end up being less than the maximum height allotted to trellises (2 - 2.2 m), thereby generating canopy shading by the adjacent hedgerows [76]. At mid-northern latitudes (35 - 45°) and in N-S layouts, the *h* to *d* ratio (trellis height to actual interrow distance) should not be greater than 1 so as to prevent one hedgerow's casting its shadow on another in the morning and afternoon hours throughout the spring-summer growing season [6,55].

There are also practical reasons why two-meter interrow spacing is almost always ill-advisable. As canopy thickness would narrow the interrow alley width to just over 1.5 m, the ensuing difficulties for vehicle transit and stability, especially in hillside vineyards, could only be obviated by using over-row machinery. Such alley narrowing would entail in turn repeated edging operations and drastically reduce the active leaf area.

For the sake of overall simplicity and to avoid problems of field management, let us assume that the interrow spacing varies from 2.5 to 3.5 m, *i.e.,* the most common range actually found in most districts, and take a look at how the top and bottom spacings of this scale perform. A sample one-hectare square (100 m per side) can thus accommodate a maximum of 40 and a minimum of 28 rows each 100 m long, or 4000 to 2800 linear meters of cropping hedgerow (Table 1).

Keeping the intrarow spacing at OISs 1.2 m means that total vine number ranges from 3333 to 2333 per hectare (Table 2). If the optimum yield is 3.5 kg per hedgerow meter (4 kg/vine) for a vineyard in a state of physiological equilibrium for a given cultivar and product type (though differences in the latter two factors can obviously change the yield optimum), the per-hectare yield will range from about 14 to about 10 metric tons (MT), given the number and overall length of our rows (Table 3).

Note that variations in vine number and yield per hectare do not affect grape quality in that intrarow vine spacing is unchanged (1.2 m), as are yield per vine (4 kg) and per hedgerow meter (3.5 kg). This supports the assumption that, in addition to the "physiological equilibrium" principle, quality and quantity are not inversely correlated in absolute terms but depend on vineyard de-

Table 2 Effects determined by variations in total hedgerow length on vine number/ha at a 1.2 m intrarow spacing (OIS) as in Figure 3.

Cropping wall length (m/ha)	Interrow spacing (m)	Total vines (no/ha)
4000	1.2	3333
3700	1.2	3083
3400	1.2	2833
3200	1.2	2666
3000	1.2	2500
2800	1.2	2333

Table 3 Effects determined by variations in total hedgerow length on yield (metric tonnes, MT)/ha at a 3.5 kg yield/hedgerow meter at 1.2 m intrarow spacing as above.

Cropping wall length (m/ha)	Per unit yield (kg/m)	Total yield (MT/ha)
4000	3.5	14.0
3700	3.5	12.9
3400	3.5	11.9
3200	3.5	11.2
3000	3.5	10.5
2800	3.5	9.8

sign (all other variables like environment and cultivar being equal) and are respectively affected by intra- and interrow spacing.

If we were now to widen just the interrow spacing to 5 m, only 20 hedgerows can be planted, or 2000 linear meters, totaling 1666 vines at the 1.2 m intrarow density; the same 3.5 kg/m (4 kg/vine) yield will result in a total of about only 7 MT, without any compensation for quality. It is thus evident that neither the number of vines nor the yield per hectare (both varying here only as to row number) has any "absolute" meaning insofar as quality is concerned.

Interrow spacing. ***Remarks:*** Our model indicates that while "yield per linear meter" is directly linked to the "demanded quality" grade, intrarow spacing (which depends on the environment), total yield and total vine number per hectare (which in turn depend on interrow spacing) are not, and can only be determined *a posteriori*. That within certain limits different interrow spacings are possible, thereby enabling as many different cropping-wall lengths (*i.e.,* a greater or lesser hedgerow number) and a resulting differentiated yield without altering quality, is of particular practical interest. The ability to increase row number and potentially to achieve higher yields than those of old plantations, in addition to the benefits modern vineyard design provides for integral mechanized management at lower overall costs, may act as an incentive to vineyard renewal wherever such renewal is needed to enhance crop traits but is objectively stymied by low returns on investment.

What we see in Europe is the direct opposite of these findings. Indeed, the current legislation for DOC districts is based on yield per hectare, this parameter being assumed as the only one governing grape quality. The guidelines for the new hedgerow systems, with their advanced design and management concepts, should instead be based on yield per meter — the key parameter determining quality. Such an innovation could also convince growers to replace many uprooted vineyards because under certain conditions total yield can be increased without altering quality, thereby putting a stop to the indiscriminate reduction of Europe's viticultural potential.

A simple example can demonstrate the anachronism of the yield-per-hectare dictum. One need look no further than at many old vineyards in such justly famous areas as Italy's Piedmont, Friuli, Veneto, and Tuscany, to see the marked gaps left in the hedgerows by various vine diseases (*e.g.,* esca, fungi, viruses) and to realize that their yield capability is often noticeably curtailed (even more than 30%). This state of affairs has sometimes led to ambiguous "underestimating" of real yield capacity and, thus, reduced yield limits in the regulations for DOC areas. It can also lend itself to the abuse of "loading" the surviving vines beyond their physiological limits so as to meet the maximum per-hectare yield requisites, the rise in output per vine and per meter of hedgerow skewing the relationships with the ecosystem and lowering grape quality. By contrast, even if grape quality is high, they can be downgraded and earmarked for distillation simply by being declared as surplus under the yield-per-hectare DOC regulations. Thus, the prestige of the DOC areas would be better safeguarded both by strict berry quality control upon delivery to vintners and, above all, by compliance with the "yield per meter" requisite.

Planting Density Limits and Physiological Equilibrium

The inescapable point of our entire discussion is to set limits to planting density and yield which are consonant with the "physiological equilibrium" found in the various viticultural ecosystems. Given that in many areas an optimum density for a hedgerow vineyard is consistent with our model of a 1.2-meter vine intrarow and a 2.5 to 3.5 interrow spacing, overall planting density can range from about 3300 to about 2300 vines/ha, for a row length of 4 to 2.8 km per hectare. If more limiting soil-climate conditions were to dictate an intrarow spacing of one meter or slightly less, the total density for a balanced vineyard at the peak 4-km length could be as high as 4500 vines/ha, although by virtue of quality control its overall yield would not exceed the acreage threshold correlated to a constant yield per meter and not per vine.

Higher densities of, say, 5000 to 6000 vines/ha, and greater hedgerow length (about 5 - 6 km/ha), which at the same yield per cordon-meter would produce a matching increase of the peak theoretical yield, can only be envisaged for divided-canopy training systems like the Geneva double curtain (Fig. 17) and lyre (Fig. 18) (wherein each row meter results in two meters of hedgerow). Because these layouts feature an architecture marked by closely arrayed, adjacent horizontal cordons along the row, they enable an interrow spacing of 3.5 to 4 m, a transit alley of about 2.5 m, and 1.2 to 1.5 m between fruiting walls. Since these systems double the per-vine cordon length with respect to intrarow spacing, they also enable spacing to be narrowed to about 0.5 m, or a maximum planting density of about 6000 vines/ha. Yet if special cases like divided-canopy systems are excluded, nearly all researchers, including the French in the *Groupe Européen d'Etudes Systèmes de Conduite de la Vigne* (GESCO) [13, 14,19,20,52,53,59,60,69,70,71], are no longer advising planting densities above 5000 vines/ha.

Worldwide data also extol the benefits of medium density planting (MDP) with respect to high (HDP) and low density planting (LDP) in ensuring well-balanced environmental conditions [1,8,58]. Australian and American researchers indicate 2500 to 3500 vines/ha as the ideal density for crop quality in most of their districts. Practical corroboration of this leaning towards MDP comes from the State of California's Extension Service. It has recently reported that the new hedgerow vineyards in the Napa Valley and North Coast, which were replanted after being wiped out by phylloxera, are usually being planted at 2200 to 2700 vines/ha [26].

Figure 17 A double-curtain vineyard at a density of about 5000 vines/ha. Only double-curtain systems enable higher densities than the usual 3000 to 4000 vines/ha in Italy's districts.

Figure 18 A lyre system next to a traditional, high-density, short hedgerow in the Champagne district. Unlike the traditional system's 6000 to 8000 vines/ha, double ones like the lyre feature taller vegetative walls and generally lower densities—2800 to 3500 vines/ha.

These densities are higher than those of the earlier LDP vineyards (1500 - 2000 plants/ha) but far lower than the textbook HDP vineyards (6 - 8000/ha peak) in various European districts. Even for many of France's reputedly "poor fertility" growing areas like Bordeaux and Champagne, the GESCO researchers have pointed out the yield and quality advantages to be reaped by replacing the traditional short HDP hedgerows with the new divided-canopy Lyre (Fig. 18) featuring taller leaf walls at MDP (2800 - 3500 vine/ha).

Countless experimental and technical data in the literature thus indicate that in all growing areas, whether under traditional or modern systems, research has established new management parameters based on a "physiological equilibrium" with the environment. This balance is held as indispensable for quality and can be attained by limited inputs only if the planting density, as assessed by proper indexes, is in line with the ecosystem's potential. These equilibrium indexes have also been used to show the inaccuracy of certain traditionally held beliefs, especially those which axiomatically established a direct correlation between planting density and crop quality and an inverse one between yield quantity and quality. Put another way, the data evince that in traditional growing areas the old HDP systems should almost always be reduced and the old LDPs augmented so as to improve quality; and that there is no basis in fact for an "absolute" negative correlation between quantity and quality (of grapes and wine) in that these two variables should be taken separately as a function of vineyard design.

Vineyard Design and Industry Guidelines for the 21st Century

Let us now return to the question 'Whither Europe's viticulture?' Obviously, some areas will need to move towards higher densities than heretofore (keeping intra- and interrow spacing within physiological limits) so as to recover quality and correct past mistakes. It is just as obvious that, at equal quality levels, many districts have a potentially higher yield capability than is commonly believed, especially where vineyard reconversion involves reducing interrow spacing within physiological and management limits.

For example, if we look at Europe's various DOC regulatory guidelines from this vantage point, there are well founded reasons to believe that they are not in the best interests of its viticultural heritage or technical progress because they generally insist on the "peak-yield-per-hectare" requisite. The result is that, often for merely psychological reasons, yield constraints are at times so artificially low (in some cases difficult to comply with) as to continue to penalize even quality grapes and, presumably, to contribute to the acceleration of vineyard uprootings and to replanting restrictions. These regulations also contain another feature that may prove to be an obstacle to a rapidly developing industry. The compulsory requisites for many DOC areas include among the parameters to be established *a priori* vine number per hectare, which instead is a typically dependent variable subordinate to the decision about the intra- and interrow spacing needed for physiological equilibrium. That certain basic scientific criteria have failed to be included in the DOC regulations is also seen in the way certain requisites like maximum yield per vine, another dependent variable, are made mandatory.

For example, a recent directive for a new DOC area in Italy states that such vineyards must have a density of at least 4000 vines/ha and yield limits of 1.5 kg per vine and no more than 6 MT/ha. A practical analysis of this directive shows that if a grower were to use a 2.5-m interrow spacing (or 4 km/ha of hedgerow), the vines would need a 1-m intrarow spacing to attain the prescribed minimum density. Yet, wherever field conditions are compatible with vine growing, yield at that intrarow spacing will almost always be higher than 1.5 kg/vine, making expensive yearly cluster thinning necessary even if the berries exceed the quality standard. But if, at the same interrow spacing, the vines were planted at 70-cm intrarow density to reduce per-vine yield to the requisite 1.5 kg (with the attendant risk of skewing equilibrium because of excessive growth), the ensuing density of 5700 vines/ha would result in a yield greater than 8.5 MT/ha. Thus, even if berry quality is high, 30% of the bunches would have to be eliminated to meet the legal requirement. Even if interrow spacing were set at 3 m (3.3 km/ha of hedgerow) to attain a density of at least 4000 vines/ha, intrarow spacing should not exceed 80 cm even in high-fertility soils, though this will still result in adverse effects on vineyard equilibrium and management.

The artificial constraints introduced by the parameters vines per hectare, yield per vine, and yield per hectare, which for agronomic and physiological reasons are independent of each other, markedly limit decision-making options and imply costly and, at times, useless corrective steps. By contrast, it would be sufficient to posit, along with the minimum quality-grade requisite, the maximum yield per meter of hedgerow to achieve better results and to leave growers greater room in decision-making. This, then, is the background against which the future of Europe's viticulture industry is to be played out.

Indeed, the time has come to change the idea that quality viticulture is embodied solely in "low-standing, low-yielding HDP" vineyards, that are forcibly kept under control through management practices both costly and at times of adverse impact on the canopy and cropping. Such approaches are not compatible with the climatic and soil conditions in many areas (not only in Italy), and they may even induce a state of precarious balance between the plants and their ecosystems without necessarily enhancing crop quality.

Thus, planting density, yield per vine, and yield per hectare would no longer be "absolute criteria." Rather, they would become technical parameters having scientifically verifiable limits and capabilities linked to the requisite quality standard and the energy resources of climate and soil. Thus in any up-to-date regulatory code, all that Europe's premium districts need are a few, clear-cut guidelines which are firmly grounded in parameters of grape and wine quality and quantitatively expressed simply by yield per meter. Indeed, the role of legislation should be to support new plantings and generate a viticulture grafted to crop quality and the principal of an equitable return on investment — a task that merely requires an open-mindedness free of preconceived ideas and commonplace notions.

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