Berry Size and Yield Paradigms on Grapes and Wines Quality

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Abstract

A key objective of this review is to open a discussion on what we really know about the effect of berry size and yield on grape and wine quality. Even if berry size and crop yield are widely recognized as important factors in the quality of resultant wines, most prior research has shown no effect of yield on wine quality, and the direct effect of berry size has not been evaluated. Recently, some pruning, thinning and irrigation experiments were done to test independently for relationships due to size and yield compared with those due to the normal cultural practices used to control yield (thinning, pruning and irrigation). Data from these experiments have clearly shown that these considerated practices affected in an independent way berry size and yield producing grape and wine of different quality. This renders the generalizations asserted in both of the paradigms unfounded.

We draw these conclusions about the dependence of composition on yield and berry size: the viticultural practices used to control yield in a vineyard may be more important than the yield or berry size values per se in determining the quality of the resulting grapes and wines.

REVISITING PARADIGMS OF WINEGRAPE QUALITY

There is good evidence that viticulture and winemaking go back almost as far as civilization itself, perhaps earlier than 5,500 B.C. (McGovern, 2004). Regardless of the specific era of their emergence, it is clear that these endeavors have been with us for a very long time. From that history, much remains as tradition and belief. Indeed, most of what we do as viticulturists and winemakers is attributable to historical and traditional causes. Mixed up in there are probably some mistaken explanations for why certain traditions or practices are in place. This is inevitable. Humans (their minds) make things up to explain to themselves what they experience and 'the nature of things'. Some long standing viticulture practices and explanations may have arisen out of superstition, mysticism, trial and error, the authority of others, or tradition. Tradition is comfortable, comforting, and effective for marketing. But, tradition is the lack of change. Science is, by contrast, modern – originating from Galileo or Copernicus, about 400 years ago – and direct to change or new understanding. Science, which necessarily involves measurement and usually experimentation, is by any account a remarkably successful way of understanding the natural world. The history, from the Age of Enlightenment, of science in agriculture reflects much progress in our understanding of how to cultivate plants for our sustenance and satisfaction. Yet, several paradigms of viticulture appear to have little basis in a science of experimentation and measurement.

This paper addresses two aspects of what we consider received knowledge in viticulture: berry size and crop yield. In particular, it was assumed that small berries and/or lower yield produce higher quality wines and quasi-science has added putative explanations for the putative observations:

Exhibit A: Small berries make better wine – due to higher surface:volume;

Exhibit B: High yield means low quality as flavor compounds get diluted.

Can science address these received beliefs? Surprisingly little data have been generated. It is easy to change and measure berry size or yield. It is less easy difficult to evaluate their contributions to wine composition and wine sensory attributes. Thus, the truth about wine quality is difficult to discover. It is of up most importance to note that this difficulty is just as present for the traditional explanation as it is for any new relationships developed by experimentation.

Can science asses how much yield or berry size affects quality? This quantitative information is fundamentally important to production decisions: if the change in wine quality with increasing yield (or berry size) is in fact negative but measurably so only at yields (or at berry sizes) above some threshold (Fig. 1 curve c), producers can exploit this knowledge to produce high quality wines over a range of yields (or berry sizes) not to exceed some value. Alternatively, if the yield (berry size) response is as shown in curves a or b of Figure 1, yields (berry sizes) above some intermediate value will all produce low quality wine, and only the wine with the lowest yield (berry size) will be best.

Moreover, sensory science is a new science, among sciences. It is difficult because the subjects are humans, who make things up to explain their sensory inputs. Wine quality scales are necessarily dependent upon the 'judges' interpretation of quality. Nevertheless, there has been much progress in developing objective metrics of the sensory experience. A more fundamental and scientifically accessible question is: what sensory attributes are reproducibly detectable as a consequence of variation in berry size and yield?

BERRY SIZE

Berry size is widely recognized as an important factor determining winegrape quality. However, this concept has gained acceptance primarily on the basis of intuition and implicit assumptions with little experimental evidence. Singleton (1972) estimated the role of berry size by removing and adding juice at crushing. However, there were no measurements conducted to indicate that the juice/solids was greater in larger berries. In its most simplistic form, the relationship, in which larger berries are less desirable, is described as a consequence of water diluting solutes of importance for wine flavor (Fig. 2a). This explanation misses important physiological factors of berry size. First, berries do not grow by 'pumping' water into a vessel (berry) of flavor solutes. Berries attain size via a double sigmoid growth habit. Growth is a complex process in which dry weight (cell wall, membrane, solutes, etc.) increases as well as fresh weight (Fig. 2b). Water flux into cells occurs because the cell sap accumulates solutes creating a water potential gradient down which water flows. The solutes in berry cells are translocated into the berry or synthesized from translocated solutes. The total amount of solute present in the berry is dynamic and generally increasing during growth and development.

For the solutes to be diluted would require that water influx exceed solute influx.

It is clear that plant tissues, and perhaps fleshy fruit like berries more than others like woody stems, act as capacitors for water on a daily basis. From this it does naturally follow that fruit harvested in the afternoon will contain less solvent water than the same fruit harvested at dawn. However, in the grape berry, this capacitance is dramatically reduced after veraison (Greenspan et al., 1994, 1996).

FLESH SOLUTES: ACCUMULATION OF SUGARS

The sugars in ripe berries are present at high concentrations in the flesh, and are not localized in the skin (Coombe et al., 1987; Possner and Kliewer, 1985). Thus, if there were a constant amount of sugar per berry, the concentration of sugars would decrease in a linear fashion as suggested in Figure 1, curve a. Matthews and colleagues collected about 1,800 Cabernet Sauvignon berries, which were sorted into 6 size categories, separated into skin, seed, and flesh, and analyzed for composition. Berry mass varied from about 0.4 to 1.6 g. The amount of sugar per berry was not constant, but increased linearly with berry size (Fig. 3). The strong correlation (r^2=0.99) indicates that the appropriate generalization is that sugar content is proportional to size; not that sugar content is constant (Roby et al., 2004).

When the concentration (Brix) was plotted vs. size, a negative relationship was obtained, although the slope was rather shallow with a 10% decrease in Brix over the 4 fold increase in berry size from 0.4 to 1.6 g/berry (Fig. 3).

Several early studies also showed some decrease in sugar concentration with increasing berry size (e.g. Muller-Thurgau, 1898; Scienza et al., 1978, Cawthon and Morris, 1982). Kasimatis et al. (1977) reported in a series of regression analyses of fruit from several vineyards, that the correlation between Brix and berry size in Sultana was as often positive as it was negative. The negative relationship between Brix and size observed in some, but not all, other studies cannot be a consequence of the surface:volume of berries, because the sugars that dominate the Brix assay accumulate in the flesh as much or more than in the skin (Coombe et al.,1987).

SKIN MASS VS. SKIN SURFACE AREA

The putative role of berry size gains support from the well-established accumulation in the skin of some solutes that are of interest in wines. Anthocyanins and some other phenolic compounds that give to red wines their unique characteristics accumulate in the skin (Coombe et al., 1987, Possner and Kliewer, 1985). Upon crushing for fermentation, there develops an inescapable dilution of those solutes by nonskin sap. Beyond this observation, we found no data relating skin solutes (except potassium, e.g. Storey, 1987) to berry size and wine composition. It has been implicit that the amount of skin and/or skin solute is constant among berry sizes or constant after veraison such that post-veraison increases in berry size occur as a balloon would expand (Fig. 2b). Both of these ideas are unfounded. It is generally assumed that larger berries have a relatively greater flesh (solvent) compared to skin (solute) than smaller berries. Thus, lower concentrations of skin solutes necessarily result in musts and wines derived from larger berries. Several authors have referred to changes in fruit composition such that this dilution would occur in a manner described by the surface:volume ratio of a sphere, i.e. 3/radius (Gladstones, 1992, Hardie et al., 1997, Matthews and Anderson, 1989 Singleton, 1972). The general shape of the response curve predicted by the surface:volume is given in curve b of figure 1. Yet, it is clear that the skin has mass and volume, and, therefore, the amount of skin, skin solute, and dilution upon crushing may not behave as assumed, depending on berry development. It is similarly clear that solutes derived from seed would also undergo size-dependent dilution if the growth of seed is not tightly coupled to the growth of the flesh. Hence, it is important to better understand the distribution of berry sizes and skin thicknesses (volumes) as well as the potential to adjust berry size and skin composition via cultural practices.

Skin fresh and seed fresh weight were proportional to berry fresh weight (Fig. 4, r^2=0.99). Thus, if the concentration of solutes in skin tissue is constant, no size-dependent change in the concentration of skin solutes in musts is expected, because the amount of skin tissue increased proportionally with berry size. Roby and Matthews (2004) found that fresh weight of Cabernet Sauvignon berries was comprised of approximately 5% seed, 15% skin, and 80% flesh regardless of total fresh weight or volume, although there was some increase in relative seed mass ([total seed mass/berry mass] x 100) with berry mass. As for sugars, the appropriate generalization shown by the high correlation, is that both skin flesh and seed mass are proportional to berry size. These data indicate that skin is not ‘stretched’ around a larger and larger flesh, but grows with it. Same is true for seed mass, it is highly correlated with berry growth. Thus, among fruit developing under similar conditions within a vineyard, the growth of the skin and of the seed appear to be coordinated with the rest of the berry (flesh).

SKIN SOLUTES: TANNINS AND ANTHOCYANINS

Coombe (1987) has reported that solute concentrations in skin exceeded those in flesh (on fresh weight basis), with potassium, inorganic anionis, phenols, and tartrate at most stage of development. Tannins and anthocyanins are extremely important phenolics compounds in grape and wine quality. Anthocyanins are present in grape skin of red varieties, while tannins are normally present in skin, seed and stem. Their amount in grape and wine are affected by cultural practices and environmental condition during the growing season, and their extraction during maceration and fermentation (Kennedy et al., 2006).

Recently Roby and co-authors (2004) have studied the effects of berry size on the soluble solids, seed and skin tannin and skin anthocyanin, they have found that skin and seed tannin and anthocyanin content increased with berry size (Fig. 5). Skin tannin content increased with berry size from approximately 0.4 to 1.0 mg/berry. The concentration of skin tannin was relatively constant among the intermediate berry size categories (from 0.65 to 1.34 g per berry), although the data do exhibit a decrease (approximately 40%) from the smallest to the largest berries. The intermediate berry size categories accounted for more than 95% of the berries population (Roby and Matthews, 2004).

The increase in skin tannin content was less than that of seed tannin, and the increase of anthocyanin content considerably less than that of skin tannin (Fig. 5). Because the increase in anthocyanin content was less than the corresponding increase in berry fresh weight, the concentration of anthocyanins decreased with berry size at an average rate of about 0.17 mg/g berry fresh weight. More recently, Romero-Cascales et al. (2005) found a higher concentration of: anthocyanins, skin, and seed tannins in the smaller (1.23 g) Monastrell berries respect to the bigger ones (1.68 g), but the two berries categories were from two different localities (i.e. environments) and not from the same vineyard.

Taken together, these observations indicate that the composition of mature berries is not dependent in a simple way on the size attained by the berry.

BERRY SIZE AND WINE COMPOSITION

When the fruit size differences in fruit composition measured in the experiments of Roby et al. (2004), Roby and Matthews (2004) and Romero-Cascales et al. (2005) were carried through to the resulting wines and analyzed for tannins and anthocyanins, the results were consistent with the berry composition data discussed above. The highest tannin concentration was in the wine made from the smallest berries, but the differences were significant only in the data reported by Romero-Cascales (2005). It is important to note that seed tannin contributes to wine as well as skin tannin, and its effect on the wine tannin concentration is not known. The concentration of anthocyanins was significantly different among berry sizes. Wine made from smaller berries had higher concentrations of anthocyanins than wines made from intermediate or large berries (Fig. 6). The difference in concentration between the large berry wine and the small berry wine was about 28%, similar to the difference found by Roby et al. (2004) in the concentration of anthocyanins among berry sizes.

The differences in wine composition were slightly less dependent upon fruit size than the juice composition, suggesting a possible difference in "extractability". Both fruit and wine composition were much less sensitive to fruit size than the theoretical dependence that is predicted from differences in surface:volume of the berries.

ENVIRONMENTAL CONTROL OF BERRY SIZE

Vine water deficits generally lead to smaller berries and to several changes in wine composition (Bravdo et al., 1985, Kennedy et al., 2002, Matthews et al., 1990). Hence, the question arises whether changes in fruit and wine composition that develop in response to drought or irrigation arise simply from resultant changes in berry size. Again, as shown in table 1, the mechanistic explanation has been the change in surface area: volume among irrigation treatments (e.g., Matthews and Anderson, 1989). The relationships among berry size and mass of seed, skin, and flesh were evaluated for Cabernet Sauvignon fruit grown on vines exposed to High, Control, and Low water statuses after Stage I (Roby and Matthews, 2004). One important observation was that the growth of berries was much less sensitive to water deficits than that reported for other shoot organs, implying a limited potential for water status to alter wines via berry size (Williams and Matthews, 1990).

Water deficits inhibited growth almost exclusively in the mesocarp for most size categories. Skin and seed masses in any size category were both greater when berries developed under water deficits (Roby and Matthews, 2004). Thus, there was greater seed and skin mass in each berry size when the berry developed under water deficits. When fruit from different irrigation treatments were separated into size categories prior to analysis, the results showed that there are effects of vine water status on fruit composition that arise independent of the resultant differences in fruit size. Water deficits increased the concentrations of skin tannin and anthocyanins, but did not significantly affect the content or concentration of seed tannin (not shown). For berries in any of the intermediate size categories, skin tannin concentration increased 22-28%, and anthocyanin concentration increased 15-33% in water deficit berries compared to controls. The results show that there are effects of vine water status on fruit composition that arise independent of the resultant differences in fruit size. The effect of vine water status on the concentration of skin tannin and anthocyanin was greater than the effect of fruit size on those same variables. The results also show that for any berry fresh weight, late season water deficits resulted in more skin and seed tissue per berry than in control fruit.

Another independent means of manipulating berry size is via the cluster microclimate. Berry size is reduced by shading. When fruit have been exposed to different shading treatments, berry composition is also affected. This section deals primarily with data from Dokoozlian and Kliewer (1996) in which clusters, rather than shoots or vines, were exposed to various light intensities. The concentration of soluble solids, and flesh solute, increased with increasing berry size when size is manipulated by light (Fig. 7). Similarly the concentrations of the skin solutes anthocyanins and total phenolics increases with increasing berry size when size is increased by exposing the developing berry to 20% of full sunlight. For both flesh and skin solutes, the increase was approximately linear over the range of the low light intensities studied. It is important to note that the data in Fig. 7 are concentration data, not just content per berry. These results indicate a qualitatively different 'response' of berry composition to berry size than was observed when size was manipulated by water status or when size was not manipulated experimentally.

Berry composition exhibits fundamentally different relationships to berry size depending on the environmental conditions that give rise to differences in berry size. Arguments that solute concentrations are a function of water transport to berry are wrong for several reasons: water transport during ripening is primarily via the phloem, which has a sugar concentration of about 1M, as far as we know, so for any dilution to take place would presumably separate what is diluted from Brix, because Brix would be going up. The berry does little shrinking that might be associated with water loss either through the epidermis or via apoplast path to rachis after veraison until very late in the season.

The results imply a limited role of berry size, independent of other environmental factors, in determining the concentration of juice or wine solutes derived from skin and seed.

YIELD

Probably the most fundamental question in viticulture is that of yield and quality.

The prevailing paradigm asserts quality decrease with yield increase, but there are surprisingly little data in the literature (Chapman et al., 2005), and in that literature the treatments imposed are often dramatic and few, with 33-50% crop dropped and compared to a standard yield as a control being typical.

In our work, yield was adjusted in the three most common ways in winegrape production: pruning, cluster thinning, and irrigation.

To optimize crop level, it is essential to have an estimate of the amount of clusters that a vine can reasonably bring to maturity and to determine how the timing of ripening is dependent upon crop level. When crop level was altered several fold by establishing a high crop load and thinning to different numbers of clusters at veraison, berry size and berry composition were largely unaffected, but the time required to reach 23.5, 24, and 25

Brix was linearly dependent on crop level (Nuzzo and Matthews, 2006). Therefore, the dependence of wine sensory properties on yield that was adjusted over a threefold range in six treatments by pruning and by cluster thinning at veraison was studied in Cabernet Sauvignon vines in the Napa Valley of California using fruit that was harvested at similar Brix (Chapman et al., 2004a). Wines were evaluated both by sensory analysis and by chemical analysis. The descriptive analysis was performed by a trained panel of 14 judges. The focus of the descriptive analysis was on flavor attributes, particularly those driven by skin and seed solutes (fruity and veggy aroma volatiles, and bitter and astringent phenolics). Among the various chemical compounds present in Cabernet Sauvignon wines, MIBP (2-methoxy-3-isobutylpyrazine) – a strong odorant that is found in bell pepper, french beans and it is an important wine grape flavor in varieties such as 'Cabernet Sauvignon' and 'Sauvignon Blanc' - was significantly and negatively correlated with yield and buds per vine (Chapman et al., 2004a). The MIBP concentration was directly related to sensory vegetal intensity ratings obtained by descriptive analysis and inversely related with the number of buds per vine (Chapman et al., 2004b). Moreover, wine tannins and astringency ratings decreased with yield, and the astringency ratings were directly related to wine tannin concentration.

When crop level was altered several fold by cluster thinning method and by pruning, the pruning treatments had a much larger effect on the sensory properties of the resulting wines than the mid-season thinning treatments. There was a significant effect on 9 or 10 of 15 attributes when yield was changed by pruning, but only 3 of 15 attributes when yield was decreased by cluster thinning. As node number increased by winter pruning, fruity attributes increased in intensity and vegetal attributes decreased in intensity. This relationship was not observed among the wines in the thinning trial.

In a separate study of the impact of irrigation, vines were subjected to three irrigation treatments: minimal irrigation (no irrigation added unless the midday leaf water potential dropped below -1.6 MPa), standard irrigation (32 L water/vine/week) and double irrigation (64 L water/vine/week) produced midday leaf water potentials that were significantly lower in the minimal irrigation treatment than in the other treatments throughout the season. The treatments created yields that varied from 15.0 to 21.7 t/HA (Chapman et al., 2005).

The standard irrigation treatment wines were rated significantly higher than the minimal irrigation treatment wines in vegetal aroma, bell pepper aroma, black pepper aroma, and astringency. We conclude that water deficits lead to wines with more fruity and less vegetal aromas and flavors than does high vine water status (Chapman et al., 2005).

Thus, the relationships of irrigation adjusted yield to sensory attributes were the inverse of the relationships for pruning adjusted yield (Fig. 8). Therefore, the viticultural practices used to control yield in a vineyard may be more important than the yield values per se in determining the sensory properties of the resulting wines.

The results of these studies have clear implications for the role of yield and berry size in wine composition and sensory attributes. These results show that the amount of each skin solute is not a constant that is diluted to varying degrees dependent upon fruit growth. Accumulation of skin solute is coordinated with growth. Accordingly, the observed changes in fruit composition caused by water deficits are not attributable simply to differences in berry growth. There is an independent effect of deficit irrigation on composition. Because deficit irrigation produces lower yield, it is important to evaluate whether there is an independent effect of yield on these quality parameters. If the extraction of each solute is independent of size and water status, wine made from larger berries would contain higher concentrations of seed tannin and lower concentrations of anthocyanin. The ratio of seed: skin tannin would increase as the size of the source berries increases, because seed tannin increases while the contribution of skin tannin remains essentially unchanged.

CONCLUSIONS

Myths are creative explanations similar to scientific hypotheses, and when not subjected to scientific tests they can become perfect hypotheses that explain perfectly what they are supposed to explain. Here we evaluated with data two longstanding and widely held paradigms of viticulture for which there had previously been little quantified observations: large berries and high yields are inferior. The data are clear in that the results of independent means of changing berry size and yield produced qualitatively different results. This renders the generalizations asserted in both of the paradigms untenable.

The high yield, low quality paradigm may be applicable to environments in which sugar accumulation is limiting factor because reducing crop generally increases the rate of increase in sugar concentration in the remaining clusters.

We draw these conclusions about the dependence of composition on yield and berry size: the viticultural practices used to control yield in a vineyard are more important than the yield values per se in determining the quality of the resulting grapes and wines; and the environmental conditions determine berry size are more important the size per se in determining the quality of the grapes and resulting wines (Fig. 8).

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Tables

Table 1. Wine color, anthocyanins, and phenols, fruit yield and berry size, from vines subjected to different irrigation regimes. Data are from Matthews and Anderson, 1989; Matthews et al. 1990.

Treatment	Color density ($A_{(420+520)}$)		Total anthocyanins (mg L^{-1})		Total phenol (mg L^{-1})		Yield (kg $vine^{-1}$)		Berry size (g)	
	1984	1985	1984	1985	1984	1985	1984	1985	1984	1985
Early deficit	9.79	8.24	167	318	1630	1930	4.8	4.6	1.17	1.05
Late deficit	9.02	5.75	136	281	1470	1520	5.2	6.8	1.26	1.26
Continual	8.51	5.50	132	232	1310	1350	5.7	9.2	1.65	1.30
Full deficit		8.56		307		1990	4.3	3.6	1.16	1.05

Figures

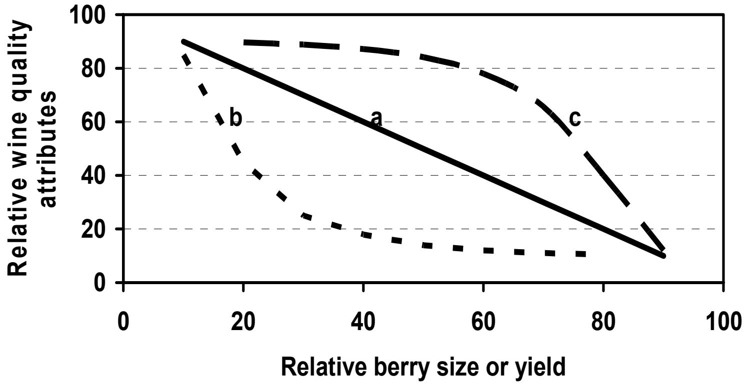

Fig. 1. Hypothetical wine quality response curves to increase of berry size or yield.

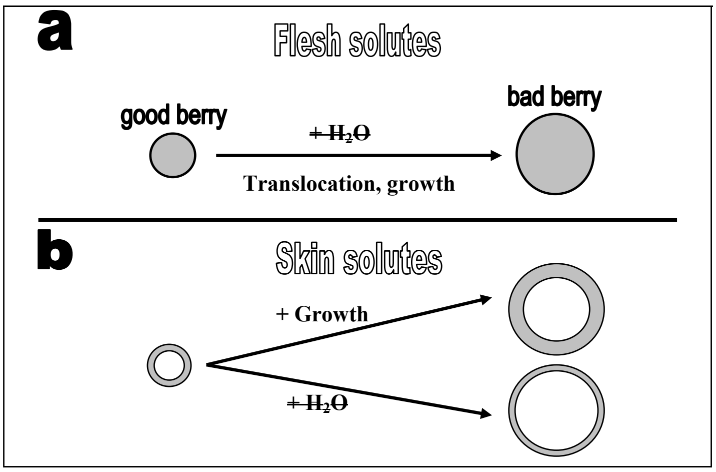

Fig. 2. The berry size paradigms for (a) Flesh solute and (b) Skin solute. Little berries are good berries because of the high surface:volume ratio (i.e. 3/radius) and become big bad berries by dilution with water. Berries do not grow by ‘pumping’ water into a vessel (berry) of flavor solutes, but final berry size is obtained after a double sigmoidal pattern of growth and fresh weight of skin tissue and seed increase proportionally with berry size (see also Fig. 4 and data from Roby and Matthews, 2004).

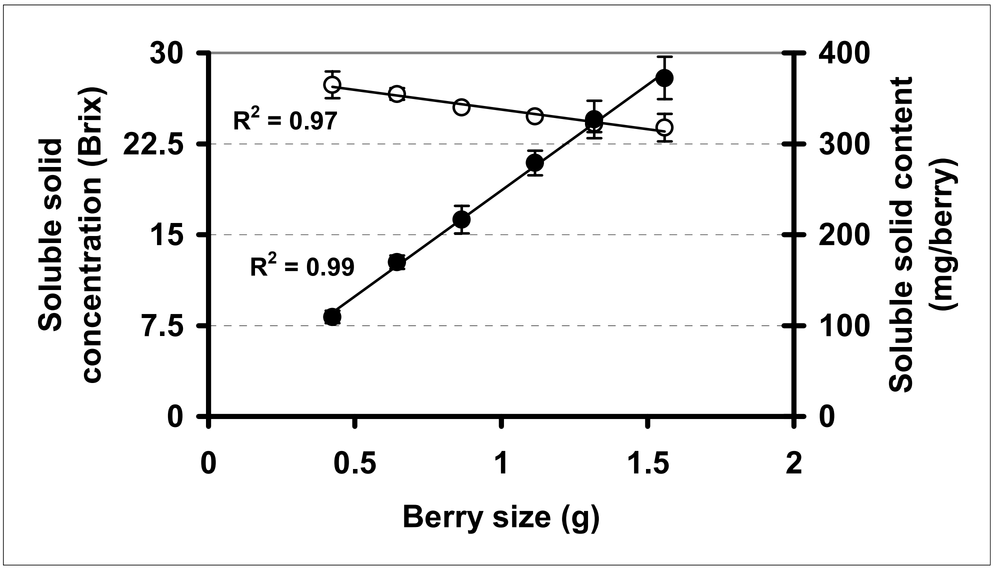

Fig. 3. The sugars concentration (Brix) decrease of about 10%, while sugars content (mg/berry) increase of about 280% over a 4 fold increase in berry size (data were re-elaborated from Roby et al, 2004).

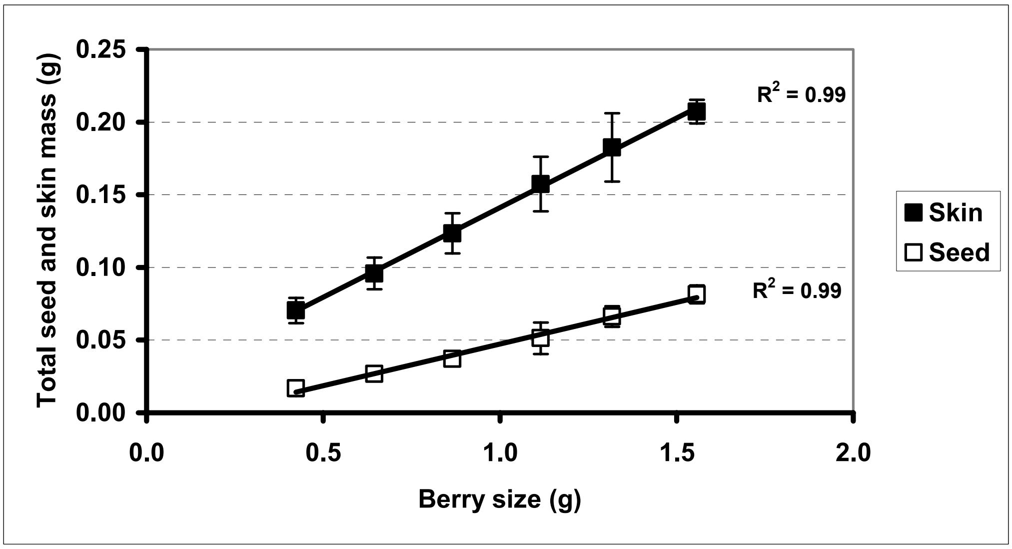

Fig. 4. Skin and seed mass in six different size categories of Cabernet Sauvignon berries (data were re-elaborated from Roby and Matthews, 2004).

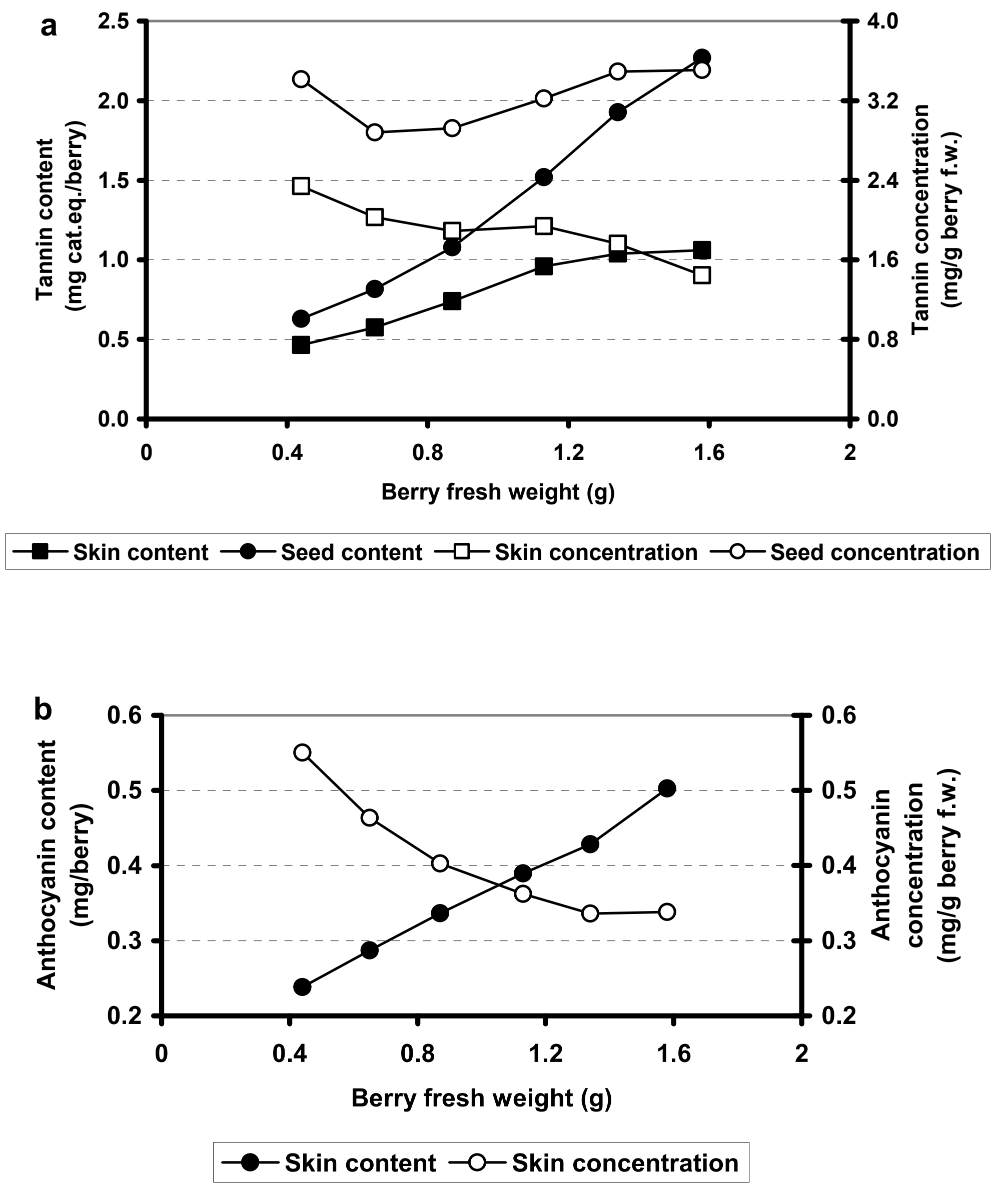

Fig. 5. Tannin and anthocyanin concentration and content in seed and skin of Cabernet Sauvignon berries (data were re-elaborated from Roby et al., 2004).

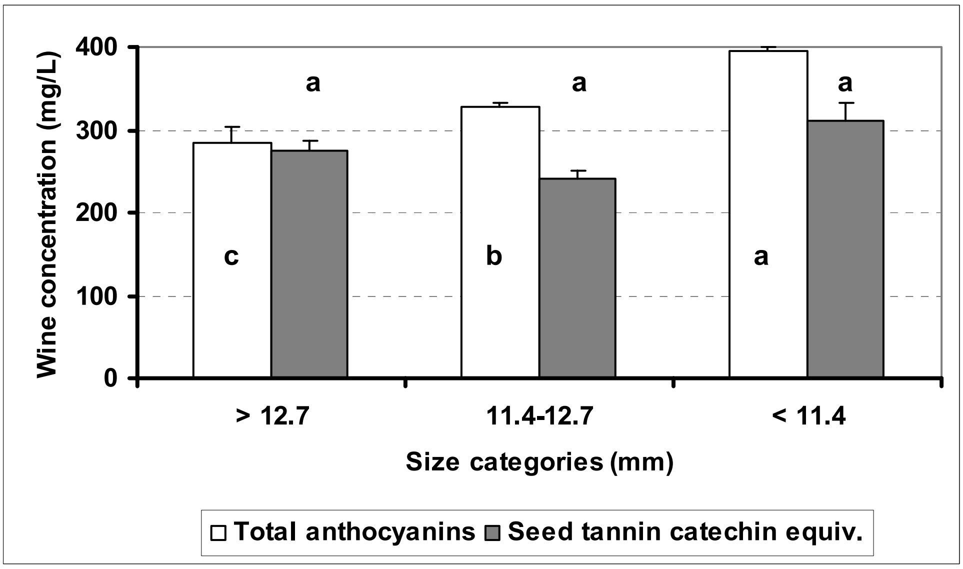

Fig. 6. Concentration of seed tannin and anthocyanins in Cabernet Sauvignon wines obtained from 3 berry size categories (Matthews, unpublished data).

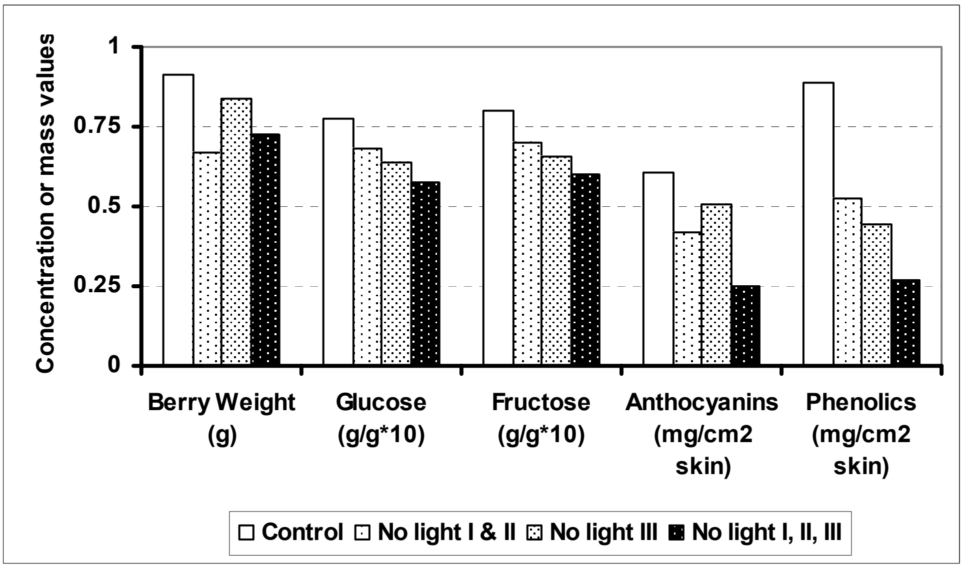

Fig. 7. Influence of cluster light exposure during various stages of fruit development on some characteristics of Cabernet Sauvignon grape berries at harvest (data were re-elaborated from Dokoozlian and Kliewer, 1996).

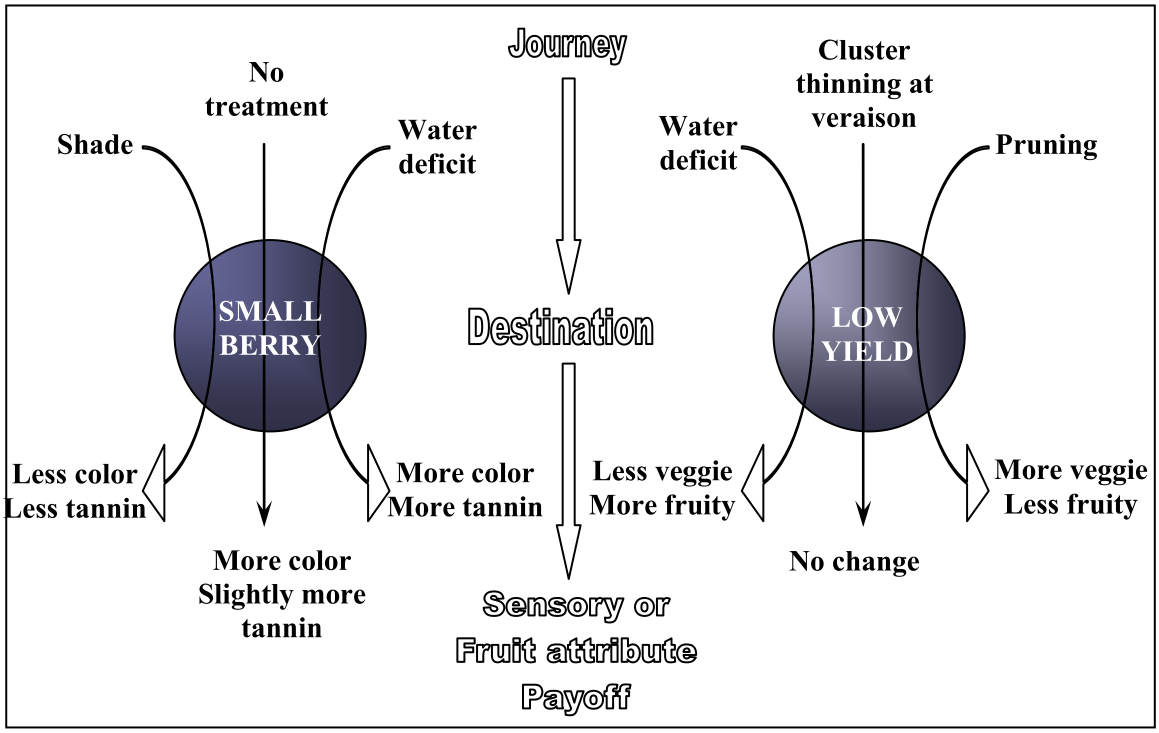

Fig. 8. A schematic representation of the effect of some treatments which produce small berries and or low yield on sensory and fruit attribute payoff.