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Grapevine Vigour and Within-Vineyard Variability: a Review

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Abstract— Vine vigour involves the production capacity of the vine. Production capacity encompasses shoot and leaf production, as well as grape production. It would benefit grape production systems to find the correct balance between the vegetative growth (shoot and leaf "production") and reproductive development (grape production). One could optimise vine performance by improving vine balance. Vine balance and optimal vine performance are functions of the vine's production capacity, including vine vigour, crop load and crop level.

Different ratios exist with regard to vine vigour and crop load, namely yield: shoot weight, yield/leaf surface and shoot weight/leaf surface. These three ratios describe the growth-yield relationship and their goal is to quantify vine vigour. Many factors influence the growth-yield relationship such as climatic and soil conditions as well as vineyard management practices. The influential factors are diverse and differ on a local and global scale with regard to viticulture. Variability exists not only with regard to climate, soil conditions and cultural practices, but also in the vineyard. This is known as within-vineyard variability. Spatial variation in vine vigour can occur even if vines are of the same age, clone and uniformly managed. Therefore it could be beneficial to the grower to understand within-vineyard variability by focusing on achieving balanced vegetative growth and reproductive development for each vine within a vineyard.

Index Terms— Vine vigour, variability, growth-yield relationship, wine quality.

1 VINE BALANCE

The concept of vine balance is a multifaceted notion, which is essential to viticulture. The vine reflects its environment and is dictated by its physiological responses to this environment. Furthermore, the grapevine is equally influenced by the cultural management practices that are applied for specific production goals. Winkler [1] offers a definition of vine balance, stating that the minimum leaf area necessary to ripen the grapes sufficiently in terms of an accumulation of soluble solids is known as vine balance. In other words, vine balance is achieved when vigour (vegetative growth) and fruiting load are in equilibrium and is equivalent to constant high fruit quality and yield [2], [3], [4], [5]. If grapevine growth is accommodated, and not hindered, by appropriate trellising and spacing, the goal of vine balance and high quality fruit can be obtained more easily. The above mentioned factors such as environmental characteristics, cultural practices and production goals all add to the complexity that constitutes vine balance.

The father of modern physics, Albert Einstein, stated, "In theory, theory and practice are the same. In practice, they are not". This rings true for viticulture as well. The concept of vine balance is perhaps easier to understand in theory than it is to apply and perfect in practice. According to Howell [6], research reports and experimental efforts during the last century have been presented with the purpose of encouraging discussion on grapevine balance. The vine balance mentioned, refers directly to the practice of balancing grapevine fruit yield, vine growth and leaf area. Additionally, it is important to understand grapevine production and physiology in relation to vine balance. It is therefore not surprising that experts from the theoretical and practical spheres of viticulture have sought to comprehend the intricate nature of grapevine balance for more than a century.

Grapevine balance occurs where vine performance, in terms of growth and capacity, and physiological responses to its environment are at harmony. Winkler [1] notes that research regarding vine growth and the production thereof was lacking until well into the 20th century. By the early 1920's however, more studies were done by investigating plant physiology and the potential link to vine production. These studies were all based on the notion that leaf area is the unit that determines the quantity, composition and quality of the crop. A study of this concept led him to question the traditional pruning of the vine and the subsequent relationship between shoot growth, fruiting capacity and leaf surface area. Ravaz [7] described the concept of the general relationship between wood to fruit and leaf production, of Aramon grapes in 1911 using an allometric approach. The Ravaz index is a commonly employed ratio in Vitis vinifera canopy management. It is a parameter used to assess the balance between vegetative and reproductive growth of a vine where 1 Ravaz = kg fruit yield/kg of shoots (winter pruning weight) [6], [8], [9]. There remains a discrepancy in the literature about what index number indicates a healthy balanced vine. According to Ravaz [7] healthy vines have a ratio of fruit/shoot mass between 0-3. Reynolds [8] confirms this by stating that an index of less than 4, constitutes balanced growth in a grapevine. Vasconcelos and Castagnoli [10] state that an index of 5-7 indicates vine balance, whereas Smart and Robinson [2] maintains that an index of 5-10 constitutes a healthy vine. It is important to note that different viticultural practices as well as environmental differences could attribute to these different findings concerning the Ravaz index. According to the Ravaz index, a specific equilibrium between shoot growth and grape yield is synonymous with grapevine balance.

Literature has shown that the extent of vine balance can be estimated during the growing season, in other words, before the upcoming harvest or after the harvest. The Ravaz index is a postharvest assessment [6]. Shaulis Pratt [11] refined the approach suggested by Ravaz by creating a practical methodology to explain the process to achieve vine balance and sustained production giving an approximation of the vine balance before harvest by using the weight of cane prunings produced in year 1 as an indicator of the maximum vine capacity that will produce and ripen a crop in year 2. Colby and Tucker [12] produced results in accordance in their work on Concord grapes. Their study confirmed that grape production is related to the fruiting pattern of individual canes. There is thus early evidence that shows the importance and value of pre-and post-harvest assessments on vine balance.

As mentioned earlier, it is important to look at the concept of vine balance from both a theoretical and practical point of view. Troubat et al. [13] published suggestions on how to prevent the potentially hazardous affect of berry shatter or coulure, to ensure vine balance and high quality grapes. He introduced a practical methodology and described the physiological responses of the vine to cultural practices. Archer and Hunter [14] proposed a practical approach to ensure controlled vegetative growth along with reproductive development. A grapevine will promote seed development during times of environmental and physiological stress in order to survive. This reaction that favours seed development benefits mesocarp development, which gives rise to high quality berry development and good grape composition. Consequently the challenge facing viticulturists is to manage the vine in a manner that continuously promotes seed development. This must be done without exposing the vine to serious stress, which can compromise the physiological processes within the grapevine. Practically, this approach will ensure that vine physiology and vineyard production amalgamate in order to reach balanced vine growth.

Nevertheless final vine and wine balance with regard to sustainability is not a new concept nor is it merely concerned with the physiological responses of the vine and environmentally friendly production practices. Dualism between productivity and quality refer to the interactions between the production sites (vineyard and winery), the quality of the final product as well as the market that buys and consumes the product. Sustainability and balance with regards to viticulture also have an economic dimension [6], [15], [16], [17], [18], [19], [20], [21]. In addition grape growing, winemaking and wine marketing are growing to be more and more a part of the same and complete concept namely sustainable viti and viniculture [22]. It remains the responsibility of the grape grower to understand the factors that govern vine physiology and to ensure a marriage of the production and economical aspects of viticulture. The following quote supports the previous statement by looking at a specific cultural practice namely pruning techniques. If the grower is to determine the most economical and profitable degree of pruning to use, he must be able to recognize the responses, which a grapevine makes to different pruning treatments [12].

2 VINE CAPACITY, VINE VIGOUR, CROP LOAD, AND CROP LEVEL

In order to grasp the concept of vine balance, it is crucial to understand vegetative and reproductive vine growth. Two terms are of importance when distinguishing between the characteristic responses of the vine to pruning namely capacity and vigour. Capacity refers to the total dry matter production of a vine; vegetative growth and crop yield expressed as total weight of vine, hence vine size. Vigour, contrastingly, is the quality or condition that is expressed in rapid growth of the vine, thus referring to the rate of growth [18], [23], [24].

Carbonneau [25] describes vigour further by looking at the evolution of the concepts of modelling the vine biology with respect to canopy management. From the 1960's to the 1980's vigour was defined as shoot growth resulting in increased fertility and yield, though excessive vigour reduces fruit set and delays maturity. From the 1980's onward vigour shoot vigour was better defined as negatively relating to pruning level, being maximized and medium leaf exposure. Vine vigour is furthermore positively linked to a non-restricted plant water status and is influenced by summer topping (pruning). Hedging, or summer topping, increases later shoot and leaf growth [25] according to the vine's compensation mechanism [26].

The vine's compensation mechanism is the regulatory reaction of the vine to changes in its environment. These changes that induce the compensation mechanism can be due to canopy manipulation. The vine can adjust itself to available resources. For example in reaction to defoliation, the size of the remaining leaves can increase to ensure the same level of photosynthesis as before the leaf removal [10], [26].

Vine vigour and grapevine capacity are interrelated with crop level and crop load. Crop level is analogous to yield but it does not imply that the entire crop will be harvestable [27]. However crop level is an inadequate measure for cropping, and Bravdo et al. [28] also state that crop load has a much more significant effect on wine than crop level.

Additionally, crop load relates to the equilibrium of shoot and fruit production Smart et al. [29] measured as the grape yield: pruning weight ratio [24], [27], [29], [30], [31].

Vegetative vine growth and reproductive development clearly plays a role in vine balance with regard to the growth yield relationship. The first part of the growth yield relationship, namely vegetative vine growth was the focal point of this thesis. Shoot weight, distribution and shoot length evolution was measured during the 2011 harvest season. This was done to gain a better understanding of the current vine vigour of all the individual vines within the study site and to start managing the variability in order to obtain homogeneity with regard to shoot growth, leaf development and berry ripening.

3 GROWTH YIELD RELATIONSHIP AND PARAMETERS

The ratio of yield to pruning cane mass is one of the parameters that describes the growth yield relationship. The weight of cane prunings is often referred to in popular and scientific literature as the vine size, thus vine vigour. It is a good estimate of carbohydrate reserves and thus capacity. The grape yield/cane or shoot pruning weight ratio depends on the fruitfulness of the vine, which constitutes the cluster number and weight per cane. Moreover Winkler et al. [23], perceived an increase in fruit quality and yields when vine capacity increase, notably due to the regulation of pruning severity and crop thinning. This collective increase of fruit quality and yield with vine capacity varies with location and cultural management practices exercised on the vine. Notably, vine vigour variation does not vary linearly with yield when extremely low and high vigour vines are considered [32].

Vigour variation also has an impact on shoot growth, leaf surface and thus on canopy density. Dixon [33], Miller and Howell [34], and Hardie and Martin [35] found that vine vigour and canopy density increased with vine size. Pruning treatments in the afore-mentioned studies showed that a higher crop load was acquired with lower pruning weights. This relationship is attributed to the competition between the developing grapes and the leaves concerning mineral salts and sugars from véraison onwards. Crop load increased with a subsequent decrease in vigour. The increased crop load also led to an increase in canopy density [33] and thus shading by leaves and fruit. The growth yield relationship or the weight of cane prunings in conjunction with grape berry yield can be used to assess vine vigour and thus vine balance.

However, one should not only use the grape yield/shoot pruning weight ratio for in-field measurements of grapevine vigour. Other parameters to determine vine vigour include leaf area: shoot ratio [36], [37], [38] and leaf area: yield ratio. The relationship between leaf area and shoot mass, focuses on the vine's vegetative growth patterns. It is an important ratio since shoot vigour and total exposed leaf surface are the main determinants of canopy radioactive balance [39]. The radioactive balance of the canopy microclimate indicates refers to incoming and outgoing thermal radiation. This thermal or solar radiation comprises direct, diffused and reflected radiation. The amount of solar radiation that penetrates the vine canopy is important for photosynthesis within the plant. Interestingly, the leaf surface: shoot ratio plays a more important role than photosynthetic output in determining the photosynthetate supply to the vine in the third week after véraison. The effect of light intensity on bud fruitfulness is well recognised in literature, notably Smart [31] found that by reducing shoot crowding in the vineyard, the radiation microclimate and the corresponding yield is increased. Additionally, pruning weight is correlated with total leaf area [40] since both determine capacity [24]. Furthermore, this exposed leaf area gives a good estimation of the physiological potential of the whole canopy [41], including shoot number and vigour.

On the other hand, exposed leaf area influences productivity with regard berry development and thus cluster number. Earlier, fruitfulness was explained as being the cluster number and weight per cane. As with all facets of grape production systems, fruitfulness varies due to different elements. These elements include scion and rootstock cultivars; climatic and soil conditions; and cultural practices. Notably, the fruitfulness of the vine is affected by canopy shading [31], [42]. Excess canopy shading naturally affects the sunlight penetration into the canopy and negatively affects berry development and composition. When the assimilate production of the total leaf area is inadequate and does not meet the demand of the cluster, a high reproductive: vegetative ratio is achieved [43]. This could delay maturity and lower grape quality. Bravdo et al. [24] found that a ratio higher than 10 led to lower quality fruit in Vitis vinifera cv. L. Cabernet Sauvignon. The literature provides essentially similar findings concerning the optimum leaf area (cm2) per gram of fresh grapes: 11-14 cm2/g [44], 10-12 cm2/g [26], [45], 7-14 cm2/g [6], 8-12 cm2/g [46], and 8-14-19 [47] depending on the particular cultivar, trellis system, climatic conditions and canopy management techniques. It is thus clear that the leaf area: grape yield ratio is a factor of the growth yield continuum.

These three ratios namely shoot/yield, shoot/leaf surface and leaf surface/yield are interconnected and hence follow the same logic. This means that they are all used to describe the growth yield relationship, hence vine balance, from different angles. However, one might wonder if all these ratios are implicitly correct. Howell [6] answers the question in part by noting that the leaf area: yield ratio of 7-14 cm2/g shows a rather large 2X range of difference. As mentioned earlier, different ratios exist [47] due to the cultural situation such as canopy management (including trellising system) [25], [29], [48], the scion/rootstock combination [24], climatic factors such as light intensity, temperature, rainfall [4], [49], soil texture, water holding capacity, fine and thick root development [14], differential water deficits, nutrition, source/sink balances [50] and disease incidence. These above mentioned differences in influential factors contribute to spatial variations in vine vigour.

4 INFLUENTIAL FACTORS

4.1 Climate

A variety of environmental factors and cultural practices influence grape production. Soil (mineralogy, compaction, granulometry, soil water reserve, depth, colour and biological characteristics), climate (rainfall, relative humidity, air temperature, soil temperature, direction and intensity of dominant winds) and topography (slope, exposition, sunlight exposure and landscape form) are the primary environmental factors that the grapevine is subject to [51], [52], [53], [54]. Furthermore, one of the most important factors that will determine quality in wine productions systems is the vine's dependence on climate [55]. Grapevines are cultivated on six of the seven global continents. More specifically, between latitudes 6°-45° in the Southern Hemisphere (SH) and 4°-51° in the Northern Hemisphere (NH). In these regions climates are diverse, i.e. oceanic, warm oceanic, transition temperate, cold continental, mediterranean, subtropical, attenuated tropical, arid and hyper arid climates. As a result the variety and scale of environmental factors influencing the vines; as well as the main environmental constraints for grape production differ from region to region [47].

Since there exists such a variety in climatic characteristics the world over, it is essential to quantify the climatic potential of a given region. This will influence decisions concerning choice of cultivar, viticultural management practices and wine production goals. The climatic potential of a region is calculated with different thermal indices for viticulture. Two examples of acceptable indices are indices proposed by Winkler et al. [23] and Huglin [56], respectively referred to as the Winkler and Huglin indices [57]. These aforesaid indices represent heat summations over the growing season and results in classification of climatic regions that are broad enough to take short-term climate variation into account [54]. Climatic variations will have a pronounced effect of within-vineyard variability.

It is important to consider three distinctive climatic levels when considering vine variability. These include:

1) Macroclimate, which refers to regional climate, extending over hundreds of kilometres and is studied over a long period of time (normally 30 years or more) by collecting annual, seasonal or monthly data [58], [59], [60], [61], [62]. It is influenced by latitude (geographical location) and proximity to large, climate-moderating water bodies.

2) Mesoclimate, which describes the climate within smaller areas. It refers to topographical climate that differs in slope, elevation, aspect and distance from large bodies of water [59]. This can concern one or several vineyard districts and measured for shorter time periods [61], [63]. This is an important consideration for viticulture 'zoning' and known/documented concept, i.e. terroir [64].

3) Microclimate is also known as canopy microclimate and is limited to the conditions surrounding a single vine [31], [59]. The canopy microclimate is largely influenced by vine vigour and cultural practices such as row spacing, orientation and canopy management techniques [61], [65], [66].

4.2 Soil

Apart from climate, soil properties and soil management play a major role in vine vigour variation, within-vineyard variability and wine quality. Soil properties are described by soil science, which is subdivided into pedology and edaphology. Pedology refers to the science of studying and classifying the pedogenesis, morphology, distribution and potential use of soil resources [67]. Edaphology is the science of studying the effect that soil properties have on plants (crops) and other flora and fauna present within the soil. Two subfields of edaphology are agricultural and environmental soil science. Moreover, the relationship between soil science and geology is crucial to understanding soil as a physical entity. Both soils science and geology exert influence on vine vigour and vine production. Geology is considered to have a potential predetermining impact on wine quality [68]. However, the effect that the geological formation has on wine quality is indirect.

Maltman [69] states that it is assumed that there exists a direct geochemical influence on wine flavour, but that this assumption remains largely undemonstrated. Three factors explain the link between geology and wine namely topography; bedrock and overlying soils; and plant available water. Plant water availability depends on soil moisture content. The hardrock influences the characteristics of overlying soil. Thus as with geology, the soil type indirectly effects wine quality. This effect is generally attributed to the soil water retention properties and grapevine vigour [70], [71], [72], [73].

For perennial crops such as vines, soils are the base of multiple agronomic factors and condition the specificity of the vine [74]. Firstly soil physical properties govern the soil volume available for root colonisation [72]. The main soil physical properties are soil colour, temperature, depth, texture, structure and soil water status [73]. Similarly to Reynolds et al. [75], Conradie et al. [68] notes that the physical soil properties determine grape quality through the effects of variables such as water drainage, soil temperature, mineral uptake [76] and water availability on vine growth patterns. Additonally, pH, electrical conductivity and nutrients comprise the main soil chemical properties. Microsite differences, for example soil physico-chemical properties, underlie spatial variation in vigour [50].

Notably, soil characteristics bring about variation in shoot and lateral lengths. The heterogeneity of the shoot lengths modifies the foliage amount and spatial arrangement of the leaves (Smart, 1985). This, in turn, leads to differences in crop maturity, yield and grape berry and wine quality attributes such as the accumulation of phenolic compounds in the fruit [32]. It is therefore clear that the soil, climatic conditions and cultural practices will influence eventual vine performance [77], which will affect wine quality.

Soil water availability is probably the most important factor that explains differences in vine root colonisation in different soil layers [78]. It is important to note that moisture within the soil profile is heterogeneous. Therefore there is variability in soil colonisation by the vine's roots. Understanding the ability of plant roots to keep functioning even as soil moisture decreases, is an important step toward comprehending the vine's response to soil moisture deficits in general [79]. Moreover, Morlat and Jacquet [80] showed that these specific soil characteristics can affect the development and activity of the grapevine root system, markedly the soil water content. In another study Morlat et al. [78] reported a positive effect of the soil available water on rooting in grapevines.

To a certain extent aboveground vine growth has been investigated more extensively, and largely independent, of the belowground vine system. One of the reasons for the difference between above and below ground development is due to technical difficulties encountered when studying roots [79]. Both fine root and deep tap root systems are important for a sustainable balance regarding above-and below ground growth [14]. Furthermore, the cultural practices such as correct trellising, plant spacing, and pruning impact on composition and distribution of the vine's root system. Correct canopy management also stimulates the development of roots, especially in the smaller diameter classes [81], [82]. A higher incidence of fine roots can increase the water and mineral uptake of the root system, resulting in a more efficient utilisation of the available soil volume and water and minerals present.

It is, however, essential to not only adopt a physico-chemical approach to soil, but to also consider soil-biological aspects [53], [83]. According to Pool et al. [84] a decrease in organic matter and nitrogen supply can result in long-term vineyard yield declines. The decreased organic matter and plant available nitrogen is directly attributed to reduced biological activity. Soil-biological characteristics of the terroir manifest at three different levels, namely root depth (notably deep root development), the endogenous soil fauna (such as acarids and earthworms) and the microflora active and present in the soil [53]. Excessive soil tillage disturbs the habitat of the microfauna and microflora. This disturbance could lead to a rapid reduction in numbers of these organisms in the soil [72]. In contrast, where organic matter is increased in the soil, earthworms and fungi populations proliferate [85]. Microflora depends on the dominant activity of either fungi or bacteria in the soil. Biopores reaches until the soil surface and promote good aeration and water infiltration into the soil. Surface-feeding earthworms create the biopores. Earthworms, along with fungal hyphae and bacteria create help stabilise soil structure [86]. Biological soil properties is clearly of the essence to achieve sustainable growth and overall vine balance.

5 CANOPY MANAGEMENT AND SHOOTS

Canopy management is the human element that adds to climatic and soil influences when looking at vine growth and balance. Climatic components such as radiation, temperature, wind speed, relative humidity and evaporation rates influence canopy microclimates in grapevines [4]. Said canopy microclimate fundamentally depends on the amount and the spatial distribution of leaf area and its subsequent interaction with the aboveground climate [35], [37]. Hence, trellis systems regarding grape production systems are cardinally important. Moreover, a trellis system must accommodate shoot growth and not limit it [14]. This in turn relates to the management of these systems (by means of cultural practices) in accordance with the climatic conditions to produce a high quality end product. Canopy management techniques need to be adjusted to stay abreast ever-evolving pruning, trellising and mechanisation techniques and technologies in the vineyard. Furthermore, canopy management must be weaked to keep up with rapidly changing climatic conditions. Both the management techniques and the climate exert an influence on eco-physiology, notably on vine physiology [25]. Accordingly, vine growth and subsequent vine balance is determined by the patterns in vine physiology, and thus dependant on canopy management, climate and soil characteristics.

As mentioned earlier canopy microclimate comprises the conditions that surround a single vine [59], [61]. The vine's microclimate is mainly influenced by vine vigour and cultural practices [61], [66]. Smart [31] outlines the three principle means of microclimate manipulation namely shoot number control, vigour control and the use of trellis systems. Furthermore, yield, maturation and ensuing wine quality is dependent on canopy structure [41], which in turn depends on the physiological functioning of the canopy. This is partially governed by the amount and spatial distribution of the leaf surface [36] as well as shoot distribution. Similarly, Dry [4] further notes that in the case of canopy (and hence microclimate) manipulation, the parameter most likely to be affected is the number of shoots per node that subsequently affects the yield. Clearly, there is strong interaction between vine vigour, also known as the vegetative expression of a vine, and vine architecture at a microclimatic level [87].

One way of measuring vine vigour is by weighing the winter cane prunings of a vine for one growing season [18], [23], [24]. If a certain mass is then attributed to each shoot, one could calculate what the ideal shoot number per vine will be according to the current vigour. Shoot number and hence shoot density can be manipulated by removing unwanted shoots (shoot thinning) or by varying pruning levels [4], [31]). Likewise, shoot positioning [39] or shoot spacing [88] are effective methods to alter the microclimate of the vine. It is important to note that as the vine is a climber, it is genetically inclined to favour shoot growth. If the conditions are favourable (such as a high temperature and a sufficient supply of water and nutrients) vegetative growth could be favoured at the expense of reproductive growth [14]. Therefore a balanced canopy management approach, in this case regarding shoot growth and the manipulation thereof, is once again necessary. By achieving balanced shoot growth, more uniform vine vigour can be achieved in the next growing season.

Solar radiation is essential for vine leaf photosynthesis and berry ripening. The density level of the canopy influences the radiation intensity in the canopy microclimate. Therefore light intensity in the canopy depends largely on canopy management practices. Smart [88] measured the light microclimate at different fruit densities and define optimal shoot spacing as providing a canopy that avoids shading and efficiently intercepting radiation. They found that the optimal shoot spacing for Gewürztraminer was between 10 and 20 shoots/m. At less than 10 shoots/m radiation interception is inadequate even though there were 55% canopy gaps. Whereas more than 20 shoots/metre resulted in no canopy gaps. In these dense canopies interior light was not sufficient for photosynthesis and interior fruits were shaded as well [88]. These results only apply directly to vertically positioned shoots. However, the principle that too narrow shoot spacing causes shading is applicable to all shoot orientations. In a comparative study done on different training systems for Vitis vinifera cv. L Syrah and Grenache noir. Louarn et al. [39] found that differences in shoot architecture (spatial shoot distribution and subsequent spatial distribution of leaves) accounted for 25% of the differences between cultivar-trellis system pairs at any given light intensity. If shoot crowding is reduced in the vineyard, the radiation microclimate is improved and the yield is increased [30], [31]. This is due to the positive effect of light on bud fruitfulness [3]. Cloete et al. [36] concur by stating that a higher physiological output of the leaves due to increased light radiation absorption will have an effect on the quantity and quality of the final yield when looking at normally developed shoots. Also, consistent high light intensity levels improve photosynthesis of interior; shaded leaves and can reduce the leaf area necessary to ripen the crop [6]. By applying the correct canopy management practices such as shoot thinning, positioning and spacing, one can optimise the radiation microclimate within the vineyard.

A relationship exists between the homogeneity of the shoot lengths and the homogeneity (or lack thereof) of berry maturation. The working definition of a balanced shoot is that it has a sufficient amount of leaves, given that the leaves are well exposed to sunlight, to ripen two bunches completely. Incorrect vine shape often results in uneven shoot length. A vine with an unbalanced permanent structure with heterogeneous shoot lengths will result in uneven ripening of grapes and thus possibly unpredictable and poor wine quality [14]. Also, labour costs will be higher in vines with heterogeneous shoot lengths. The heterogeneity will translate to foliar development in which case there might not be enough leaves to ripen all of the bunches. Grape thinning will have to be done regularly due to lack of uniformity in vegetative growth and reproductive development. A vine with consistent shoot lengths will also be able to ripen a much larger crop. Archer and Hunter [77] found that a general effective length for shoots to ensure a balance structure and crop is between 1.2-1.6 metres. This of course depends on the cultivar, trellising system and growing conditions. Cloete et al. [36] stated that the average length for "normally developed grapes" were between 1.05-1.15 metres long. According to Pérez and Jofre [18] shoots with a length of 1.2 metres and a weight of approximately 50 g each tend to ripen fruit adequately and produce the desired results during vinification in the Priorat (Spain) wine region. Vine shape and shoot length should often be checked and modified according to the soil and climatic conditions. The result of the eventual vine shape and size will be tasted in the fruit and the wine.

6 VARIABILITY VERSUS UNIFORMITY

These afore-mentioned factors clearly have different effects on vine vigour and capacity as such as well as the resulting wine produced. It is clear, as with all agricultural production systems, that variability is an inherent part of everyday practices since the vine is essentially a spatially variable entity. Spatial variation in vine vigour can occur even if vines are of the same age, clone and uniformly managed [50]. Vineyard variability and the management thereof is not a new occurrence [89].

The grower should look upon his vines as individuals and allowing for gradations in vigour resulting from the presence of insects or diseases, soil differences, and weather conditions, should handle them in such a way that vine growth and yield of well-matured clusters are balanced yearly [12].

In the vineyard, as with variable climatic conditions, vine variability can be illustrated by using three scales namely macro, meso and micro [6]:

1) Macro scale. This refers to vineyard variation within a region on a national and international scale.
2) Meso scale. This refers to within-vineyard variation patterns to topographical, geological, soil and climatic differences and is visible through vine vigour variation.
3) Micro scale. This refers to grape bunch variation on the vine as well as berry variation within that bunch.

Consequently, within-vineyard variation patterns result in a variation in yield. However, one should not focus merely on yield at the expense of quality. To many winemakers, the variation in fruit composition and quality is more important than just yield variation [89], [90]. For instance, overcropping can result in a pervasive lowering in quality of the grapes. It is thus clear that a yield/quality trade-off exists in winegrape production systems. Understanding the physical and physiological responses of the vine to variation is of cardinal importance [1], [89]. Soil- associated variations in vigour have been shown to cause variation in canopy density and physiology [33] and shoot and lateral shoot lengths [31]. Likewise, variation in vine vigour, health, root system and yield can lead to differences in berry ripening and characteristics, thus impacting wine quality as mentioned above [90], [91], [92]. Within-vineyard variability patterns do not only influence yield, but clearly grape and wine quality too.

Different strategies have been employed to manage variability in the vineyard. Vineyard blocks can be managed uniformly whereby inputs and resources are applied uniformly with regard to cultural practices, irrigation and nutrition as have been done traditionally. It would be preferable for the inputs and resources to vary spatially according to vigour and within-vineyard variability. Furthermore, uniform irrigation application for example (to a block with variable vigour) leads to spatially inefficient resource use [50] and thus variable grape and wine quality [93]. Consequently, discord exists between the uniformity of actions taken at parcel level and the differential yield obtained. This uniform management can be attributed to the inadequate knowledge of the magnitude of the variation within the vineyard and an inability to adjust their management to account for it. Along with this, Bramley and Hamilton (2004) stated that a lack of means to measure and monitor vineyard variability prior to 1999 also contributed to growers managing whole blocks uniformly. Vineyard variability is present any given year and its patterns remain adequately stable between years. The concept of zonal management in accordance with seasonal performance of a vineyard is closely linked to the balance mentioned in the vine-wine-market continuum. This approach could aid the growers in identifying premium fruit parcels and thereby maximise their commercial returns.

A modern answer to this question about managing vineyard variability started with precision agriculture. It's a system based on data collection, and subsequent interpretation and evaluation of the acquired information followed by interpretation and implementation of management decisions in response [94]. This technological advancement with regard to general agriculture and an increasing demand for higher quality grape products has impacted the wine sector greatly and resulted in precision viticulture in recent years. Precision viticulture has greatly aided in monitoring and managing spatial variations in productivity related variables within single vineyards [95]. The practical implementation of this system is dependent on various technological developments such as crop sensors and yield monitors; local and remote sensors; Global Positioning Systems (GPS); Variable Rate Application (VRA) equipment, Geographical Information Systems (GIS) and systems for data analysis and interpretation [93]. The precision viticulture approach to vineyard management is a continued cyclical process [89]. The chosen techniques of precision viticulture vary significantly according to the requirements of individual farms [94].

Despite the benefits of precision viticulture systems, such diversity with regards to the equipment restrains the rate of adoption of these technological tools, which varies from region to region [96]. Moreover, growers of smaller vineyards and with less technological tools available, should also be able to manage their vineyards according to variable vigour zones. This study aims to understand the concepts of vigour and within-vineyard variation to obtain an even maturation and quality grapes and wines for small vineyard operations. Furthermore the option of learning to manage vigour variation rather than redeveloping areas or replanting the whole block could also prove more economically sustainable. The investigation will attempt to shed new light on the vigour variability concept as well as propose simple techniques to acquire more harmonious vegetative growth and berry development.

7 CONCLUSIONS

This article has presented an overview of the literature with regard to the key concepts relevant to this study of vine vigour and within-vineyard variability. Vegetative vine growth, particularly winter cane mass and shoot lengths, emerged as important concepts in understanding one of the components in the shoot-leaf-fruit continuum. Harmonious shoot growth is pivotal to more uniform leaf area. Both shoot growth and leaf surface related to final berry composition and the homogeneity or heterogeneity of grape ripening. The omission observed in the literature relates to the ambiguity concerning influences of vigour variation of vine physiological performance, the effect of shoot length heterogeneity on vine vigour and quality, and the lack of means currently available to measure and monitor vineyard variability. This study seeks to address these lacks by contributing to an understanding of the vine vigour concept as a whole by quantifying the variability present in the vineyard and allocating a precise number of shoots according to the vigour of each vine. Furthermore, the shoot growth of the vines will be monitored and physiological aspects examined. The results may shed light on the effect on shoot length heterogeneity on vine vigour as well as on the manner in which vine vigour and variability is monitored and measured.

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