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Review Article

Viticulture for Sparkling Wine Production: A Review

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Abstract: The current understanding of the influences of climate, viticultural practices on fruit quality at harvest and sparkling wine quality is reviewed. Factors such as variety, clone, planting density, pruning method, local climate and soils and current and future climate warming are discussed in the context of achieving a desired harvest quality. A common observation was the relatively less intensive viticultural management applied to grapes destined for sparkling compared to table wines throughout the world. Few studies have been focused on management of fruit specifically for sparkling wine production. However, given that it is accepted that a low pH, higher titratable acidity and lower soluble sugars than table wine are considered desirable for sparkling wine production, as well as a balanced and specific phenolic profile, the literature from viticultural studies of fruit production for table wines which influence these desired fruit quality parameters has been reported. Specific findings around canopy management, leaf removal and yield manipulation for the production of table wines indicate potential for application and development to optimize fruit for the production of sparkling wines. This review has highlighted that fruit quality targets are remarkably uniform across international growing regions but that distinct combinations of variety, clone and management are currently employed to arrive at those targets. Further, studies of viticultural management, particularly those that alter cluster temperature and exposure to incident light, yield manipulation and fruit quality are likely to best inform production techniques that result in fruit quality ideal for the production of icon sparkling wines. Further challenges emerge with the need for increasing mechanisation to maintain cost-effective production. A critical emerging issue is that of climate warming,

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which is currently challenging for the production of fruit for premium sparkling production with respect to flavour development and high acidity. A current and increasing trend is the diversification of growing regions to cooler regions that enable the production of high acid fruit and increased exploration of alternative varieties and clones better suited to a warmer climate.

Key words: sparkling wine, viticultural practices

Introduction

Until the late 1600s, French winemakers were still trying to rid their wines of the carbon dioxide bubbles created by the fermentation process that caused bottles to explode. Subsequently, a rise in preference for these sparkling wines by the British, and in particular royalty, led to the process of deliberately capturing bubbles for good quality sparkling wine which was primarily driven by the Champagne region of France (Robinson 2006). Over time, sparkling wine production has been introduced in many areas including Germany, Portugal, Spain, Italy, South Africa, the United States of America, the United Kingdom and Australia.

It is widely recognised that winemaking techniques significantly influence sparkling wine style. Many processes can influence the structure and complexity of the finished wines such as; reduced phenolic extraction by whole bunch pressing, oxidative handling, fining, yeast strain selection, the development of other flavours such as those introduced by malolactic fermentation (MLF), oak use, and time on lees for both base and tiraged wines (McKenzie 1994). These techniques are applied variously to produce a multitude of styles, however far less is known about practices which can be applied in the vineyard to target fruit quality for sparkling wine production.

In France the viticulture for producing Champagne is prescribed by the region, with aspects of varietal use, grape growing, wine production and maturation regulated by the Appellation d'Origine Contrôlée (AOC) designation (Jackson 2008). This is also the case for Cavas, sparkling wines produced in some Spanish regions in which grape variety and yield are regulated (Pozo-Bayon et al. 2004). In other sparkling wine

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producing areas such as cool climate regions of Australia, management is not regulated, and some vineyards make decisions about which blocks of fruit are destined for sparkling wine as late as veraison in the harvest year. Given the profound impact of seasonal variability on fruit quality, a viticultural program tailored to sparkling wine would be far more ideal. However, there are few published studies on the influence of vineyard management on the quality of sparkling wine, in contrast to the considerable research outlining the relationship between vineyard management and table wine quality (Pozo-Bayon et al. 2004). Sugar concentration, total acidity and pH are the principal fruit quality criteria used for determining harvest dates for sparkling wine and hence wine quality (Hancock 1994). Knowing that a relatively low pH, high titratable acidity and low soluble sugars are considered desirable for sparkling wine production as compared to table wine, it is possible to apply management strategies developed for the production of fruit grown for table wine to the production of fruit grown for sparkling wine.

This review will investigate the available research on viticultural practices for producing high quality sparkling wine, including that applicable from the table wine literature, highlight knowledge gaps and trends and identify research directions for going forward.

Fruit Quality Goals for Sparkling Wine

Fruit destined for sparkling wine production is generally harvested at a relatively low pH, higher titratable acidity and lower soluble sugars than fruit for table wine. In Champagne, harvest date is decided for each region by the National Institute of Appellation of Origin (INAO) who tracks maturity by sampling every 3 to 4 days. The desired maturity at the beginning of harvest is fruit that will produce 9 % alcohol (v/v), and contain 12 g/L as tartaric acid for acidity and pH 2.9, however these figures vary from year to year (Coppolani 1994). The targeted values are remarkably similar among sparkling production countries, for example among those specified in France, California and Australia (Table 1). Fruit and juice flavour and aroma are also important considerations for harvest date as achieving a desired style may not be possible if the juice is overtly varietal (Zoecklein 2002). Hancock (1994) suggested that ripe fruit flavours are required to give rise to complexity in sparkling wine, at approximately 10-11 % (v/v) alcohol. Hancock

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(1994) further stated that sugar concentration, total acidity and pH are the principal criteria used for determining harvest date, but flavour, colour (especially in the red varieties) and cleanliness are very important considerations.

Grapes for sparkling wine are typically harvested at lower sugar levels than grapes for table wines (Anderson et al. 2008a, Martinez-Lapuente et al. 2013). Coelho et al. (2009) observed that grapes picked at maturity, or one week after maturity provided sparkling wines with the highest content of volatiles, with wines made from grapes picked earlier exhibiting more intense herbaceous notes. Zoecklein (2002) reported the fruit maturity of some Californian varieties for sparkling wine production based on averages across several viticultural regions, as shown in Table 1. As higher acid levels in fruit are desirable for sparkling wine production, greener flavours and aromas are preferred over riper fruit.

With these fruit quality parameters for sparkling wine production in mind, growers can establish dedicated blocks and use specific management techniques in order to produce superior quality fruit for production of sparkling wines. Such factors and management techniques include grape varieties, vine density and pruning, canopy management, climate and soil, and yield.

Grape Varieties

De La Presa-Owens et al (1998) described grape variety as one of the three major factors influencing the character of bottle-fermented sparkling wines along with vineyard location and yeast autolysis. Different sparkling wine producing regions utilise different grape varieties to produce their desired styles of sparkling wine, as summarised in Table 2. In Champagne the permitted varieties are restricted to Chardonnay, Pinot Noir, Pinot Meunier and rarely used are Petit Meslier and Arbanne (Coppolani 1994). Each of the three main varieties contribute individual attributes to the finished wines, described by Jackson (2008) as ‘finesse and elegance’ by Chardonnay, ‘body’ by Pinot Noir and ‘fruitiness and roundness’ by Pinot Meunier. A sparkling wine made only from white grapes and usually Chardonnay is called a ‘Blanc de Blancs’ and a sparkling wine made only from dark skinned grapes, usually Pinot Noir and/or Pinot

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Meunier grapes is called a 'Blanc de Noirs' (Chamkha et al. 2003). Chenin Blanc is grown in the Loire Valley of France for sparkling wine production, in particular for its naturally high acidity retention (Robinson, 2006). Chenin Blanc is also grown in the Limoux region of France along with the more traditional variety of Mauzac for sparkling wine production (Robinson, 2006).

Pinot Noir, Chardonnay, Pinot Meunier and Pinot Blanc are varieties most commonly used for sparkling wine production in California (Zoecklein 2002; de la Presa-Owens et al. 1998), whilst Chardonnay and Pinot Noir are predominantly used in cool climate regions such as New Zealand (Hancock 1994) and Australia, with the occasional use of Pinot Meunier and Pinot Blanc. In hot regions varieties including Parellada, Xarello, Macabeo, Chenin Blanc and Semillon are also used for sparkling production, and in both warm and cool climates Gamay is also used (Dry and Ewart 1985; cited in Zoecklein 2002). Spanish grape varieties Verdejo, Viura (Macabeo), Malvasia, Albarin, Godello, Garnacha, and Prieto Picudo were evaluated for high-quality sparkling wines, and Prieto Picudo, Albarin, and Verdejo were the most promising varieties due to their superiority in sensory profiling (Martinez-Lapuente et al. 2013).

Coehlo et al. (2009) found the volatile composition of sparkling wines was more influenced by variety than by soil type or stage of ripening when comparing Fernão-Pires and Baga varieties. The more traditional sparkling wine or Champagne varieties of Chardonnay, Pinot Blanc, Pinot Noir and Pinot Meunier have been shown to contribute different aroma profiles to base wines (de la Presa-Owens et al. 1998). De la Presa-Owens et al. (1998) found that Chardonnay and Pinot Blanc base wines were characterised by floral, citrus and apple aromas, whereas Pinot Noir and Pinot Meunier base wines were characterised by berry and vanilla/butter aromas, however the aroma profiles exhibited by the base wines did not enable prediction of the sensory profiles of the sparkling wines after ageing on lees for 18 months. Caution must be taken when predicting sparkling wine flavour and aroma profiles from base wine flavour and aroma profiles, due to the modification of organoleptic properties by yeast autolysis (Alexandre and Guillox-Benatier 2006) and the amplification of aromas during the secondary in-bottle fermentation (Zoecklin 2002).

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Each of the three main grape varieties used for sparkling wine production have different wine maturation rates with Pinot Meunier the fastest maturing variety, Pinot Noir intermediate and Chardonnay the slowest (Thibaut and Parsiot 1994, Jackson 2008). Autolytic development is predominantly determined by yeast strain, but is also influenced by other factors such as base wine composition and ageing time (Alexandre and Guillox-Benatier 2006).

The different grape varieties also impact upon foaming properties of sparkling wines (Andres-Lacueva et al. 1997). Marchal et al. (2001) reported that sparkling wines from Pinot Noir display the greatest foam height, followed by Pinot Meunier, with Chardonnay the lowest, whereas Andres-Lacueva et al. (1996, 1997) found Chardonnay cavas gave high foamability and the lowest stability time. Blending of different varietal wines improved the foaming properties with respect to each varietal wine separately, owing to a synergistic effect among components (Andres-Lacueva et al. 1996).

Clones

Clonal evaluations have been reported throughout the wine-producing world, by research teams in Burgundy, Champagne, Australia, Canada, New York, Oregon and California (Anderson et al. 2008a). Localised studies are valued because of field observation that clonal performance varies in different locations (Cirami and Ewart 1995), presumably affected by mesoclimates and soils.

Notably in France, clonal selection of Pinot Noir for sparkling wines has been conducted independently from clonal research on Pinot Noir for table wine (Barillere et al. 1995; cited in Anderson et al. 2008a), a fairly unique exception to the general lack of research specific to fruit production for sparkling wine. Sparkling wine producers typically look for Pinot Noir clones with higher acidity, higher yield, and lower anthocyanin and tannin content than their table wine counterparts (Barillere et al. 1995, Bernard 1995, Pool et al. 1995). In Champagne the Chardonnay clones available are numbers 75, 76, 95, 96, 121 and others; for Pinot Noir, numbers 386, 521, 870, 779, and others (Coppolani 1994).

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In California, Anderson et al. (2008a) evaluated the viticultural characteristics of 12 Pinot Noir clones specifically selected for sparkling wine production in Champagne, France. These were compared to eight Californian clones. Results showed yield and yield components differed widely among clones. Clones were harvested on a soluble solids basis, with a target of 20 ºBrix. There was a 15 day difference in harvest date on average from first to last clone harvested. Ranges in titratable acidity and pH values were statistically significant. Unfortunately, measurements of phenolics such as anthocyanins were not made in this study. Vegetative growth, measured as pruning weight, differed more than two-fold among clones. The relative performance of the individual clones differed in studies conducted in other regions, highlighting that clones perform differently under different conditions. In a second study in California, differences among clones of Pinot Noir were reported to be greater than those reported by others for clones of Chardonnay (Mercado-Martin et al. 2006). The study indicates that some clones have potential for high yield and others for excessive vegetative growth. Differences in yield were largely due to cluster weight, and more so than for other varieties investigated yield of Pinot Noir was affected by cluster number. It is not clear however, whether this difference was due to fruitfulness of nodes retained or differences in numbers of blind buds.

In a Californian study by Wolpert et al. (1994) where the performance of six Chardonnay clones was tested, clones differed in yield, cluster size, berries per cluster and yield to pruning weight ratio, which varied greatly. In another Californian study of thirteen Chardonnay clones, two of Californian origin and eleven of French origin, variations in yield, berries per cluster, berry weight, cluster weight and clusters per shoot were detected when all clones were harvested at 21 ± 0.5 °Brix (Anderson et al. 2008b). Whether distinct clonal performance between regions is due to climate, soil, rootstock choice, or cultural practices has not been determined. However, there are clear implications of clonal selection for adequate yields and sugar:acid characters for the production of fruit for sparkling wine, although impacts on fruit quality have largely been ignored, which is a significant knowledge gap and key for production of premium quality fruit and wine.

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Vine Density, Pruning System, Canopy Management and Harvest Method

Both vine density and pruning system have been tightly legislated and controlled in Champagne by the INAO (National Institute of Appellation of Origin) since 1938 (Coppolani 1994). The sum of the distance between rows and vines must be less than 2.5 metres which results in a high density planting in the order of 8000 vines per hectare. Coppolani (1994) explains that Champagne has a high annual rainfall, resulting in soil water being available to vines throughout the year, which is prejudicial to maturity. The high planting density is thought to stimulate root competition for water and other nutrients and assists fruit reaching adequate maturity by reducing vegetative growth (Coppolani 1994), however studies supporting this speculation could not be found. Reynolds et al. (2004) reports that the view that closely spaced grapevines are necessary for high quality wine is a widespread misconception, and showed minimal impact of vine spacing upon yields and fruit composition under situations where soil conditions were not limiting. For vines grown in more fertile soils, a high density planting may result in reduced density of buds, as well as an increase in the proportion of secondary buds bursting, both factors having an impact on the rate of ripening.

Hancock (1994) states that planting distances and row orientation, trellis training and pruning are all important considerations for quality sparkling wine production, by controlling fruit exposure and vigour which impact on fruit flavours and acid balance. However, no such standard practice for planting density occurs for sparkling production in New World countries such as Australia. In Champagne, the height of buds from ground level at pruning should not be more than 0.6m to limit the canopy height to around 1.3 m and therefore limit the degree of inter-row shading (Coppolani 1994), but this will be a function of row width. The permitted pruning systems in Champagne are Chablis, Royat, Guyot, Vallée de la Marne, however only the Chablis and Royat systems are permitted for Champagne '*Grands Crus*' (Coppolani 1994). New World sparkling wine vineyards commonly employ vertically shoot positioning (VSP) for

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ease of management, or a Scott Henry trellis which has the advantage of being adaptable for either cane or spur pruning.

Bernizzoni et al. (2009) concluded that with Barbera, similar crop potential and quality expression can be achieved in either cane or spur pruned training systems when properly managed. The authors demonstrated that vine spacing had no effect on Barbera grape composition, when inter-row spacing varied between 0.9 m and 1.5 m, across vertically shoot-positioned spur-pruned low cordon (SPC), single high-wire cordon (HW), single Guyot (SG), and vertically split double Guyot (DG). In the same trial must composition at harvest was similar among vertically shoot-positioned spur-pruned low cordon, single high-wire cordon, and single Guyot, while vertically split double Guyot produced grapes of overall inferior quality, and no significant differences were found in yield per vine across training systems. The inferior quality of split double Guyot was thought to be due to a somewhat delayed ripening. The SPC fruit was of a significantly higher pH and lower titratable acidity, suggesting that it would be less desirable for sparkling wine production than the other training systems. Bernizzoni et al. (2009) advised that vine spacing at 0.9 m within-row was preferable, as it ensures 20% higher yield per hectare of comparable grape quality across training systems, although disease pressure could be a consideration with planting density on relatively high humidity sites.

In a comparison of four training systems for production of Pinot Noir for table wine in Italy (simple Guyot, double Guyot, horizontal spurred cordon, vertical spurred cordon), yields ranged among systems from 7.5 to 9.7 t/ha, but training system had little or no impact on grape or wine composition, with sensory analysis showing no difference among systems (Pertlunger et al. 2002). The Simple Guyot training system resulted in a higher pH and a lower titratable acidity, and the Double Guyot also resulted in a lower titratable acidity, suggesting these two systems would perhaps be less desirable for sparkling wine production than the other training systems. Van Zyl and van Huyssteen (1980) found that microclimate differences among four training systems in Chenin blanc vines had no effect on fruit composition. These studies indicate that, with the appropriate training system, yield can be increased with no detrimental

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impact on fruit quality for these varieties which are commonly used in sparkling wine production (Reynolds and Vanden Heuvel 2009).

With a rise in the use of mechanical pruning, trials comparing the fruit and wine quality from spur and cane pruned vines are becoming more common, however to date studies have focussed on table wine rather than sparkling wine. Jackson and Lombard (1993) reported that Pinot Noir aroma is reduced when grown using spur pruning, despite yield and maturation being similar to cane pruned vines. A study by Goma-Fortin et al. (2013) comparing Chardonnay under traditional Royat trellis and with vines mechanically pruned, showed that mechanically pruned vines had a greater number of smaller clusters than did vines on Royat trellis. Tasters noted mechanically pruned vines had more intense fruit flavours and quality aromas. It is possible that the increased intensity of aroma and fruit flavours was a result of the smaller berry size under mechanised pruning. Poni et al. (2004) demonstrated that short mechanical hedging can be successfully applied even on cultivars with low fruitfulness of basal buds, showing no detriment to grape quality and a cut in labour demand by 55 to 60%.

Canopy management in the form of different trellising options can be employed to manipulate key berry attributes at harvest. Phenolics of Pinot Noir were increased by divided canopies including Scott Henry, lyre and Geneva Double Curtain, over undivided up-right shoot canopies, but the wines from undivided canopies had more typical fruit flavour and aroma (Jackson and Lombard 1993). Many studies by Smart and colleagues suggest that a shaded microclimate increases the pH and potassium (K) content of the must and reduces both wine colour and content of phenolic compounds (Smart 1984, Jackson and Lombard 1993).

A common method to increase light incidence on berries is to remove leaves, predominantly in the fruiting zone. This can lead to faster grape maturation measured by increased sugar concentration at harvest (Reynolds et al. 2007), can have no significant effect (Percival et al. 1994, Tardaguila et al. 2010) or can decrease sugar concentration due to limitation of photosynthates (Iacono et al. 1995, Koblet et al. 1995).

Similarly variable responses of fruit pH and TA to leaf removal have been reported (Koblet et al. 1995, Percival et al. 1994, Reynolds et al. 2007), highlighting the need for local, variety specific investigations into the practice to determine suitability of this management practice to meet the fruit quality goals for sparkling wine production.

Removing different quantities of leaves as they appeared on Pinot Noir vines resulted in slower initial berry growth and final size, and a delay in veraison in a study by Petrie et al. (2000). The authors reported soluble solids and total sugar content increased more rapidly when more leaves were retained, and final soluble solids and sugar content at harvest were decreased by all degrees of leaf removal. Shade, whether natural or artificial, nearly always reduces sugar levels and usually increases acidity on any one date, a response which is normally interpreted as delayed maturity (Reynolds et al. 1985). For this reason, it is possible that a degree of shading may be beneficial for sparkling wine production.

Hydroxycinnamates are known to impact on texture and mouthfeel of sparkling wines (Kerslake et al. 2013). Changes in cluster exposure as a result of leaf removal, resulted in differences in UV absorbance of juice samples at 310 and 330nm (Kerslake et al. 2013), wavelengths that are indicative of hydroxycinnamates (Verette et al. 1988). Results suggest that there was a significant decrease in hydroxycinnamates in the Pinot Noir and Chardonnay base wines when leaf removal occurred. An increase in light exposure due to leaf removal is a possible explanation for the differences, and Kolb et al. (2003) found that berries with increased light exposure had decreased levels of hydroxycinnamic acids.

Leaf removal, when performed sufficiently early, has been shown to have beneficial effects on cluster morphology and the resulting fruit composition. Working with Barbera, Poni et al. (2005) demonstrated early leaf removal led to looser clusters and improved quality traits, especially increased soluble solids and colour, and Tardaguila et al. 2010 showed similar findings working with Graciano and Carignan. In a study by Sabbatini et al. (2010) early defoliation did not significantly affect any parameters measured, revealing only a slight decrease in cluster weight for Pinot Noir. The difference in cluster size between the

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varieties of the two studies could explain the different results. Graciano and Carignan are both very large clustered varieties and Pinot Noir, Pinot Gris and Vignoles are small clustered (Sabbatini et al. 2010).

In order to achieve the highest quality sparkling wine quality, traditional, "late" (pre-veraison) leaf removal should be avoided, as it usually permanently overexposes clusters and leads to an undesirable decrease in malic acid. "Early" (i.e. flowering) leaf removal does not seem to lead to overexposure, since the season is long enough to cast some shade on the clusters, while several authors have found that an early leaf removal promotes tartaric acid. The decision about early season leaf removal needs to consider the cost involved and the potential improvement in the resulting wine quality.

The composition of juice will also be affected by harvesting method, which in Champagne is limited to hand harvesting only (Coppolani 1994). Hancock (1994) reports that machine harvesting of fruit can damage the berries which can result in oxidation of the juice. Further the time and extent of skin contact of machine harvested fruit will also impact on fruit and juice quality, however this observation is anecdotal only. The size of the picking containers can impact upon fruit integrity (Hancock 1994), again another parameter regulated to the use of small bins with holes in Champagne (Coppolani 1994). Pocock and Waters (1998) showed that despite greater extents of juice oxidation occurring in mechanically-harvested fruit when compared with hand-harvested fruit, this had little effect on the protein content of the wine, suggesting that mechanical harvesting of fruit will not have adverse effects on sparkling wine quality when the appropriate wine making techniques are employed.

Climate and Soil Factors

De La Presa-Owens et al. (1998) described vineyard location as one of the key factors influencing the character of bottle-fermented sparkling wines. Climate was attributed by Thibaut and Parsiot (1994) as the most important factor affecting quality in Champagne. Windows of adverse weather conditions during the growing season, in particular later in the season, can have disastrous results for wine quality. For example

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rainfall prior to harvest can lead to fungal infection in the fruit (Soar et al. 2008). This highlights the need for flexible viticultural management programs for successful sparkling wine production, particularly in cool and variable climates.

In managing vines for sparkling production, the effects of local climatic patterns, both seasonal and diurnal, on basic juice composition should be considered. Several studies have shown that sugar accumulation is influenced by temperature in the first two phases of berry growth (stages I and II) but that in the final berry growth phase (stage III) temperature has little effect on final sugar level (Buttrose et al. 1971, Hale and Buttrose 1974). In contrast Hofäcker et al. (1976) found that sugar was related to temperatures in stage III. Cool nights associated with warm day temperatures led to lower pH and higher acidity at harvest compared with warm days and warm nights (Kliewer 1973). A general rule of thumb is the warmer a sparkling wine producing region is, the earlier the grapes need to be harvested to ensure low pH and high acidity levels, as sparkling wines with higher pH and lower acidity levels tend to develop more quickly and are more likely to display more overt fruit flavours and less complexity (Zoecklein 2002). Chamkha et al. (2003) found that variation in total phenolic content of Pinot Noir and Chardonnay champagnes was a function of the vintage. It was concluded that abundant rain in 2001 diluted flavour compounds relative to the 2000 vintage.

Soil type, and in particular physical aspects, including depth and texture, will greatly affect vine vigour (Hancock 1994). Van Leeuwen et al. (2004) reported that soil type was a major influence on berry weight and as important a factor as cultivar for explaining variation in berry sugar and anthocyanin concentration in a study of the table wine varieties Merlot, Cabernet Sauvignon and Cabernet franc. Soil type was less important for total acidity and pH of the grape juice. A strong relationship exists between improved grape quality and water deficit before veraison, when water deficit probably affects grape quality indirectly. The study by van Leeuwen et al. (2004) showed that an early water deficit induced early shoot growth cessation and reduced berry size. Under these conditions, berry sugar and anthocyanin concentrations are increased because of more rapid ripening. The authors concluded that the effects of soil on vine development and grape composition can be explained in large part by their influence on vine water status. Similarly, Coelho et al. (2009) compared sparkling wines made from grapes produced in three types of soil and concluded that soil type impacted on wine quality. The clay-calcareous and clay soils that had good water-holding and drainage capacity produced wines richer in volatiles than wines produced from fruit grown on sandy soils. Tesic et al (2002) suggested that physical characteristics of different soil types should be considered relevant at least because of their apparent effect on soil temperature and soil moisture content, which in turn impact on vine growth and resulting wine quality. A greater degree of flexibility in the required soil attributes and the resulting influence on vine water status exists for sparkling wine production than for table wine varieties such as the Bordeaux varieties examined in the work of van Leeuwen et al. (2004), due to the lower sugar concentration required at harvest.

Yield

Yields in Champagne are prescribed by the AOC, so if predictions exceed permitted yields, fruit removal is necessary prior to harvest (Coppolani 1994). A similar regulation exists in Spain for the production of cava (Pozo-Bayon et al. 2004). There is a lack of research specifically with sparkling wines to support the notion that lower yields lead to higher quality, and it is quite possible that if the crop level is too low, the fruit may become overripe, especially in warm seasons. In some regions the decision to limit yield may not be related to fruit quality, but rather to limit wine production and retain higher prices. In other cool climate sparkling wine production regions, such as New Zealand, crop level is managed in order to improve fruit flavour intensity (Hancock 1994) by manipulating vine balance. In Australia, while evidence is based on commercial experience, higher yields (for example up to 16 T/ha using a VSP system on a fertile site) for sparkling wine production are more accepted than those for table wine production, however these are not regulated and price is set using quality perceived by winemakers. The ideal cropping level may be dependent on the style of sparkling wine aimed for, with some producers preferring high acid, less fruit driven styles.

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Winter pruning is the first opportunity to manipulate yield. A primary aim when choosing bud number per vine is to achieve balance between vegetative and fruit growth whilst simultaneously providing appropriate fruit composition for winemaking (Jackson and Lombard 1993, Tassie and Freeman 2004). The exposed leaf area to fruit ratio affects the rate of maturation of the fruit, which will in turn influence grape and wine quality (Zoecklein 2002). Pruning as a method of yield regulation will also assist in control of vigour and influence fruit exposure, fruit flavours and acid balance later in the season (Hancock 1994). In Champagne, vines are not pruned too early in the attempt to avoid early budburst and possible spring frost damage (Coppolani 1994). The link between later pruning and later budburst is supported by Martin and Dunn (2000) where delaying pruning by six weeks delayed budburst, and maturity by approximately 5 days, thus pruning time may be an important factor to consider in planning vineyard operations for sparkling wine production.

Recommendations in Champagne are that fruit removal around veraison is ideal and that removal of 30 % of the fruit will result in less than 0.5 % increase in potential alcohol whereas removing between 30 – 50 % could increase potential alcohol between 0.5 and 1.5 % (Coppolani 1994). However, fruit removal is a costly exercise and it is yet to be economically proven that crop load reduction at veraison produces a significant enough increase in fruit and sparkling wine quality to justify the cost. A trial with Chardonnay for table wine found that the cost of cluster removal outweighed the fruit quality benefits (Reynolds et al. 2007), and similar results were found for Riesling, where the substantial increases in fruit price necessary to offset from the costs of cluster removal were not warranted (Preszler et al. 2013). Research into the effects of cluster thinning on fruit quality and the cost:benefit analysis for fruit destined for sparkling wines is needed.

Pozo-Bayon et al. (2004) reported that the concentrations of most phenolic compounds were higher in sparkling wines (cavas) made from high yielding vineyards than in those with a low yield of the Parellada variety. Unfortunately no information was given regarding the vine characteristics, management practices or environmental conditions of the different vineyards, making it difficult to interpret the results. It is

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possible that the higher yielding vines were grown on more fertile soils, allowing for a larger crop to be ripened and a greater degree of phenolic development. There were no significant differences between the foam characteristics of the wines from different yielding vineyards. Overall, the tasters favoured wines from grapes grown in low yielding vineyards, due to better sensory quality than the wines from high yielding vineyards, this was despite the lower phenolic concentrations in wines from low yielding vineyards. Also working with Parellada for cava Riu-Aumatell et al. (2002) found differences in composition between wines from low and high yielding vineyards. Both TA and pH were significantly higher in fruit from high yielding vineyards. However the maturation index, the ratio between the TSS and TA, which represents a balance between sugar and acid (Gris et al. 2010), did not vary significantly, suggesting that although the acidity was lower in wines from low yielding vineyards, they were not riper.

Increased crop level in production of fruit for table wine has been shown to delay maturity in grapevines by resulting in lower fruit composition parameters at harvest, such as sugar (total soluble solids [TSS]) and titratable acidity (TA) (Winkler 1970). A study of Pinot Noir found that increasing nodes retained at pruning, from 20 nodes per vine to 30 nodes per vine, resulted in a significant drop in pH, and a significant positive regression existed between pH and total soluble solids, regardless of the number of nodes retained, when nodes varied between 10 and forty (Heazlewood et al. 2006). A study in New Zealand found that by increasing the number of nodes retained at winter pruning, yield increased by 3.5-fold in Chardonnay and other varieties, with little effect on the basic fruit composition parameters of TSS, pH and TA, contrary to the findings of the Heazlewood et al. (2006) trial (Jackson and Steans 1983-4, Jackson et al. 1984).

Yield of wine grapes will modify fruit composition in two ways: first by intrinsic changes which are directly due to yield, including soluble solids, organic acids, pH, phenolics and anthocyanins; and secondly, by changing the rate of ripening (Jackson and Lombard, 1993). Because high yields (to the point of overcropping) delay maturity (Winkler 1954), direct effects are not always easy to measure, since they require grapes to be harvested at equivalent maturity.

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Studies of crop removal have shown that soluble solids will increase after thinning until a specific crop level is attained, below which little effect will occur. Low crop levels will possibly also increase pH and lower TA, increase anthocyanins and aromatic constituents such as volatile terpenes and enhance perceived wine quality (Jackson and Lombard 1993). In a trial examining the effects of cluster thinning and leaf removal, Mazza et al. (1999) showed that Pinot Noir had higher phenolic levels when vines were subjected to cluster thinning treatments at veraison than leaf removal treatments. Cluster thinning at bloom also resulted in higher phenolics. Cluster thinning has been shown to increase total anthocyanins and total phenolics (Jackson and Lombard 1993, Prajitna et al. 2007). Mechanical thinning by Diago et al. (2010) showed an increase in soluble solids by 3°Brix for high intensity thinning of Grenache, as well as a decrease in titratable acidity and an increase in pH; while no effect was observed in Tempranillo. Clearly the principles developed around yield manipulation for table wine fruit production have the potential to be applied and further developed with respect to fruit production specifically for sparkling wines, and trials should be run in different regions. However, the studies reported here demonstrate an increase in sugar, decrease in titratable acidity and increase in pH as a result of cluster removal, suggesting that the practice may be detrimental to sparkling wine quality.

Impact of Climate Change and Possible Techniques for Mitigation

The changing climate is having a profound impact on sparkling wine production at global and regional scales. Increased temperature and changes in precipitation patterns could impact on grape production in positive and negative ways depending on the present climate of that region. The projected rate of warming is not consistent between regions, so too the projected precipitation, some will become drier and others wetter (Webb et al. 2013). For most regions, over the summer period median model results indicate a drying of the climate. Winter precipitation is projected to increase slightly for the more northern European locations, US regions and New Zealand. For Australian sites, Southern European regions and South Africa, a likely reduction in winter precipitation is projected (Webb et al. 2013).

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A growing body of evidence indicates that as climates warm, wine grape phenology progresses more rapidly and grapes ripen earlier (Webb et al. 2011). As fruit composition is strongly influenced by temperature, with higher temperature increasing the speed of sugar accumulation, hastening acid degradation and altering flavour compounds (Webb et al. 2013), sparkling wine quality could be compromised in the future in some regions currently focussed on sparkling wine production. Elevated temperature has been shown to decouple anthocyanins and sugars in berries of red wine varieties, which has consequences for the colour: alcohol balance in the finished wine (Sadras and Moran, 2012) and may lead to higher alcohol content, an issue which will have relevance for sparkling wines.

Growers are faced with decisions about which varieties will be best suited to sparkling wine production in a future warmer environment, and developing management techniques to assist them to cope with faster ripening and changes in fruit composition. Introducing flexibility into the traditional regulatory systems which exist in France, Italy and Germany may be necessary to allow for changes to permitted varieties in those regions, and changes in management for example the introduction of irrigation. It is also likely that viticulture for sparkling wine may move into new regions, for example places which are currently considered too cool for viticulture such as areas of southern Australia, North and South America and England.

It is possible that vineyard management techniques may be applied to mitigate some of the negative impacts of increased speed of ripening. Palliotti et al. (2013b) showed that mechanical leaf removal post-veraison on Sangiovese vines, apical to the fruiting zone, is a practical strategy to delay sugar accumulation in the berry by about 2 weeks as compared with non-defoliated vines. The application of the film-forming antitranspirant Vapor Gard, post-veraison above the cluster zone was also shown to be an effective, simple technique to slow berry sugar accumulation (Palliotti et al. 2013a).

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Conclusion

Clearly fruit quality goals are distinct for sparkling wine versus table wine, yet remarkably similar across international growing regions. However, in order to achieve these uniform quality attributes, clear differences in viticultural management for sparkling wine production exist between different countries. In France and some regions of Spain, the viticulture for producing Champagne and cava is predominantly prescribed by the region, with aspects of varietal use, grape growing, wine production and maturation regulated by authorities, whereas in other sparkling wine producing regions such as Australia, there is no legal regulation. The relatively low management input applied specifically for grapes destined for sparkling wines as compared to table wines in wine producing regions throughout the world is clear.

This review has highlighted difference in vegetative growth, yield and fruit composition of varieties and clones grown in difference regions, clearly necessitating distinct viticultural management between regions given the relatively uniform objectives for fruit quality across regions found during this review. Yield, effects of crop load management and leaf removal can improve fruit quality for table wine production but equally these practices can be ineffective or even detrimental, depending on the vintage and variety. Research on viticultural practices that arrive at the desirable attributes of fruit for sparkling wine, including a lower pH, higher titratable acidity and a lower ˚Brix than for table wines, is a knowledge gap in the literature. This review identifies the effect of increasing the temperature and changes in the light environment around the clusters as a particularly important area for future research into viticulture for fruit specifically for sparkling wine production, in addition to the need to test the interaction of local terroir with viticultural management techniques, such as cluster thinning, on fruit quality and sparkling wine.

Mechanisation of pruning, canopy management, crop load manipulation and harvest is expected to become the way of the future, due to its ability to reduce labour costs considerably. Coupled with the ability to slow the rate of grape ripening by manipulating the vine canopy, the choice of training system in the future may be primarily based on establishment and management costs, the latter including different degrees of, or no mechanisation at all. Research into producing top fruit quality in systems designed to accommodate mechanisation is warranted.

Finally, a critical emerging issue is that of climate warming which may compromise the production of fruit for premium sparkling wine, with respect to maintaining flavour development and high acidity. This represents a significant challenge to fruit production given the documented effects of temperature increase on ripening and loss of acidity. The current, and likely future, move to alternative varieties and clones will require increased research effort, as will movement of production to cooler regions, that are associated with additional challenges such as late frost and increased disease pressure.

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Table 1 Fruit chemistry of some grapes varieties for sparkling wine (adapted from Zoecklein, 2002).

	Chardonnay		**Pinot Noir**		**Colombard**	**Chenin Blanc**
	California	Australia	California	Australia	California	California
˚Brix	18.0 -19.0	16.2-21.6	18.0 -20.0	18.0-21.6	17.5-20.0	17.5-19.0
Titratable acid g/L	11.0-14.0	11.0-16.0	10.0-13.0	11.0-16.0	12.0-14.0	10.0-11.0
pH	2.90-3.15	2.90-3.2	2.90-3.15	2.90-3.2	2.90-3.20	3.10-3.20

Table 2 Summary of different styles of sparkling wine, categorized by their country of origin and varieties used.

Place of origin	**Style**	**Variety**
France	Champagne	Chardonnay
		Pinot noir
		Pinot Meunier
	Sparkling wine	Chenin blanc
		Mauzac
Germany	Sekt	Riesling
		Silvaner
		Pinot blanc
		Pinot noir
		Pinot gris
Italy	Franciacorta	Chardonnay
		Pinot noir
		Pinot blanc
	Asti	Muscato bianco
	Prosecco	Prosecco
	Lambrusco	Lambrusco bianco
		Lambrusco nero
	Talento	Chardonnay
		Pinot noir
		Pinot blanc
Spain	Cava	Macabeo (Viura)
		Parellada
		Xarel.lo
		Garnacha
		Chardonnay
		Albarin
		Godello
		Malvasia
		Verdejo
		Prieto Picudo
America, Australia, South Africa, New Zealand	Sparkling wine	Pinot noir
		Chardonnay
		Pinot Meunier