Vineyard variability in Marlborough, New Zealand: Characterising spatial and temporal changes in fruit composition and juice quality in the vineyard

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Abstract

Background and aims:
Previous work has demonstrated that vineyards are spatially variable and that this variability can be understood in terms of the underlying characteristics of the land (soils, topography) supporting the vineyard. Selectively harvesting blocks in response to this variability may be highly profitable. Whilst it has also been shown that crop maturation is spatially variable, there may also be temporal variations in the rate of maturation. Integrating knowledge of how vineyard spatial and temporal variation interact has not previously been attempted and is the key objective in this work.

Methods and Results:
We used a proximal sensor to map vine vigour at high spatial resolution in a 5.9 ha Marlborough vineyard planted to Sauvignon Blanc. Vigour measurements were also related to fruit soluble solids, titratable acidity and pH - key indices of crop maturity. A knowledge of crop phenology and maturation was used to predict how these indices changed with time. The pooled opinion of over 50 Marlborough winemakers on the optimum levels of soluble solids, juice pH and titratable acidity at harvest to produce a “typical Marlborough Sauvignon Blanc”, was used to develop a juice index which in turn was mapped in space and time at the study site. The juice index showed marked spatial and temporal variation.

Conclusions:
In addition to being spatially variable, grape quality in vineyards is also temporally variable. Thus, the optimisation of decisions about harvest timing requires a knowledge of spatial variability. Conversely, strategies such as selective harvesting cannot be properly optimized without a knowledge of crop phenology – which is also spatially variable. In this study, we have shown that by integrating a knowledge of crop phenology with an understanding of vineyard variability and winemaker objectives, it is possible for the optimum harvest decision to be made such that fruit destined for a particular end-use is harvested at the right time and from the right place.

Significance of the Study:
This is the first study in which knowledge of both spatial and temporal vineyard variation has been integrated. It demonstrates that in order to be optimal, strategies such as selective harvesting need to incorporate knowledge of crop phenology rather than relying on knowledge of spatial variation alone.

Keywords: Wine quality, phenology, terroir
Introduction

The importance that fruit composition has in determining the flavour and aroma characteristics of wine was summarised by Rankin (1991) when he said that "the potential quality of wine is established in the vineyard and carried to fruition in the winery". Identifying and predicting the date when the balance of flavour and aroma precursors are at their optimum could be considered the "holy grail" of viticultural research. Conceptually, growers and winemakers will have harvest targets in respect of attributes such as yield, disease status, other berry damage, soluble solids, acidity, colour and more recently flavour and aroma characteristics. These targets may be modified, based on weather predictions and harvesting infrastructure. Some targets may be well defined (in particular disease status, soluble solids and yield) and may form the basis for payment schedules from wineries; other targets are less clear. In addition, juice analyses are usually described as mean values, and fruit sampling protocols attempt to achieve the best estimate of mean vineyard fruit composition. However, vineyards are variable and identifying the target fruit composition becomes more complicated when the differences in vine growth and fruit composition within a vineyard are considered. When the variation in composition around the mean is large, it is likely that over- and under-ripe flavours are present in the juice and subsequent wine (Trought 1997). The importance this has in determining overall juice quality largely depends on the variety being considered. For example, typical Marlborough Sauvignon Blanc displays “ripe” and “unripe” characteristics in the wine (Parr et al. 2007) However, the same unripe character in a Cabernet Sauvignon may be considered to be inferior. Whatever the relationship between variability in fruit composition and final wine quality, understanding and predicting the variability is important if vineyards are to be managed appropriately and fruit harvested at a ripeness to make the target wine style.

Recent research using precision agriculture techniques has provided tools to understand variability in vineyards (Bramley and Hamilton, 2004, 2007; Proffitt et al., 2006; Tisseyre et al., 2007). To date this knowledge has been used by viticulturists and/or winemakers to either differentially manage parts of the vineyard to reflect this variability or to selectively harvest areas within the vineyard (Bramley, 2010; Bramley and Hamilton 2005, 2007; Trought et al., 2008) and optimise the composition of parcels of fruit (Bramley et al., 2005; Bramley and Hamilton, 2007). Hitherto, selective harvesting strategies have relied on knowledge of spatial variation alone. Typically, they involve either harvesting a block on a single occasion into two or more product streams and/or harvesting different parts of a block at different times. In the latter case, the objective may be either to enable allocation of the fruit from the entire block to the same product stream, or to maximise the match of the harvested parcels to their intended end use (Bramley et al., 2005). By understanding how fruit composition is changing in different areas of the vineyard, it may be possible for such harvesting decisions to be optimised in both time and space.

This alternative approach requires an understanding of the differences in fruit composition throughout the vineyard and how composition changes with time. Identifying the optimum date for harvest can
then be determined from the mean value and the variability around that mean. To do this, the influence of various juice components on the overall value of the juice have to be defined, while at the same time, changes in fruit composition with time need to be understood along with the impact on these of vineyard factors such as soil texture or depth.

Trought (1997), Bramley and Hamilton (2007), Trought et al. (2008) and most recently Bramley et al. (2010) have previously drawn attention to the variability of vineyards in the Marlborough region of New Zealand, and the likely role that soil variation plays in driving this. In particular, the active nature of the Wairau River flood plain has resulted in a pattern of silty hollows dissecting the sandier, more gravelly soils which predominate (Rae and Tozer, 1990). As these hollows run predominantly in an approximately east-west direction, whilst row orientation is generally north-south, the full range of within-vineyard variation is commonly observed in a single row. This presents grape growers and winemakers with a difficult challenge in regard to issues such as fruit parcelling and the scheduling of harvest.

To our knowledge, the extent to which spatial variation in grape composition in a vineyard changes with time has not been investigated before. Trought et al. (2008) measured trunk circumference and pruning weight to characterise vine vigour and related variation in these attributes to variation in fruit quality and soil properties (texture and temperature). In a companion paper (Bramley et al. 2010), spatial analysis was used to identify relationships between trunk circumferences, soil texture and canopy Plant Cell Density (PCD) measured using both remote and proximal sensing. In this paper we explore how the spatial analysis of Bramley et al. (2010) could be integrated with models describing aspects of phenological development and juice quality to better understand vineyard variation in Marlborough, and thus, evaluate the likely commercial opportunities which might arise from such understanding, particularly through improved harvest management.

**Methods and Materials**

The 5.9 ha trial site formed part of a commercial vineyard on the north side of the Wairau Plain (173°35'E, 41°29'S). Details can be found elsewhere (Trought et al. 2008), but briefly, Sauvignon blanc vines (clone UCD1 on SO4 rootstock) were planted in 1994 in rows, approximately orientated north-south; the row spacing was 2.4m with a vine spacing in the row of 1.8m. The vines used in this study were pruned using a 2-cane vertical shoot positioning system (Smart and Robinson, 1991), retaining 12 nodes per shoot. Foliage wires were used to maintain a narrow canopy approximately 0.4m wide and 1.6m tall and vines were trimmed to maintain these dimensions three times during the growing season. Vines were drip irrigated and pest and disease management was achieved by following NZ Sustainable Winegrowing practice (http://www.nzwine.com/swnz/). The trunk circumference of all of the vines in four rows was measured 10cm above the graft union and 10cm below the head of the vine. Six plots, (comprising of four vine bays) in each row were chosen to give a range of circumferences ranging from 165 to 220cm.
Fruit composition was monitored approximately weekly from 18th February 2006 (just before veraison) to harvest. Berry samples (32 berries) were collected from each plot, cooled in an insulated box and analysed in the laboratory where fruit was gently macerated by hand, coarsely sieved and the juice prepared for analysis. The soluble solids (°Brix) was determined using an Atago PAL-1 digital pocket refractometer and pH was measured using a Metrohm 744 pH meter. The titratable acidity (TA) was measured on a juice sample (2.5 mL until TA ~ 15 g/L after which time a 5.0 mL sample was used) using a Metler Toledo DL50 autotitrator. The juice was diluted with 50 mL distilled water and titrated using 0.1 M NaOH to pH 8.4. The titratable acidity is expressed as g/L tartartic acid equivalent.

A range of spatial data were collected and mapped to aid understanding of spatial variability within the block (Bramley et al., 2010). These included the canopy plant cell density (PCD; the ratio of infrared: red reflectance) measured using both airborne remote sensing, proximal sensing from the side using a Crop Circle™ sensor (Holland Scientific, Lincoln, NE, USA), apparent electrical soil conductivity (EM38; Geonics, Canada) and the measurements of trunk circumference described above. Of particular importance to the present study are the Crop Circle data collected in March 2007 (Figure 1), which were shown in our earlier study (Bramley et al., 2010) to closely mimic the other measures of vine vigour (remote sensing, measurement of trunk circumference), irrespective of when these measures were collected. Thus, Bramley et al. (2010) demonstrated that, in the same vineyard as used for the present study, proximally sensed PCD provides a useful characterisation of vineyard variability at high spatial resolution. Importantly, the spatial structure in a map of trunk circumference derived from measurements made on the same target vines used here closely matched that in the higher resolution PCD map. It should also be noted that, in spite of the changes in vine vigour shown in Figure 1, yield differences over the block were small and not related to other measures of spatial variability (Bramley et al., 2010).

Modelling changes in juice composition

Curves were fitted to juice analysis data from each plot using Sigma Plot v9 (Systat Software Inc., Chicago, IL, USA). A Gompertz 3-parameter curve was chosen to describe changes in soluble solids as this provided a better model of soluble solids in a number of the plots when compared to a quadratic polynomial. Quadratic polynomials were fitted to pH and titratable acidity. Interpretation of these curves enabled us to estimate juice composition for each of the plots in the vineyard on any date based on measurements made on 9 occasions during the season. These modelled values were used in the subsequent analyses.

The PCD values for each plot were extracted from Figure 1 and related to the soluble solids, pH and titratable acidity on a range of dates from shortly after veraison (Figure 3). A 3-parameter sigmoid algorithm was fitted to the relationships between PCD and soluble solids and linear polynomials to the relationships between PCD and titratable acidity and pH. Using this method we were able to use the Crop Circle map (Figure 1) as a surrogate basis for the production of vineyard maps of these components of grape juice and view how their values change on a daily bases. The daily values for
each of these components were also used to calculate the changes in the Juice Index Score (see below) with time.

Development of a Juice index

Conceptually, growers and winemakers have juice composition targets for harvest. To develop a juice index, 52 participants at a Sauvignon Blanc Seminar in Marlborough, held in November 2005, were asked how they would rate juices to make a “typical Marlborough Sauvignon Blanc”. The participants consisted of 17 grapegrowers or viticulturists, 31 winemakers and the balance were either consultants, laboratory staff, or did not indicate their role, although overall, the 52 participants had an average industry experience of 11.3 years.

Scales of soluble solids values (between 18 and 27 °Brix in 0.25° steps), titratable acidity (between 5 and 14 g/L in 0.25 g/L steps) and pH (between pH 2 and 5 in pH 0.1 steps) were presented to the participants. These ranges covered values well to either side of the expected optima. Participants were asked to give a value to each point on the scale where 1 was not preferred and 5 strongly preferred. A Gaussian 4-parameter curve was fitted to each data set and from this, a preference score (ps) could be determined for each value of soluble solids (SS), pH and titratable acidity (TA). The participants were also asked to ascribe a weighting (w) to each of the three components when making their harvest decision. These were used to develop the overall Juice Index (JI):

$$\text{Juice index (JI)} = (SS_{ps} \times SS_w) + (TA_{ps} \times TA_w) + (pH_{ps} \times pH_w)$$

We recognise that other factors influence that decision, such as winery logistics and weather events and a number of the respondents also introduced comments on flavour and fruit health. However, as we were unable to quantify the intensity of these comments, they were not included in the analysis.

Using the modelled juice composition (as above) for each trial plot on each day during the later stages of fruit ripening (from 22 March) and the relationships between these modelled values and Crop Circle PCD (Figure 1), values of $SS_{ps}$, $TA_{ps}$ and $pH_{ps}$ and thus, JI were calculated for every pixel (2m x 2m) in a map grid imposed over the vineyard area. These values were also used to determine the distribution SS, pH and TA composition in the vineyard as a whole.

Results

Fruit collected from the 24 plots increased in soluble solids from 5.2 to 22.3 °Brix during the course of the monitoring period (Figure 2). At the same time, the pH increased from 2.56 to 3.05 and TA decreased from 38.9 to 9.3 g L$^{-1}$ (Figure 2). However, the rate of change was not the same across the whole vineyard. Fitting the Gompertz 3-parameter curves to soluble solids data and quadratic polynomials to titratable acidity and pH values from each plot enabled us to estimate the fruit
composition for each plot on a daily basis. The daily values were used to estimate the variability and map the vineyard.

Vines with low PCD (i.e. low vigour) had higher soluble solids and pH and lower TA early in the ripening period (March 22), when compared with those of higher PCD (i.e. higher vigour; Figure 3). As fruit ripened, the soluble solids became less variable, with all vines (except those of PCD greater than 10.7) achieving a soluble solids of approximately 23.0 °Brix. The predictive power of the PCD also changed with time, reflecting the changes in the ripening profile (Figure 4). The PCD gave a good prediction of differences in fruit soluble solids (an R^2 of up to 0.75) early in ripening, but its predictive utility then decreased as the slope of the relationship decreased (Figures 3, 4). This reflected the slower rate of soluble solids accumulation by fruit where vines had low PCD (those growing on stony soils) when compared to those with high PCD on soils with higher silt content. Similar changes were observed in the relationships between PCD and pH and TA. Vines with low PCD generally had lower TA and higher pH early in the ripening period, but differences between the plots decreased to low levels later in ripening (Figure 3). The predictive ability of PCD for TA and pH was less robust than soluble solids, but interestingly, increased later in the ripening period (Figure 4). The changes in the relationships between PCD and TA and pH values across the vineyard (Figure 4) indicate that at times during ripening, vine to vine differences in these fruit components were unrelated to vine vigour as measured by PCD and/or trunk circumference. We recognise that the fit of our regressions has low predictive ability on some dates, but persist with this approach here as a means of developing the proof of concept. The important factor to note is that the ability to predict fruit composition is best early in the ripening of the fruit, which might be valuable for the early planning of harvest strategies or product allocation.

The differences in fruit composition were reflected in the spatial variability of the vineyard (Figures 5-7), with vines on the eastern side of the vineyard, generally achieving a higher soluble solids and pH, and lower TA earlier than those on the west. In general, the variability in soluble solids decreased across the whole vineyard as fruit ripened (Figure 8). The distribution was skewed to the left throughout the ripening period, although a maximum value of between 23.5 and 24 °Brix was achieved by 1st May (Figure 8). The pH and TA achieved a minimum degree of variability on April 21, and then appeared to become more variable as fruit ripened further (Figure 8).

The optimum values for the juice components determined from the questions posed to the Sauvignon Blanc workshop participants were 22.5 °Brix, TA 9.0 g/L and pH 3.2 (Figure 9) with the weighting given to each component in considering harvest decisions being 49.3, 27.7 and 23.0 % respectively. These data enabled mapping of changes in juice index (equation 1) as the crop matured (Figure 10). As a consequence of the earlier ripening profile of fruit on the (north) eastern side of the vineyard, this area reached its maximum juice score earlier than elsewhere. In this part of the block, the juice index generally reached a value of >4.25 between the 11 and 21 April (Figure 10). However, by 1 May, the soluble solids was greater than 22.5 °Brix and as a result the juice index started to decrease. In contrast, the slower ripening on the western side of the vineyard, meant that the juice index failed to reach 4.25 by 1 May. The influence that the increasing soluble solids has on juice index distribution is
demonstrated in Figure 11, which shows that by May 1, the mean index value had decreased from an average of 4.2 back to 3.3 as soluble solids became too high.

Discussion

Despite the potential importance that differences in maturity class within a harvest sample potentially have for a final wine, it has seldom been demonstrated. Carroll et al (1978) sorted Carlos Muscadine grapes by colour using a photoelectric light source and concluded that wines made from optimum ripeness were superior to those made from under- or over-ripe fruit. However, the importance of variation in fruit composition on wine style may depend on the variety being considered. For example, Long (1987), compared wine quality from two Californian vineyards and reported that the vineyard with the least variation in ripeness consistently produced the better quality wine. In contrast, Parr et al (2007) suggested that “archetypical” Marlborough Sauvignon Blanc has both “ripe” and “unripe” flavours in the wine. This suggests that regardless of the wine style, it is important to understand and be able to predict both the variability in fruit composition in a harvest sample, and also the range of wine aromas and flavours that are likely to be derived from the fruit.

Identifying the optimum time to harvest grapes in a variable vineyard is a challenge facing most viticulturists and winemakers. Whether a vineyard is harvested or not is a decision made by viticulturists and winemakers, often based on the question: “do I think this fruit will be better next time the logistics of winery intake will allow the fruit to be processed?”. Viticulturists and winemakers generally have compositional targets, which in some cases may form the basis of winery payments for grapes. To integrate various common juice parameters, we developed the concept of a “juice index”. Traditionally, fruit is sampled to obtain a representative value of key maturity indices (e.g. soluble solids, pH and TA) and little regard is given to either the variability around that mean, or the location of sample collection; representativeness is assumed. However, as vineyards are variable some areas may be unripe while others are overripe. Wines made from these juices will have different flavour and aroma profiles. For example, as soluble solids levels increase, the resulting wines may have higher alcohol concentrations. In contrast, unripe fruit may have excessively high acidity and/or herbaceous character.

By measuring changes in composition with time, we have modelled how soluble solids, TA and pH change in a variable vineyard in an attempt to identify the optimum harvest date. Our results show that early in ripening, considerable variation in fruit composition is observed and this is related to other measures of variability (e.g. PCD and trunk circumference). Vines with lower PCD had higher soluble solids and pH and lower titratable acidity and ripened earlier when compared to vines with higher PCD values. The vines with low PCD had smaller trunk circumferences and were growing in soils with greater proportions of stones in the profile (Bramley et al. 2010; Trought et al. 2008; Mills 2006). In contrast, vines growing on deeper, siltier soils in the lower lying parts of the vineyard failed to achieve the target maturity values by May 1 (Figures 10, 12). Other areas did eventually ripen to target levels,
but the fact that the majority of the vines were now past their optimum ripeness level meant that the overall value of the juice index decreased between April 21 and May 1. This indicates that, if the vineyard was to be harvested as a single parcel, the optimum date to harvest fruit was about April 21 (in this particular season), when the overall variation in vineyard juice index was small and the mean value was highest.

The modelled data clearly show the date and location of fruit with the highest juice index. For example on April 21st 88.5% of the vineyard area had achieved a juice index of more than 4.4, with the balance of the vineyard still unripe (Figure 12). However, by delaying harvest beyond this date, soluble solids increased above the optimum concentration and juice index values decreased (Figure 10). Understanding the spatial variability in a vineyard helps viticulturists make informed harvesting decisions. Indeed, previous work has shown that selective harvesting, based on such knowledge, can increase overall vineyard profitability (Bramley et al., 2005). In the case of our study block, such a strategy might involve partitioning the block into two areas. The first area, which achieves a juice index of 4.4 or greater (Figure 12), may be processed to a wine with a higher price point compared to the remaining second area. However, as Figures 5-7 and 10-12 illustrate, this variability potentially changes with time. This reflects differences in the rate of change in key volatile and non-volatile grape components in various parts of the vineyard, reflecting differences in vine vigour, which in turn are a consequence of factors such as soil texture (Bramley et al., 2010). By taking this spatial and temporal variation into account, the optimum harvest date for the whole vineyard can be determined (Figure 12). Likewise, the consequence of delaying harvest to all or part of the vineyard on potential juice quality can be evaluated. In our example, the fruit on the western side of the vineyard fails to reach a juice index of 4.4 by early May, when short days and cool temperatures (and the risk of frost) means that it is unlikely that fruit will ripen further.

Spatial variability in vine growth (e.g. trunk circumference) in this vineyard reflects variation in soil texture (Mills, 2006; Trought et al., 2008; Bramley et al 2010) and is therefore unlikely to change between seasons. However, the magnitude of variability in juice composition does change as the fruit ripens. It is also likely that the relationships between PCD and fruit composition parameters will be different between seasons and as a result the optimum date of harvest will change. By understanding the spatial variability in the vineyard, the relative balance of soluble solids, pH and TA early in ripening (shortly after veraison) and how season affects fruit composition, the modelling approach we used may be able to predict the optimum harvest date. This will be investigated in a further paper.

It might be suggested that more robust estimates of the juice index and its spatial and temporal variability may have been obtained had we measured indices of juice composition on a spatially distributed array of target vines in the manner of Bramley (2005) rather than relying on the PCD map (Figure 1) as the basis for extrapolating juice compositional data from our fewer, more spatially restricted target vines. Such a strategy would certainly have enabled maps similar to those shown in Figure 5-7 to be produced, but these would have had a greatly reduced ‘support’ (Webster and Oliver, 2007) compared to the PCD maps derived from (very) high resolution data. Indeed, the 24 target vines used here are insufficient for geostatistical analysis and are obviously far fewer than the 41,660 PCD
values which underpin Figure 1. Furthermore, a practitioner is never going to have the time to monitor more than a few target vines – certainly too few to produce maps from – yet they may buy some remotely sensed imagery or rent (or even buy) a proximal sensor such as the one used here in order to get the high resolution data which Figure 1 derives from; the collection of these data and subsequent map interpolation requires just a few hours work.

Our results also have implications for the concept of terroir. Bramley and Hamilton (2007) have previously raised questions as to the scale at which the concept of terroir is useful. They suggested that there is a mismatch between the common regional-scale use of this concept and the within-vineyard scale at which it might contribute to an understanding of the style and sensory attributes of a wine as a consequence of the biophysical environment in which its source grapes were grown. Whilst the present results are consistent with those of Bramley and Hamilton (2007), they also suggest a temporal component to terroir which has arguably been ignored in the past. Thus, a wine reflects both the location in which the source fruit were grown, and also the time at which that fruit was harvested. In this connection, both ‘location’ and ‘time’ can be thought of as means about which there is considerable variation (Figures 8 and 12).

Conclusions

For viticulturists and winemakers to anticipate the optimum harvest date for a vineyard, or to adopt differential management strategies within it such as selective harvesting, a knowledge of both spatial variability and its interaction with crop maturation is needed. In this study, we have shown that by integrating our knowledge of crop phenology with an understanding of vineyard variability and winemaker objectives, decisions about where and when to harvest can be optimised. Further work is required to take this beyond the proof of concept, particularly with respect to the extrapolation of our method to other locations, other varieties and growing seasons. However, whilst the objective here was not to remove the sensory evaluation of the winemakers from the harvesting decision process, our results suggest that an appropriate understanding of vineyard performance in both space and time will help their decision processes at a busy time of the year.

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