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Making sense of a sense of place: precision viticulture approaches to the analysis of terroir at different scales

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ABSTRACT

Traditional 'terroir zoning' has largely relied on heuristic 'expert' opinion coupled with approaches to land classification based on thematic mapping to describe the influence of soil conditions and climate on wine composition. Recent advances in geographical information systems (GIS) and digital mapping have enabled more robust quantitative methods to be developed, but with few exceptions recent terroir research has remained reliant on heuristic opinion and conformity to previously defined terroir units, rather than employing data-driven approaches. Using two case studies at regional scale, the aim of this paper is to illustrate how the use of methods of quantitative spatial analysis, as used to guide understanding of production system variability and to underpin precision viticulture (PV), may assist in better understanding terroir at a range of scales.

In the Barossa region of Australia, cluster analysis of indices of soil physical and chemical fertility (available water capacity and cation exchange capacity), with critical climate variables (growing season rainfall, mean January temperature and growing degree days), clearly delineates differences between the Barossa and Eden Valleys but does not robustly promote further sub-division. Meanwhile, in the Marlborough region of New Zealand, interpolation of data supplied by wine companies from over 450 vineyards over several seasons suggests a consistent and characteristic regional 'terroir' in terms of vine yield and harvest date. Similarly consistent results were obtained for sub-regions of the Wairau Valley and a comparison of the Wairau and Awatere valleys. Thus, with scale-dependent modification, the methods of spatial analysis used to underpin PV and studies of within-vineyard variability offer much potential for terroir analysis and the identification of terroir zones. Importantly, these methods are unbiased, data-driven, and not reliant on heuristic opinion.

KEYWORDS

vineyard variability, spatial analysis, terroir zoning

INTRODUCTION

'Terroir zoning' has traditionally relied on qualitative 'expert' opinion of wines and/or fruit and heuristic views of the biophysical factors that might impact them, coupled with classical approaches to land classification and cartography, to describe the influence of soil conditions and climate on wine composition and vine management. Thus, for example, Jones *et al.* (2004) assessed the suitability of topography, soil, land use and climate in the Umpqua Valley (Oregon, USA) to identify "the best terroirs of the region". Vaudour *et al.* (1998) used a somewhat similar approach in the Côtes du Rhône (France), and sampled Grenache fruit to demonstrate grape compositional differences between four of the identified terroirs. However, advances in geographical information systems (GIS) and digital mapping have enabled more robust quantitative methods to be developed; Vaudour *et al.* (2015) provide a review. Despite these advances, with few exceptions (e.g. Fraga *et al.*, 2017; Lacorde, 2019), recent terroir research has remained reliant on heuristic opinion and conformity to previously defined terroir units (Carey *et al.*, 2009; Vaudour *et al.*, 2010; Bonfante *et al.*, 2011; Bonfante *et al.*, 2018), rather than employing purely data-driven approaches. As a consequence, the approach has tended to be one of seeking to validate terroir zones defined historically through an appellation or geographical indication system, rather than using the new methods or, in many places, new data at much higher resolution than was previously available, as a basis for identifying what zoning might be justified. For example, the 'GlobalSoilMap.net' project (https://www.isric.org/projects/globalsoilmapnet) makes soil property information available globally at a resolution of approximately 100 m, which is in marked contrast to a conventional soil or land resource survey at a scale of 1:50,000 (e.g. Hall *et al.*, 2009). Furthermore, because much of this terroir zoning research has been conducted at a regional scale and has tended to rely on relatively few samples and/or sampling conducted over quite wide biogeographic areas, it has arguably contributed little to a true understanding of the drivers of terroir, or to a consideration of how terroir might be manipulated to enhance the opportunity to produce wines of desired style (Bramley *et al*, 2017). A further difficulty is presented by the notion of terroir zones being homogenous (e.g. Fraga *et al.*, 2017), despite variation being evident at scales ranging from between-regions (hundreds of km) to a few metres within individual vineyards (Johnson and Robinson, 2019; Bramley *et al.*, 2011a, 2017). We suggest that data-driven approaches may enable identification of new consistent units of distinct wine styles and/or challenge the robustness of some existing units that derived from historic, heuristic assessment.

At a previous Terroir Congress, Bramley and Hamilton (2007) explored a precision viticulture (PV) approach to the understanding of terroir. Using examples from the Padthaway and Murray Valley winegrowing regions of Australia, they demonstrated how a combination of yield monitoring and mapping, remotely sensed imagery, a digital elevation model and spatial analysis, coupled with targeted sampling of vines, could promote an understanding of variation in terroir at the within-vineyard scale. For the Murray Valley site, this work was expanded considerably to include analysis of soils, grapes and small-lot wines (both chemical and sensory analysis; Bramley *et al.*, 2011a), with the differences between zones identified within the vineyard shown to be of commercial significance (Bramley *et al.*, 2011b). Somewhat similar examples have been reported from other winemaking countries in both the Old and New World (e.g. Tisseyre *et al.*, 2008; Arnó *et al.*, 2011; Trought and Bramley, 2011; Priori *et al.*, 2013; Ledderhof *et al.*, 2017). Recent research undertaken in the Australian sugar industry (Bramley *et al.*, 2019a) used a similar analytical approach to explore spatial and temporal yield variation at regional scale. In this work, the focus was on testing the appropriateness of an assumed 'district yield potential' as an input to nitrogen (N) fertiliser recommendations for sugarcane. Instead of using data from yield monitors fitted to harvesters and within-field yield mapping at fine resolution as in the above wine-related examples (interpolation onto map pixels of a few m^2), yield data recorded on a per-block basis following delivery of sugarcane to sugar mills were used to generate yield maps (pixels of 1 ha) over seven seasons for an entire sugarcane growing region (approximately 70,000 ha). Just as Bramley and Hamilton (2007) and others were able to demonstrate temporal stability in the patterns of within-vineyard yield variation, and to provide insights as to the cause of this variation and its implications for wine quality and the expression of terroir, temporal stability in patterns of within-region sugarcane yield could also be demonstrated (Bramley *et al.*, 2019a). When used as an input to the standard sugar industry N fertiliser recommendations, the 'block yield potential' derived from these regional scale maps provided the basis for more targeted use of N fertiliser and a consequent reduced risk of N loss to the Great Barrier Reef compared to when the 'district yield potential' was assumed. These maps also provided a new basis for the delivery of local agronomic advice. Of particular note here is the important difference between the vineyard and sugarcane examples on the one hand, and the majority of terroir zoning research on the other, in that the methods used by Bramley and Hamilton (2007), Bramley *et al.* (2011a), Bramley *et al.* (2019a) and others noted above are purely data-driven; there is no heuristic opinion or other classification of data layers prior to analysis of 'zones', as occurs, for example, in terroir studies based on land use classification (e.g. Jones *et al.*, 2004; Bonfante *et al.*, 2011).

Based on experience with work on within-vineyard variability and regional scale mapping of sugarcane yield, the objective of this paper is to illustrate the potential for applying this data-driven approach for terroir zoning. We use two case studies to do this, from Australia and New Zealand. Both are 'works in progress' but we report on the approach used here with the intention of contributing to an early and rapid advancement of terroir zoning research and hence improved understanding of wine terroir, its core drivers, and ways in which winegrowers might take advantage of this understanding.

CASE STUDY 1: REGIONAL SCALE VARIATION IN MARLBOROUGH SAUVIGNON BLANC

Seasonal variation in the yield of wine grapes is a challenge confronting both grapegrowers and winemakers (Dunn and Martin, 2003; Trought, 2005). Accordingly, much recent and current research (we are aware of several projects on-going around the world) is focused on improved grape yield estimation, with various approaches being explored including those based on sensors (Diago *et al.*, 2014; Diago *et al.*, 2015; Nuske *et al.*, 2014; Herrero-Huerta *et al.*, 2015; Liu *et al.*, 2017; Liu *et al.*, 2020), better understanding variation in the components of yield (e.g. Zhu *et al.*, 2020), and on targeted sampling (Myers and Vanden Hueval, 2014; Araya-Alman *et al.*, 2019; Myers *et al.*, 2020). A major focus of this work is on the delivery of an accurate yield estimate early enough in the season for it to enable any required remedial management decision – whether in the vineyard (e.g. crop thinning), at the winery (e.g. installation of additional tanks), or in the marketing or supply logistics departments.

Even if the various sensor-based approaches are completely successful in providing accurate early season yield estimates, for reasons of both cost and logistics it is highly unlikely that such sensors will be deployable ubiquitously; wine companies and vineyard managers will need to target their use. Accordingly, if a sensor-based approach is to be deployed, it is likely that this deployment will need to be carefully targeted. Two key questions then are: Can knowledge of yield at one location be used to infer yield at another? If it can, may an *estimate* of yield made in one location, be used to infer the likely yield at another? To answer both questions requires understanding of patterns of spatial variability in yield and of their temporal stability.

Vineyard variability research (see references above and many others; Bramley (2020) provides a review) has overwhelmingly been undertaken in spur-pruned vineyards. However, in the Marlborough region of New Zealand, Sauvignon blanc is cane pruned. Recent research (Bramley *et al.*, 2019b) has demonstrated that, for all practical purposes, within-vineyard variation in the yield of cane-pruned Marlborough Sauvignon blanc can be regarded as random, even though variation in vine vigour shows systematic patterns of variation. These patterns of vigour variation are stable from year to year and related to underlying variation in vineyard soil and topography. This vigour variation has important consequences for fruit composition (Trought and Bramley, 2011), but is seemingly unrelated to variation in yield. Accordingly, within an individual block, a yield estimate may be made using randomly selected vines, although given the relationship between vine vigour and fruit composition a targeted sampling approach such as that recommended by Myers *et al.* (2020) may offer efficiencies. However, many wine companies in Marlborough either own vineyards throughout the region, or purchase fruit from growers whose blocks are scattered throughout Marlborough. Whether a yield prediction made in one part of the region can provide useful information about the likely yield in another is therefore an important issue. This question is the focus of this case study.

1. Materials and methods

The approach used in this work was similar to that used in the Bramley *et al.* (2019a) study of sub-regional differences in sugarcane yield. As a first step, a spatial coverage of all vineyards was obtained from the Marlborough Regional Council. The 'Merge' and 'Dissolve' functions in the ArcGIS software suite (v10.4.1; ESRI, Redlands, CA, USA) were used to remove small gaps between properties due to roads, houses and gardens, and other small areas of non-vineyard land use, to generate a coverage of 'vineyard area' from which a raster grid of 1 ha (100 m × 100 m) pixels was generated (Figure 1).

The sugarcane grown in the Herbert River is delivered to one of two sugar mills; both are owned by the same company. Accordingly, yield data for every block of sugarcane in the district, other than those under fallow, were available to the Bramley *et al.* (2019a) study. This resulted in a *support* for yield maps of approximately 2,500 yield records per year for each crop class (i.e. years since planting or ratoon number). When crop class effects were removed, approximately 13,000 records underpinned each map. Each of these yield records were georeferenced to the centroid of the associated sugarcane block. Because of the highly fragmented nature of the wine sector, which comprises many grapegrowers *and* many wineries, there was no single data source that was accessible for the present study. However, as a part of existing yield estimation, harvest management and grower payment processes, several wine companies keep detailed records of yield and associated metrics. Accordingly, wine companies were approached to contribute data for this project. Here, we focus just on yield and the date of harvest and, given the availability of data, on the five growing seasons that ended with the 2014–2018 vintages. Note that yield was expressed as kg/m rather than t/ha to minimise the effects of variation in row and vine spacing. Whilst we acknowledge that management differences (e.g. vine age, cane number, etc.) may influence yield and harvest date, and excluded vineyards less than three years from planting from the database, the vast majority of vineyards are pruned to retain four canes. Reducing the retained cane number to three and two might be expected to reduce yield by 15 % and 22 % (Greven *et al.*, 2014), but the proportion of two cane pruned vineyards is

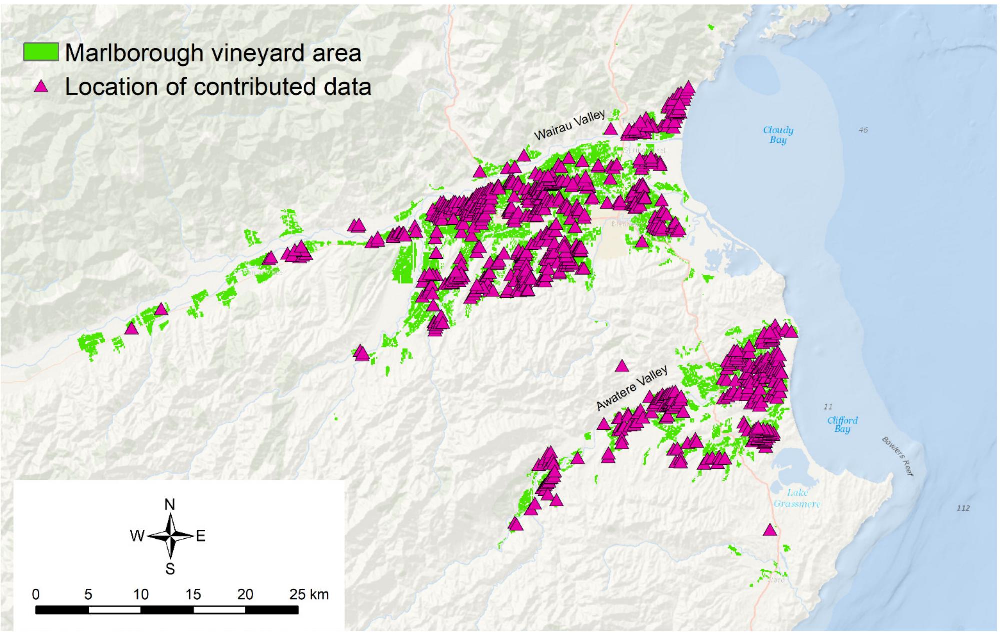

FIGURE 1. The Marlborough winegrowing region, located at the north of New Zealand's South Island. Also shown here are the Marlborough vineyard area and the locations of vineyard blocks for which data were available for the 2018 vintage (the amount of data available varied from year to year). Note that the Marlborough vineyard area is predominantly located in two river valleys: the Wairau Valley to the north, and the Awatere Valley to the south. The basemap layer was sourced from ESRI and its collaborators through the ArcGIS software.

small. Other management differences and any clonal effects were ignored; Sauvignon blanc vineyards in Marlborough are generally consistently trimmed to retain a VSP canopy approximately 1100 mm tall (from the fruiting wire to the top of the canopy, 2000 mm from the soil surface) and 400–500 mm wide; and approximately 98 % are planted to the same UCD1 clone.

Yield data were normalised (mean of zero, standard deviation of one) prior to mapping to assist in addressing data privacy concerns, and harvest dates were expressed as Julian numbers (1st of January= 1). In some instances, as provided, these data were georeferenced to particular vineyard blocks. In others, the data were georeferenced to our best estimate of the location of the centroid of the relevant vineyard block using Google Earth (www.google.com/earth/) and one or both of a vineyard address and paper property map. It is accepted that for some blocks there will be a positional error in the georeferencing of data used in this work, but these errors (< 100 m) were considered of little consequence given the total vineyard area in the entire Marlborough region (27,792 ha; Figure 1).

For each season, regional scale maps of yield and harvest date were interpolated onto the 1 ha raster (see above; Figure 1) in VESPER (Minasny *et al.*, 2005) using local point kriging with a data cloud of 100 points and an exponential variogram. To assess similarity in patterns of spatial variation, the resultant maps were then clustered using *k*-means clustering in JMP (v.14.0.0, SAS Institute Inc., Cary, NC, USA) with the optimum number of clusters identified using the Cubic Clustering Criterion (SAS Institute Inc., 1983).

2. Results

Regional scale yield maps for Sauvignon blanc grown in New Zealand's Marlborough wine region (2014–2018) are shown in Figure 2. Whilst normalised data were used here to address concerns over data privacy, a benefit of having done so is that seasonal effects are removed from the analysis. Thus, whilst Figure 2 indicates that some parts of Marlborough seemingly have patterns of yield variation which are not obviously temporally stable (the upstream or western parts of both the Wairau and Awatere Valleys being examples,

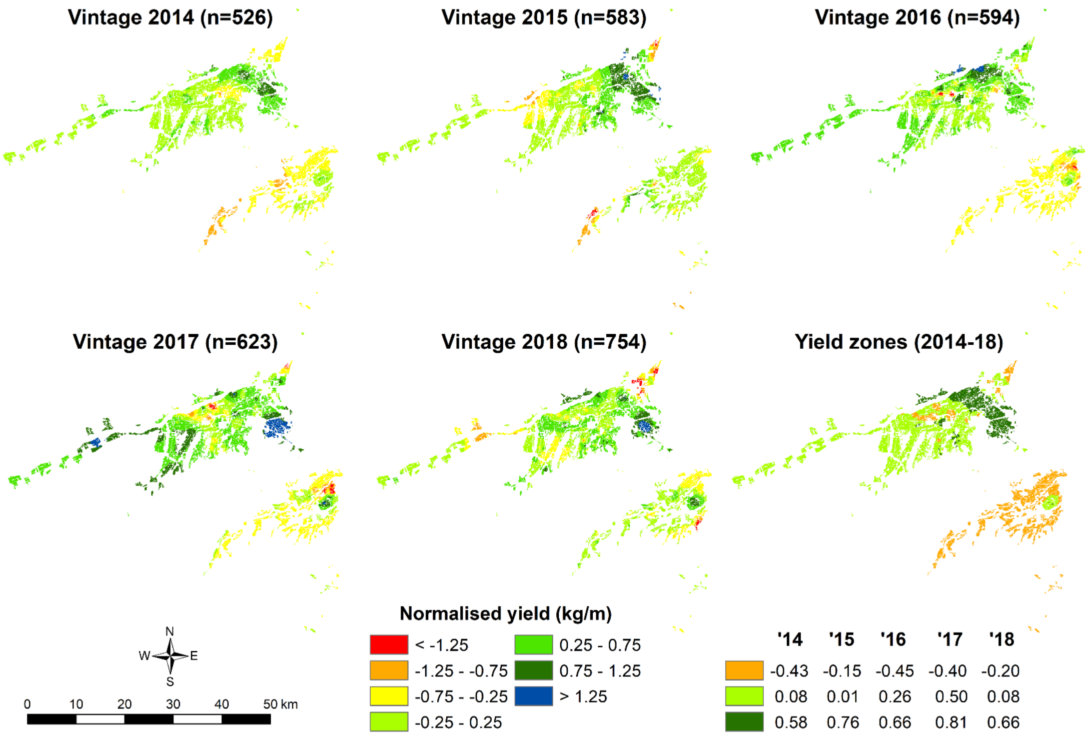

FIGURE 2. Regional scale variation in the yield (kg/m) of Marlborough Sauvignon blanc, 2014-2018. Also shown here are the numbers of data points (i.e. vineyard blocks) underpinning the map for each season, and the result of clustering these seasonal maps into 'yield zones' using *k*-means. As the data have been normalised (μ = 0, σ = 1), the units for all maps are standard deviations. The numbers in the legend to the yield zones map are the zone means.

presumably due to a paucity of data from these areas), over much of the region, areas that are lower or higher yielding one year tend to be similarly lower or higher yielding in other years. As a consequence, when the map layers for each of the five seasons are clustered using *k*-means (bottom right map in Figure 2), three 'yield zones' are readily identified. Thus, the Awatere Valley is seemingly inherently lower yielding than the Wairau Valley, whilst the downstream (eastern) end of the Wairau Valley has a band of inherently higher yielding vineyards. The only management effect factored into this analysis is row and vine spacing, that is, any effect of vine age and the number of canes retained have been ignored; we have no means of assessing farmer skill. Thus, the fact that this area of higher yield aligns with a band of siltier soils compared to those predominating in the rest of the lower Wairau (Rae and Tozer, 1990; see also https://maps.marlborough.govt.nz/smaps/?map=eeeff21e2a664dbeba7e07d5b177d593) is strongly suggestive that the yield variation seen in Figure 2 is a terroir effect. Differences in growing degree days between the Wairau and cooler Awatere Valleys (Sturman *et al.*, 2017), and the consequent later date of flowering in the Awatere Valley (Parker *et al.*, 2014) could similarly be exerting a terroir effect.

Temporal stability in patterns of variation in harvest date (Figure 3) was even more evident than for yield (Figure 2). Despite marked inter-annual variation in dates of harvest, the central Wairau Valley and an area close to the mouth of Wairau River are consistently harvested earliest in the season, whilst the Awatere Valley and the area of higher yielding, siltier soils in the lower Wairau are harvested latest. In the former case this is presumably due to the cooler temperatures and later phenology, and in the latter the higher yields resulting in a greater fruit mass:leaf area ratio and a slower rate of soluble solids accumulation from veraison (Parker *et al.*, 2015). Clustering the yield and harvest date data (not shown) supports this conclusion.

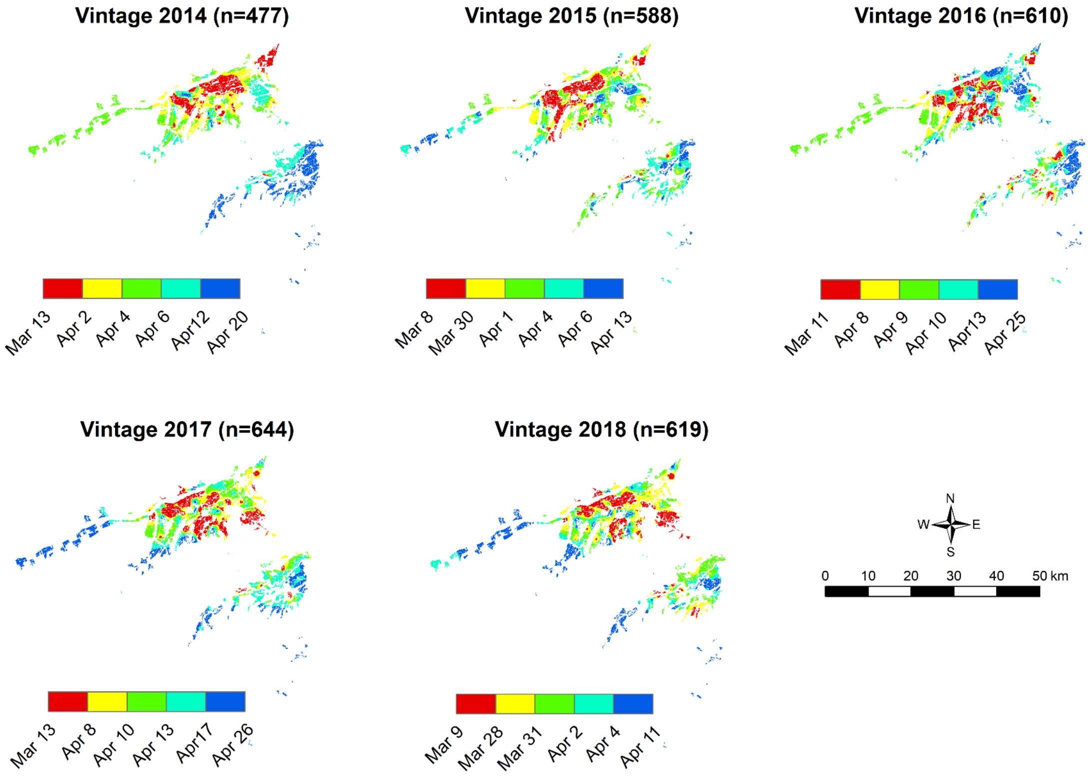

FIGURE 3. Variation in the date of harvest of Sauvignon blanc in the Marlborough region of New Zealand, 2014-2018.

In each map, the data have been classified such that 20 % of the data lie in each coloured class. The first date in each legend is the date of the earliest harvest recorded in the dataset for that year. The last date listed is the latest date of harvest for that year, whilst the other dates are those that divide the map classes. Also shown are the numbers of data points (i.e. vineyard blocks) underpinning the map for each season.

Overall, these results support the view that the Marlborough wine region is a far from uniform area; that is, it has a varied terroir. Whereas yield estimation might reasonably be undertaken in an individual block either at random locations, in a randomly selected row or group of vineyard rows, or where the intended product range supports a possibility for selective harvesting, guided by remotely sensed imagery (Bramley *et al.*, 2019b), at regional scale location clearly matters. The maps shown in Figure 2 indicate how yield estimation in one part of the region might assist in informing estimates in other locations, especially if such maps can be based on a larger *support* than in this preliminary investigation. Likewise, those in Figure 3 could aid in harvest planning and the management of winery logistics. When coupled with other data, including soil properties, climate, grape and wine chemistry and wine sensory analysis, they could contribute to improved understanding of a Marlborough terroir.

CASE STUDY 2
SUB-REGIONALISATION IN THE BAROSSA VALLEY

Several winegrowing regions in Australia have been considering the merits of identifying sub-regions within their established geographical indications. This follows the idea that such a strategy might nuance the 'premiumisation' of Australian wine (Wine Australia, 2015) and promote an ability to enhance the marketing of wines using stories based on terroir. Sadly, this is a process that in some regions has arguably become captive to wine writers and marketeers with many of the 'stories' characterised by a lack of underpinning science and/or focused on variation in a single attribute (Bramley, 2017). A similar comment could be made in relation to much of the popular commentary on terroir more broadly (Brillante *et al.*, 2020).

The Barossa Grounds is a project through which the Barossa Grape and Wine Association (BGWA) is seeking to better understand variation in wine style across the Barossa Zone, with a particular focus on Shiraz wines (www.barossawine.com/vineyards/barossa-grounds/). The Australian Geographical Indications define the official boundaries of the Barossa Zone and the regions within it, which are the Barossa Valley and Eden Valley (Figure 4). A sub-region of High Eden is also recognised. In addition to understanding differences between these (sub) regions, there is also interest in exploring variation within the Barossa Valley itself. Thus, at the time of writing, three 'distinctive Grounds' have been identified (Northern Grounds, Central Grounds and Southern Grounds), with two smaller grounds (Eastern Edge and Western Ridge) also acknowledged.

Two major activities led to the elucidation of these 'Grounds'. In the first (Robinson and Sandercock, 2014), a traditional land use classification approach was followed, combining reconnaissance 1:50,000 soil survey (Hall *et al.*, 2009) with elevation and climate data (rainfall and temperature). Of the 61 'soil sub-groups' or 'soil types' identified in South Australia (Hall *et al.* 2009), 33 exist within the Barossa Zone (Robinson and Sandercock, 2014), reflecting the complexity of soil variation in this part of South Australia. Thus, to simplify characterisation of Barossa soils, and in consultation with a group of local experts and technical viticulturists, the soils were re-classified into six classes based on the available water holding capacity (AWC) of representative soil profiles described by Hall *et al.* (2009). The boundaries between these classes were determined on the basis of their perceived viticultural significance; whether the representative soil profiles from which the AWC data were derived included those from the Barossa is uncertain. In a similar way, the local experts separated the 580 m elevation range into four classes and the 464 mm range of annual rainfall into five classes. In respect of temperature, season growing degree days (GDD), defined as the cumulative mean daily temperature in excess of 10 °C during the growing season (1 October to 30 April), which has a range of over 700 degree days, was separated into five classes. Whereas the GDD classes were of equal width (with the exception of the lowest and highest), those for AWC, elevation and rainfall were not. The classes were overlain in GIS from which it was identified that 147 of the 600 possible combinations occur within the Barossa zone. Given the close correlation between temperature, rainfall and elevation, the analysis was revised to focus solely on AWC and elevation, resulting in 21 unique classes of viticultural landscape identified in the Barossa zone.

The second activity leading to the elucidation of the 'Grounds' was an unpublished sensory analysis of local un-oaked wines carried out by local winemakers, with statistical analysis provided through the University of Adelaide. Given the complexity of the Barossa landscape as identified by Robinson and Sandercock (2014), it is perhaps no surprise that the identification and depiction of the Barossa Grounds appears to have relied more heavily on this sensory analysis than on consideration of the biophysical data. Thus, the map of the Barossa Grounds made available to an interested public is much more artwork than detailed cartography (https://issuu.com/barossadirt/docs/barossa_chapters_grounds); indeed, it is hard to see how the biophysical analysis was brought to bear on identification of the Barossa Grounds. Given the biophysical complexity identified in the thematic mapping approach of Robinson and Sandercock (2014), it was of interest to see whether an alternative approach to the analysis based on that used in PV (see above) was of value. Note that it is not our intention in this work to seek to either 'referee' or discredit the previous identification of the Barossa Grounds; our interest is in exploring the utility of an alternative approach to analysis of biophysical data as it may pertain to terroir.

1. Materials and methods

In large part, this analysis relied on the dataset used by Robinson and Sandercock (2014). Indeed, the climate data originally sourced from the Australia Bureau of Meteorology by Robinson and Sandercock (2014) were passed to us for this study. Data for GDD, mean growing season temperature (GST), mean January temperature (MJT), annual rainfall (AnnR) and growing season rainfall (GSR) were provided as 5 km rasters (i.e. pixels of 25 km^2). Spatial coverages depicting the Barossa geographical indications and the locations of vineyards were obtained from Vinehealth Australia (Figure 4). Elevation data were downloaded from the ELVIS website of the Australia and New Zealand Land Information Council's (ANZLIC) Intergovernmental Committee on Surveying and Mapping (ICSM; https://elevation.fsdf.org.au/); we used the hydrologically enforced digital elevation model (DEM-H; Gallant *et al.*, 2011) derived from the 1 second Shuttle Radar Topography Mission (SRTM) for this work. Since the time of the Robinson and Sandercock (2014) study, the Soil and Landscape Grid of Australia (SLGA; Grundy *et al.*, 2015), a part of

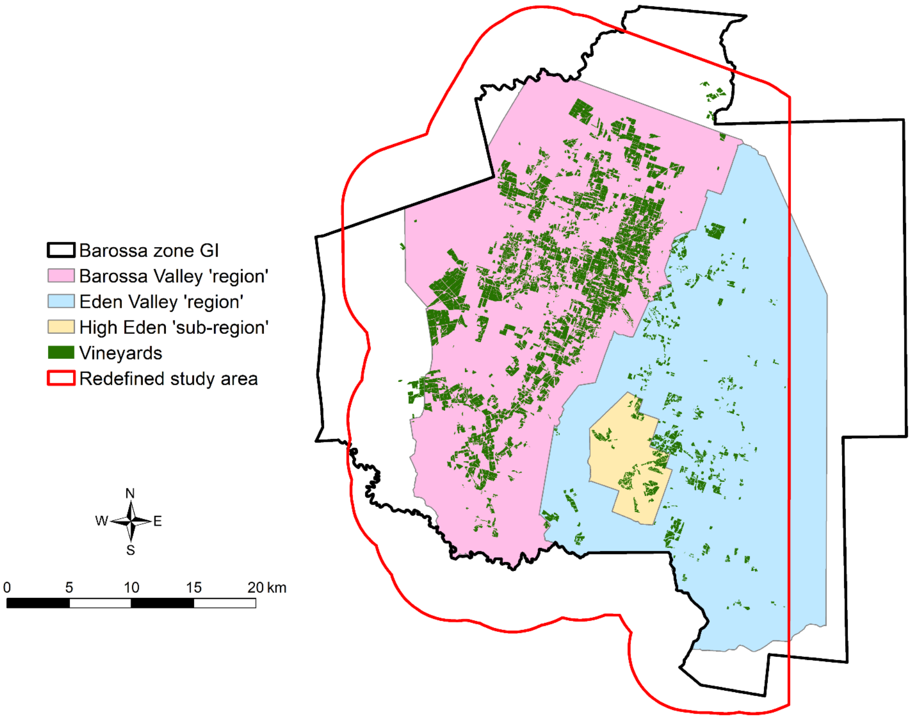

FIGURE 4. Geographical indications in the Barossa wine region of South Australia.
The Barossa zone comprises the regions of Barossa Valley and Eden Valley and the High Eden sub-region. Also shown are the locations of vineyards and a redefined boundary used for the present study.

the aforementioned 'GlobalSoilMap.net' project, has been made available. SLGA makes individual soil property data available in raster format at a resolution of 90 m in depth increments of 0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, 60–100 cm and 100–200 cm. Taking the lead from Robinson and Sandercock (2014), we obtained data for AWC (https://aclep.csiro.au/aclep/soilandlandscapegrid/GetData.html). However, we also included data for cation exchange capacity (CEC) in our analysis as a surrogate indicator of soil fertility. Given that in Barossa vineyards, vine roots tend to predominate in the top 60 cm of the soil profile, and given also the marked similarity in patterns of spatial variation in both AWC and CEC down the profile throughout the Barossa zone (data not shown), a profile-weighted mean value for AWC and CEC for the 5–60 cm depth range was calculated in ArcGIS (v10.4.1; ESRI, Redlands, CA, USA).

As can be seen in Figure 4, the extent of the Barossa zone extends well beyond the land area used for viticulture, especially to the west and east, in the latter case onto land that is unlikely to be used for viticulture; there are also vineyards to the north and west which fall outside the defined regions. For these reasons, and also in light of the alignment of the 5 km resolution climate data (see above), we applied a modified boundary for the purposes of this study. With the exception of the eastern side of the Eden Valley, this was based on a 5 km buffer around the existing regions; to the east, it was based on the locations of existing vineyards. From this boundary a 1 ha raster grid (100 m × 100 m) was derived (as in the Marlborough case study). The soil and elevation data (see above) were re-sampled to this 1 ha raster. In the case of the climate data, values were extracted from the centres of the 25 km^2 pixels and new surfaces for the climate attributes were interpolated onto the new 1 ha raster using global point kriging in VESPER (Minasny *et al.*, 2005). Thus, our base dataset for further analysis was a set of map layers for each of the variables

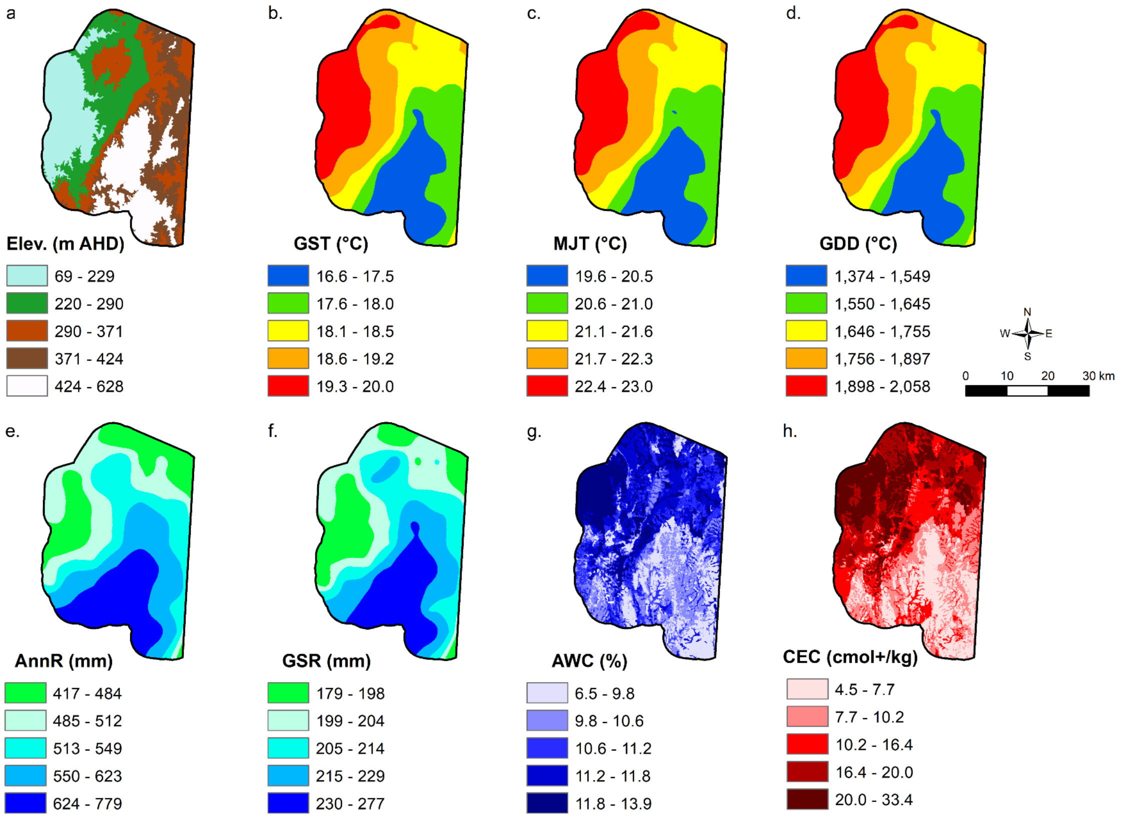

FIGURE 5. Base data layers used in analysis of biophysical variation in the Barossa Valley, Australia. (a) Elevation (Elev); (b) mean growing season (1 October to 30 April) temperature (GST); (c) mean January temperature (MJT); (d) season growing degree days (GDD); (e) annual rainfall (AnnR); (f) growing season rainfall (GSR); (g) soil available water holding capacity (AWC) in the 5–60 cm depth increment (profile-weighted mean); and (h) soil cation exchange capacity (CEC; 5–60 cm). All data have been classified based on the 20th percentiles to facilitate identification of patterns of variation.

of interest all mapped to the same 1 ha raster (Figure 5). As in the Marlborough case study, similarities amongst the patterns of variation in these map layers were investigated using *k*-means clustering in JMP (v.14.0.0, SAS Institute Inc., Cary, NC, USA) with the optimum number of clusters identified using the Cubic Clustering Criterion (CCC; SAS Institute Inc, 1983).

2. Results

Comparison of Figures 4 and 5 clearly indicates the distinctive separation within the Barossa zone between the Barossa and Eden Valleys. Thus, patterns of variation in indices of both temperature, rainfall, soil hydrology (AWC) and fertility (CEC) are strongly influenced by topographic variation (Figure 5). Accordingly, and consistent with the observations of Robinson and Sandercock (2014), patterns of variation in annual and seasonal rainfall (Figure 5e–f) and in various temperature indices of viticultural significance (Figure 5b–d) follow very similar patterns. It is therefore of no surprise that, when these data layers are clustered using *k*-means, cluster means for temperature (Figure 6a) follow the same rank order, as do those for rainfall (Figure 6b), albeit in the expected opposite order. However, of interest in the context of sub-regionalisation, the cluster analysis only identified three temperature and four rainfall zones (Figure 6a–b), with four zones being identified when temperature and rainfall were clustered together (Figure 6c). Unsurprisingly, the areas of greatest rainfall are those of greatest elevation (Figures 5a,e–f; 6c) centred on the High Eden sub-region (Figure 4); these are also the coolest parts of the Barossa zone (Figures 5b–d, 6a,c).

Possibly due to the complexity and short-range nature of soil variation in the region (Hall *et al.*, 2009; Robinson and Sandercock, 2014), only two soil zones were identified on the basis of variation in AWC and CEC, with the more clayey soils of the Barossa Valley floor having higher CEC and AWC compared to the more topographically variable Eden Valley (Figure 6d). This same two Valley separation was maintained when the two seasonal climate factors for which four zones were justified (Figure 6c) were clustered with the soil data (Figure 6e); that is, the cluster separation was seemingly dominated by the soil data. However, inclusion of MJT as an additional climate variable led to the identification of five clusters (Figure 6f), with some marked separation within the Barossa Valley identified in addition to the

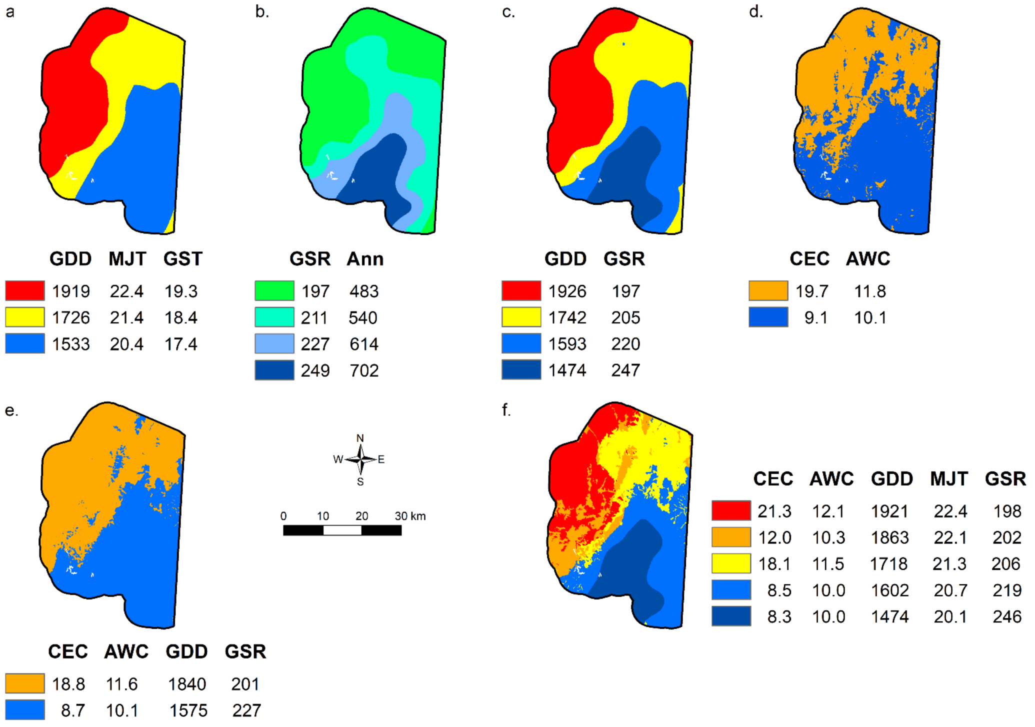

FIGURE 6. Results of clustering the data layers shown in Figure 5 using *k*-means.
For each combination of input data, the result shown here is that selected as optimal based on the CCC.

contrast between the Barossa and Eden Valleys. Overall, however, a sub-regionalisation of the Barossa zone based on the attributes included in this study appears equivocal, with the major delineation being the existing separation of the Barossa Valley, Eden Valley and High Eden regions, driven strongly by topographic variation (Figure 7). Of course, the extent to which this zonation is justified, or indeed a finer scale division such as implied by the identification of the Barossa Grounds, requires incorporation of wine sensory data and compositional information for both grapes and wines. Conversely, the analysis of biophysical variation reported here suggests that a finer delineation of regional terroir should perhaps be treated with caution.

DISCUSSION

Brillante *et al.* (2020) have recently called for the use of unbiased approaches in terroir research, highlighting for example, the merit of abandoning arbitrary climatic limits for the production of fine wines that express their place (van Leeuwen and Seguin, 2006) and instead seeking better understanding, on a location-specific and scale-appropriate basis, of the factors that impact on wine characteristics. Similarly, White (2019) has bemoaned the fact that whereas water, N supply and soil temperature may be claimed to be the major factors driving the soil component of terroir in unirrigated vineyards (van Leeuwen and de Rességuier, 2018), there remains a lack of quantitative understanding of relationships describing the effects of these factors on terroir. Experimentation may assist with this, but a prior and robust elucidation of the factors to be experimented with is needed for understanding of terroir to be advanced. Data-driven approaches offer an unbiased route towards that understanding. They also provide a more rigorous basis for using terroir as a platform for both viticultural manipulation and wine marketing than ‘imagining place and quality’ (Skinner, 2020).

Both case studies illustrated here are incomplete in as much as the data analysed were a subset of the total required to present robust descriptions of the terroir of either Marlborough or the

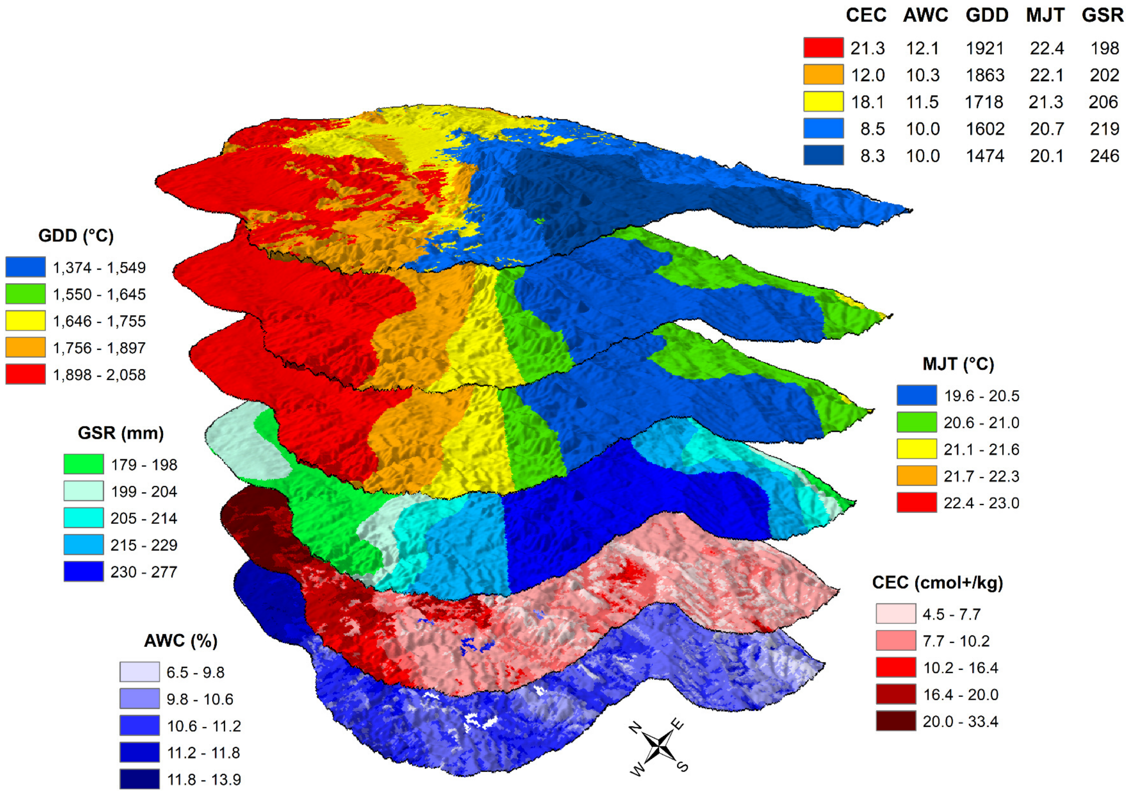

FIGURE 7. A preliminary sub-regionalisation of the Barossa zone based on biophysical variation. The top layer in this stack is the cluster solution shown in Figure 6f. It is overlain on the elevation model and the five map layers from which the clusters were identified using *k*-means. Note that the position of the north arrow is approximate only and that elevation has been exaggerated by a factor of six relative to the horizontal.

Barossa. In the Marlborough example, data acquired solely from vineyards were used to identify regional scale differences in respect of the yield and date of harvest of Sauvignon blanc. In contrast, the Barossa study did not use any vineyard data and instead made use of publicly available information to explore the possibility that inherent variation in range of biophysical factors might lead to identification of areas within the Barossa zone which, in turn, might be used to underpin further exploration of Barossa terroir. Yet both studies used the same methods of data analysis – methods that were data-driven and independent of either prior classification of the input data or any expert opinion, aside from in respect of the selection of the variables analysed. As such, the approach used was unbiased.

There are some obvious next steps for both studies, some of which are common to both, and some informed by what was done in one, but not the other. In Marlborough, in addition to enhancing the support of the analysis (at the time of writing we are finalising collation of data from around 250 further vineyard sites and also have vintage 2019 data to add to this expanded dataset), the opportunity exists to incorporate soil and landscape information, as used in the Barossa, along with climatic (Sturman *et al.*, 2017) and phenological (Parker *et al.*, 2014) modelling, analysis of Sauvignon blanc wines (e.g. Jouanneau *et al.*, 2012) and sensory analysis (Parr *et al.*, 2009). Indices of grape juice quality (Trought and Bramley, 2011; Pinu *et al.*, 2019) may also be useful. The present results also suggest that there may be merit in considering the Wairau and Awatere Valleys separately (Figures 2 and 3) in any repeat analysis, although whether this would either be of interest to the marketers of New Zealand Sauvignon blanc, or justified by chemical and sensory analysis, remains to be seen. Note that the current legal geographic indicators in NZ are regionally- rather than wine area-based. Similarly, the Barossa study will benefit from the incorporation of the sensory analysis of Danner *et al.* (2020), along with analysis of the chemistry of grapes and wines currently being undertaken (Paul Boss (CSIRO) and Keren Bindon (AWRI), personal communication). Importantly, and should the local industry be willing, the opportunity exists to incorporate vineyard-specific data such as were used in the Marlborough work. The latter highlights a further need for refinement. As will be obvious from Figures 5–7, the present analysis has focused on the entire Barossa Zone, or at least, a refinement of it. Yet Figure 4 indicates clearly that a significant proportion of the land area within this zone is not planted to grapevines. The question therefore remains as to whether the zonation identified in Figures 6 and 7 is maintained when confined solely to those parts of the Barossa supporting winegrowing, or indeed, to those vineyards in which Shiraz is grown. In turn, this leads to a further important question (Bramley, 2017) given that Shiraz is arguably a less dominant variety in the Barossa by comparison with Sauvignon blanc in Marlborough: is any sub-regionalisation that is justified on the basis of Shiraz wines and their interaction with biophysical factors, also similarly justified for Grenache, Cabernet-Sauvignon or Chardonnay? If it is, then the opportunity to advance understanding of terroir and its zoning could progress markedly. Conversely, if terroir is expressed quite differently by different varieties, then the problem becomes much more complex than it already appears. In both Marlborough and the Barossa, the effects of climate change will doubtless also need to be considered (Petrie and Sadras, 2008; Brillante *et al.*, 2020; Salinger *et al.*, 2020).

CONCLUSIONS

An approach used in the characterisation of within-vineyard variation and implementation of precision viticulture was successfully applied at regional scale to explore variation in the biophysical characteristics of Australia's Barossa, and of the yield and harvest date of Sauvignon blanc grown in New Zealand's Marlborough region. Because the approach is unbiased and data-driven, it offers potential as a tool for advancing understanding of wine terroir across a range of scales.

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