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Vintage by vine interactions most strongly influence Pinot noir grape composition in New Zealand

Damian Martin[1*], Franzi Grab[1], Claire Grose[1], Lily Stuart[1], Claire Scofield[2], Andrew McLachlan[3] and Tanya Rutan[4]

[1]The New Zealand Institute for Plant and Food Research Limited, Marlborough
[2]The New Zealand Institute for Plant and Food Research Limited, Clyde
[2]The New Zealand Institute for Plant and Food Research Limited, Palmerston North
[4]Bragato Research Institute, Marlborough

*corresponding author: damian.martin@plantandfood.co.nz

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ABSTRACT

Vine genetics, fruit maturity, region and vineyard are perceived as factors that strongly influence Pinot noir grape and wine composition. Our study aims to understand the relationship between grape (and ultimately wine) composition and the physical appearance and performance characteristics of a vine (i.e. vine ideotype). Our experimental approach controlled these variables by studying within-block differences in vine performance across multiple seasons and vineyards. Grapes were sourced at commercial harvest from 20 single vines from 12 vineyard sites in three Pinot noir growing regions (Central Otago, Martinborough and Marlborough) of New Zealand.

Across three vintages yields ranged from 0.1 kg to 6.3 kg per metre, but there was no general relationship between yield and berry soluble solids. On a vine by vine basis normalised yields did not correlate among seasons. Berry extract colour measures were, on average, three-fold higher in 2019 than in 2018.

Principal Component Analysis has indicated that vintage dominated berry composition effects that might otherwise be associated with yield per vine, region and vineyard. The extent of the variation in performance of the same vines between seasons largely excludes factors that are stable between seasons as primary causes. Changes in management of the same vine from year to year appeared the most likely contributors to variation. We have derived highly significant negative linear relationships between vine yield class and the frequency of vines that were within a benchmark specification established for icon vines, providing evidence of the quality risk associated with higher yield. The results also indicate that a proportion of vines meet the benchmark specification at higher yields. From results to date we can further our research confident in the knowledge that factors such as vine yield, region or vineyard are, in themselves, unlikely to be the principal drivers of major differences in Pinot noir grape and wine composition.

KEYWORDS

Pinot noir, grape, vine, yield, vigour, phenolics, vintage

Supplementary data can be downloaded through: https://oeno-one.eu/article/view/4021

INTRODUCTION

Most winegrowers would argue that high quality Pinot noir wines are predominantly a result of the composition of the grapes. Pinot noir grape composition is influenced by environmental factors (climate and pedoclimate), soil chemical and physical properties, biological factors (e.g. clone, rootstock and soil microflora) and viticultural management outcomes (e.g. yield, leaf area to fruit weight, canopy density, bunch exposure). Pinot noir vineyards targeted for the production of high quality wines are typically managed to relatively low yields compared with other varieties (Uzes and Skinkis, 2016). Pinot noir is also considered to be a difficult variety to produce, being environmentally sensitive (Jackson, 2008), with thin skins, high susceptibility to diseases, and lower anthocyanin concentrations often leading to reduced wine colour intensity (Dambergs *et al.,* 2012). Pinot noir grapes destined for ultra-premium wines are therefore generally more expensive to produce because of high vineyard management costs (Uzes and Skinkis, 2016). In New Zealand, mechanisation of vineyard tasks such as crop thinning, leaf removal, and harvesting is less prevalent in Pinot noir grape production, especially compared with Sauvignon blanc.

1. Environment

From a high-resolution topoclimate model, Ferretti (2020) was able to classify the different vineyard characters in South Tyrol, Italy, using a Solar Radiation Index (SRI). Zones with different SRI produced differences in Pinot noir wine anthocyanins and tannins. The topoclimate classification can inform questions of varietal adaptation, site selection and mitigation of climate change.

Blank *et al.* (2019) found that growing degree day sums between budburst and flowering were correlated to the total phenolic potential and primary amino nitrogen (N) content of the grape berries at harvest. While no explanation was given by the authors, it is plausible to associate elevated spring temperatures with faster N mineralisation in the soils and hence higher N uptake by the vine. Recently published work on the antagonism between the phenylpropanoid pathway and the amino content of the berries (Soubeyrand *et al.,* 2014; Soubeyrand *et al.,* 2018) may also provide an explanation as to why, or how, the berry phenolic potential might be influenced by environmental factors prior to flowering and fruitset. Fuentes *et al.* (2020) developed machine learning models using weather and soil moisture information from a Pinot noir vineyard for vintages 2008 to 2016 as input variables and wine aroma profiles as targets. Artificial neural network analyses were accurate in the prediction of aroma profiles and chemometric wine parameters.

2. Capacity, vigour and canopy density

The main driver of Pinot noir fruit composition is the vine canopy. A dense, unmanaged canopy may shade bunches, slowing polyphenol development and leading to poor colour (Cortell *et al.,* 2007a; Cortell and Kennedy, 2006). Air flow may also be impeded, placing the fruit at increased risk of bunch rots such as botrytis and powdery mildew (Smart and Robinson, 1991).

Vine planting density, bud load and training system are important factors in determining vine capacity, shoot vigour and canopy density. Planting density is a key determinant of vine capacity because it affects the amount of light and the volume of soil available to each vine. Archer & Strauss (1991) concluded that while closer vine spacing reduced cane mass and yield, the denser plantings led to less dense canopies with a higher leaf area to fruit weight ratio owing to reduced yield per vine. Although yield per ha was higher, closer spacings (1 x 1 m; 1 x 0.5 m) needed significantly higher inputs for canopy management, harvesting and pruning and as such, the suitability of a given planting density is also a function of the quality and price of the desired product. Vine capacity is also affected by soil properties. Bramley *et al.* (2011) found that soil conductivity was closely correlated to trunk circumference, an index of vine capacity. When studying spatial variations in vine capacity (described as vigour by the authors), Song *et al.* (2014) found that berry soluble solids were lower and berry mass and pH were higher in high-capacity zones of the same vineyard.

For a given vine capacity the bud load retained after winter pruning or an adjustment of shoot number post budburst will affect shoot vigour and yield potential. Trials in Switzerland showed the optimum bud load to be 14–18 shoots/vine (Basler, 1978), while Zamboni *et al.* (1997) determined that vines with a high number of nodes (50) developed a larger total leaf area but had the same total leaf area:fruit weight ratio as those having the lower node number (30). Greven *et al.* (2014) in a study of Sauvignon blanc in Marlborough found that mean cane mass and variation of cane mass on a vine varied with the

node number laid down at pruning. The authors also found a multi-season and dynamic yield and shoot vigour compensation response over time when node numbers altered. Anecdotal evidence in New Zealand suggests that Pinot noir behaves in a similar way. In Pinot noir grown in Tasmania, pruning to a higher bud number decreased the number of bunches per bud but no other yield component (Heazlewood *et al.,* 2006). Shoot thinning, especially pre-flowering, also alters canopy density and shoot vigour but may not greatly alter the leaf area:fruit weight ratio. Reynolds *et al.* (2005) found that the timing of shoot thinning did not have a consistent impact on Pinot noir must composition, and in fact shoot thinning had very little impact on Pinot noir wine composition at all.

Vine training systems through mediation of vine capacity and shoot vigour can alter the performance of Pinot noir. Choi & Kim (1998) found that Pinot noir cluster length and width were highest in the open lyre system.

3. Yield and leaf area to fruit weight

Most studies of grapevine yield as a factor in grape composition, including those undertaken on Pinot noir, have employed either differing pruning regimes or shoot and/or crop thinning to generate different yield treatments experimentally. Altering bud numbers at pruning and shoot thinning early in the season alters shoot vigour without necessarily altering the leaf area to fruit weight ratio of the vine (Hristov *et al.,* 1999; Koblet *et al.,* 1997; Zamboni *et al.,* 1997).

All other factors being equal (which they almost never are), higher yields are thought to accumulate soluble solids in the berry on a concentration basis more slowly than lower yields. Results are, however, often confounded by larger yields originating from higher bunch weights and/or higher berry weights. The latter are thought to be a factor in a decreased rate of soluble solids (i.e. °Brix) and increase largely because a higher soluble solids import per berry is required in a larger berry to achieve the same concentration as in a smaller berry (Song *et al.,* 2014).

Lower leaf area to fruit weight ratios (LA:FW) delay ripening (Parker *et al.,* 2014; Petrie *et al.,* 2000) and can lead to poorer quality fruit (Cortell *et al.,* 2007a; Cortell *et al.,* 2007b). The cumulative effect of this in cool or more humid climates is a greater risk of the crop not achieving a minimum oenological maturity (Agnew *et al.,* 2018).

Crop thinning when carried out at a 40 % intensity soon after fruitset did not significantly reduce yield, whereas later-season interventions were much more effective in reducing the crop (Karoglan *et al.,* 2011). In a study in Oregon the benefits of moderate crop thinning on Pinot noir grape composition were not clearly demonstrated (Reeve *et al.,* 2018), whereas in Central Europe, Karoglan *et al.,* (2011) found an improvement in must composition with pre-véraison thinning at 40 % intensity. In a three-year study on crop thinning, Mawdsley *et al.* (2019) could not find any consistent or predictable effects of thinning treatments on Pinot noir grape and wine composition despite an average yield reduction of 43 % by thinning. Seasonal factors influenced grape and wine composition more than thinning. The authors concluded that the initial vine yields and crop loads in the study were not sufficiently high to demonstrate a benefit from thinning.

Many New Zealand ultra-premium Pinot noir producers currently adopt a sequential approach to thinning whereby vines are thinned pre-véraison to one bunch per "effective" shoot. This is then followed by a manual "green thin", sometimes in multiple passes from mid to post-véraison, with a view to reducing the within-crop variation in maturity by removal of the least visually ripe (green or pink bunches) fraction of the crop. To our knowledge the combined effects of this combination of thinning techniques on Pinot noir grape composition have not been the subject of published research.

4. Fruit exposure

Lateral shoot removal, and fruit zone leaf removal are key management strategies to manage cluster exposure to incident sunlight. These tasks are often done manually in vineyards for the production of ultra-premium Pinot noir wine, at significant effort and cost. Pinot noir grape composition is altered by cluster exposure to sunlight, but effects are variable depending on the extent, frequency and timing of the intervention and the seasonal conditions.

In several studies, leaf removal treatments did not significantly affect standard grape composition (Feng *et al.,* 2017; Feng *et al.,* 2015;

Kemp *et al.,* 2011; Lee and Skinkis, 2013), while in another, berry soluble solids content and pH were found to increase (Song *et al.,* 2015).

Pre-flowering leaf removal from the fruiting zone altered fruitset, bunch morphology and fruit composition in Pinot noir (Acimovic *et al.,* 2016). Early leaf removal from the fruiting zone up to 7 days after flowering generated the highest concentrations of total anthocyanins, colour density and flavan-3-ols (Kemp *et al.,* 2011; Lee and Skinkis, 2013; Lemut *et al.,* 2013) in wines across different sites (Lee and Skinkis, 2013). Increases in anthocyanin composition were often evident for later (pre-véraison) treatments (Feng *et al.,* 2017; Feng *et al.,* 2015; Lee and Skinkis, 2013) but were typically of lower magnitude. Severity of leaf removal treatments was a factor. Treatments removing 100 % of leaves from the fruiting zone resulted in the highest concentrations of quercetin, malvidin- and petunidin-3-monoglucoside anthocyanins, compared with a 50 % removal treatment and a 0 % removal control (Feng *et al.,* 2015).

Wines produced from early leaf removal treatments contained higher concentrations of catechin, epicatechin gallate and gallocatechin than wines produced from control vines with no leaf removal treatments, or from vines with late leaf removal treatments (Kemp *et al.,* 2011). Control vines which had no leaf removal in the fruiting zone and late leaf removal vines produced wines with the lowest tannin content, but with relatively more seed tannin in wines (Kemp *et al.,* 2011). The mean degree of polymerisation between treatment timings was found to be non-significant (Kemp *et al.,* 2011). This would indicate that tannin polymerization is not dependent on cluster sunlight exposure, or on length of sunlight exposure.

Leaf removal resulted in an increase in volatile aromatic compounds, specifically terpenoids and C13-norisoprenoids (Feng *et al.,* 2017; Feng *et al.,* 2015; Song *et al.,* 2015; Song *et al.,* 2014). The effect of leaf removal on ß-damascenone, an important aroma for Pinot noir wine, was variously reported as both having a significant impact on concentrations (Feng *et al.,* 2017) and having no effect (Song *et al.,* 2015). Leaf removal was not found to affect the concentration of esters (Feng *et al.,* 2017).

Differences between vintages heavily influenced results from leaf removal treatments (Kemp *et al.,* 2011; Lee and Skinkis, 2013; Lemut *et al.,* 2013), primarily showing differences in catechin and epicatechin concentrations. This may have been due to different sugar content (°Brix) at harvest, influencing general berry ripeness, along with potential extractability of tannin through alcohol concentrations produced during fermentation.

To date, Pinot noir viticulture research has often focused on determining how specific vineyard practices or manipulations will influence fruit and wine quality. In practice however, manipulation of an element of vine management most often leads to an array of changes in the grapevine's physiology and performance. Rather than adopt a reductionist approach to understanding the individual effects of a suite of vineyard management techniques, our research attempts to identify and describe the appearance and performance of an ideal vine in the context of specific Pinot noir production goals (i.e. the vine ideotype). An integrated approach requires consideration of the vine as a whole, because a wide range of management and biological factors ultimately determine a wine's composition and its consequent quality attributes. Not the least of these is the decision, made by winemakers and viticulturists, about when to harvest the grapes. Other factors such as clone, region and vineyard are perceived by practitioners as factors that strongly influence Pinot noir wine composition. Our experimental approach controls these variables by studying within-block differences in vine performance across multiple seasons and vineyards, to understand how factors such as season and vine performance attributes (e.g. yield) affect wine composition.

METHODS

1. Region selection

The majority of New Zealand's Pinot noir vineyards (86 % by vineyard area) grow in the drier regions of the South Island (New Zealand Winegrowers, 2020), with the cool nights and mild days preserving the acidity and characteristic fruit flavours of the wine (Shaw, 2012). The regions selected for this study, Central Otago, Marlborough and Wairarapa, are well known for producing high quality Pinot noir, the last-mentioned being situated in the lower North Island with a similarly cool climate.

2. Vineyard block selection

A lengthy and detailed vineyard block selection process was undertaken. In discussion with the research programme's industry advisory group and numerous other experienced Pinot noir

producers, a long list of vineyard blocks thought to be suitable for study was compiled. Over the period from December 2017 to January 2018 the long list of blocks was progressively shortened following email and phone correspondence with the winegrowers. Site visits were conducted in February and March 2018 to finalise the selections. The objective was to select four mature (10- to 20-year-old) vineyard blocks in each of three regions (Central Otago, Marlborough and Wairarapa) planted with the same clone/rootstock combination and managed with comparable cane-pruned and Vertical Shoot Position (VSP) systems. Two-thirds of the selected vineyard blocks supplied commercially available high-value single-vineyard wines, while the remaining third were more commercially managed and supplied affordable blended regional varietal wines. A wide range of clone and rootstock combinations are planted across New Zealand Pinot noir vineyards. This study, however, is attempting to remove clone and rootstock as variables and is conducted on the Abel clone, which is reportedly derived from a cutting taken from Domaine de la Romanée-Conti in Burgundy (Hoskins and Thorpe, 2010) and grafted to 3309C rootstock. Aside from common usage, the clonal choice was driven largely because of the high productive potential of the Abel clone, allowing for the study of a wide range of yields per vine even in cool or poor fruitset seasons. The Abel clone is also rated highly by winemakers and features in many high priced single-vineyard wines. Summary details for the selected vineyard blocks can be found in Table 1 and additional descriptions of the vineyards can be can be found in the Supplementary Information (Figure S1, Tables S1–S3 and in section 26).

3. Within-block vine selection

Twenty vines that displayed widely differing capacity and yield within the same vineyard block were selected and marked in March 2018 in the lead-up to harvest. The individual vine selections in each of the 12 blocks were made in discussion with one or more experienced viticulturists. The attributes that were visually assessed during the selection process were: grapevine trunk diseases (absence of visible trunk cankers, absence of dieback at the head or cordon of the vine and absence of leaf symptoms of trunk disease); absence of obvious grapevine leafroll (GLRaV-3) virus leaf symptoms; vine capacity (trunk diameter); and vine age (i.e. not obviously a replant). The aim was to ensure the selected vines represented the widest range of visual vine "types" that exist within the single vineyard block. The vines were selected to be within close proximity to each other, no greater than 200 m between the two furthermost vines in a block and typically spaced between 5 and 10 m from one selected vine to its nearest selected neighbour. While the vine selection process partially integrated within-block variation in soil texture

TABLE 1. Summary details for the vineyard blocks selected for the New Zealand Pinot noir Ideotype Vine study.

Vineyard ID	Region	Sub region	Block area (ha)	Year planted	Row spacing (m)	Vine spacing (m)	Pruning system	Target yield (kg/m)	End-use class
OA	Otago	Bannockburn	0,3	2000	2,2	1,13	2-cane	1,3	Icon
OB	Otago	Bannockburn	0,13	2008	1,6	0,9	2-cane	1,1	Icon
OC	Otago	Bendigo	0,5	1996	1,5	0,9	2-cane	1,1	Icon
OD	Otago	Pisa Range	1,56	2008	2,4	1,5	10-spur	2,3	Affordable
MA	Marlborough	Brancott	0,08	1993	1,5	1,25	2-cane	1	Icon
MB	Marlborough	Brancott	0,72	2006	3	1,4	2-cane	2,5	Affordable
MC	Marlborough	Wairau	4,62	2013	1,6	1,25	2-cane	2	Affordable
MD	Marlborough	Waihopai	0,75	2005	1,8	1,15	2-cane	1,1	Icon
WA	Wairarapa	Martinborough	0,28	2003	2	1,2	2-cane	1	Icon
WB	Wairarapa	Martinborough	0,67	2009	2,4	1,4	2-cane	1,8	Affordable
WC	Wairarapa	Te Muna	0,3	1998	2,4	1,25	2-cane	1,6	Icon
WD	Wairarapa	Te Muna	0,95	1999	1,6	1,2	2-cane	1	Icon

All blocks are Pinot noir Abel clone grafted to 3309C rootstock and trellised to a Vertical Shoot Position canopy.

or topography, the selection was not specifically designed to proportionally quantify vine variation at the block scale, because block sizes varied from approximately 0.1 to 5 ha. The approximate area of the study zone within each block is provided in the Supplementary Information (Table S2). Random measurements of vine trunk diameter were made at 30 cm above ground level on 10 vines in each block to broadly establish mean, maximum and minimum values, and spot checks of trunk diameters were made to ensure that the selected vine set spanned a similarly wide range. Relative yield differences from vine to vine were assessed using non-destructive (but therefore approximate) bunch counts. A visual scale rating-system that classified bunches and berries as large, moderate and small was used to assess relative differences in bunch and berry size at a vine level. The subsequent harvest of the vines and sampling of the berries in the first year provided supporting data to validate the selection of the vines for the subsequent years of the study. The same 20 selected vines in each block were therefore studied in each subsequent season and constitute the "marked vines".

4. Phenology monitoring

Individual canes from four vines (from within the population of 20 marked vines) at each site were selected prior to budburst for phenological monitoring. The four vines in each block were selected using a random number function in Microsoft Excel® and the north-oriented cane (on 2-cane vines) was chosen by default. These same vines were monitored each year except in cases where a suitable cane was not laid down, in which case the north-oriented cane on the nearest marked vine was used. Budburst, flowering and véraison progression were assessed visually every 5–7 days during the relevant periods. Budburst was assessed on each bud on the monitored cane while flowering and véraison were assessed on each inflorescence or cluster on all the shoots arising from the monitored cane. A 9-point BCCH scale (Lorenz *et al.,* 1995) was used for budburst, while a percentage score estimated in 5 % increments was used for flowering and véraison. Dates for 50 % budburst, flowering and véraison were estimated using linear interpolation between the closest observations either side of 50 % (usual case) or extrapolated back from the two closest observations above 50 % (punctual case). As the research programme did not commence until February 2018, phenological observations for the network of blocks were not obtained for budburst, flowering or véraison in 2017/18 but were estimated from data collected in nearby vineyards in other phenological monitoring programmes. These estimated dates were then adjusted by one to three days to take into account patterns in site-related differences in phenology subsequently observed in 2018/19 and 2019/20.

5. Harvest methods

Within 2 days of the date of commercial harvest the marked vines in each block were hand harvested and yield components (vine yield, bunch number and mean bunch weight) were determined. Commercial harvest dates were determined by the individual producers using industry standard but partly subjective techniques. For each three vintages (2018, 2019 and 2020), data were collected from 11 of the 12 sites and a total of 220 vines per year. Each year one site of 12 was not able to be harvested, but it was not always the same site. Fruit from the 20 marked vines were packed into individual clean cardboard cartons for each vine and freighted to the New Zealand Institute for Plant and Food Research Limited, Marlborough, on chilled overnight transport. In the laboratory all bunches from a single vine were individually weighed. When the yield per vine was above 2 kg, 15 bunches were randomly subsampled from the box to provide sufficient fruit for berry sampling. Bunches were subsampled with snips to produce individual berries with the pedicel intact. The snipped berries were uniformly distributed across three sample containers such that the 15 bunches produced 1 x 50-berry fresh sample for basic maturity analysis 2 x 100-berry samples. One of the 100-berry samples was stored at -20 °C for whole berry colour and phenolic measurements, and one sample was stored at -80 °C, originally intended for more in-depth metabolite analysis. Because of the low berry weights these two subsamples were ultimately pooled to provide sufficient sample mass for berry phenolic measurements.

6. Vine photography

Vines were photographed after leaf fall but prior to winter pruning with a Nikon DS70 DSLR Camera using a 10–24 mm focal length wide angle Tamron lens to capture the full width of the vine in a single photograph. The photographs were taken perpendicular to the row at approximately 1.5 m distance from the vine. A background screen comprised of a large stretchable fabric sheet tensioned between two aluminium poles was held behind the vine. A small whiteboard of known dimensions (250 x 250 mm) was hung on a trellis

wire to both label and scale the images. In future the vine photographs will undergo image analysis but the current work was confined to visual counts of shoot number per vine undertaken on a desktop computer. An example of the vine photography is included in Supplementary Information (Figure S3).

7. Weather and climate data

Long-term and comparative seasonal meteorological information was sourced from weather stations operated by the National Institute for Water and Atmosphere (NIWA) in Martinborough (AN 21938, 41.252S, 175.390 E), Blenheim (AN 12430, 41.497S, 173.963E) and Cromwell (AN 26381, -45.035S, 169.195E). These stations are centrally located within the Wairarapa, Marlborough and Otago viticultural regions, respectively. The meteorological stations used complied with World Meteorological Organisation specifications (Zhu *et al.,* 2020).

Local weather information for each vineyard was sourced from the nearest Plant & Food Research-(PFR) or NIWA-managed station which was typically at a similar elevation and within 2 km of each study site. In cases where validated local weather station data were not available, data were sourced from the NIWA Virtual Climate Station Network (VCSN) http://data.niwa.co.nz/. The VCSN is a network of over 11,000 data points covering a grid of the entire New Zealand area (including some offshore areas). Climate data are not actually measured at these points; they are calculated by NIWA's supercomputer by interpolating measurements made at actual monitoring stations located in the surrounding area. Daily interpolated values of maximum and minimum air temperatures along with total rainfall were obtained.

Seasonal and regional variations in weather were compared using climate metrics expressed as accumulated deviations from Long Term Average (LTA) data (Agnew *et al.,* 2018). For regional and seasonal comparisons, daily Growing Degree Days above 10 °C (GDD) were calculated for the growing season period from 1 September to 30 April in 2017/18, 2018/19 and 2019/20. Seasonal Water Balance (SWB) on any given day was calculated as the difference between average daily ET° and average daily rainfall observed over the preceding 90-day period. The accumulated daily SWB was then subtracted from the LTA accumulated SWB to give the SWB deviation. Accumulated Diurnal Variation (DV) was calculated as the sum of the difference between daily maximum and daily minimum temperatures from 1 September to 30 April each season. The accumulated daily DV was then subtracted from the LTA accumulated DV to give the DV deviation. For site-based comparisons the accumulated growing degrees were calculated for the phenological period from budburst to harvest observed at each site.

8. Berry analyses

The 50-berry fresh samples were weighed and recounted to calculate mean berry weight. Berries were crushed by hand while in the plastic sample bag and the crushed fruit pressed using manual pressure through a small kitchen sieve with approximately a 1-mm mesh. Juice was centrifuged in a 50-mL tube for 10 minutes at 4600 rpm using a Heraeus® Multifuge 3SR+ and analysed for total soluble solids (TSS), pH and titratable acidity (TA). If sample volume was greater than 30 mL, a sample was run through the Foss® Winescan FT2. TSS was determined on a hand-held Atago refractometer, while pH and TA were determined on a Mettler Toledo T70 autotitrator. Acid concentration was determined using an end-point titration to pH 8.2. Aqueous sodium hydroxide (0.1 M) was used as titrant and TA was expressed as g/L of tartaric acid equivalents (Iland *et al.,* 2000, Iland *et al.*, 2004). Grape samples were analysed for tannin, colour and phenolics using a modified method originally developed by the Australian Wine Research Institute for their WineCloud™ service:

- https://www.awri.com.au/commercial_services/analytical_services/the-winecloud/
- https://www.awri.com.au/wp-content/uploads/2013/08/sample-prep-guide-grape-portal.pdf
- https://www.awri.com.au/wp-content/uploads/2014/01/measuring-grape-tannins.pdf.

Because of the small berry sizes often encountered, the 2 x 100-berry representative samples (stored at -20 °C and at -80 °C respectively) taken at harvest from each vine were pooled to make up approximately 200 g of berries. At the time of analysis, which was within 3–6 months of harvest each year, 70 % of the grapes in each pooled sample were allowed to fully thaw at room temperature for approximately 1 hour, while the remaining 30 % was kept frozen until homogenisation. The thawed and frozen samples were combined and

homogenised for 2 x 1 minute cycles to ensure all seeds were thoroughly disintegrated using a 1200 Series Nutribullet®. The homogenate was stirred and 1 g was weighed into a 50-mL centrifuge tube, in duplicate, where 10 mL of acidified 50 % v/v ethanol/Milli-Q water solution was added. The samples were allowed to extract for one hour with constant mixing via a Chiltern® rotating wheel. The homogenate was centrifuged Heraeus® Multifuge 3SR+ at 4600 rpm for 5 minutes. Once clarified, 1 mL or the supernatant was placed in a new 50-mL tube and diluted with 10 mL of 1.0M HCl to make a total volume of 11 mL. Samples were incubated for one hour in a dark room. Absorbance readings expressed in Absorbance Units (AU) were taken of each duplicated sample at 280 (OD_{280}), 320 (OD_{320}) and 520 nm (OD_{520}) with a 10-mm quartz cuvette using a Thermospectronic® Genesys 10 spectrophotometer.

9. Statistical analysis

Relative Standard Deviations (RSD) were calculated as the Standard Deviation/Sample Mean. Data were analysed using one-way ANOVA and using Principal Components Analysis (PCA) on a correlation matrix of the data. PCA analyses were performed using Genstat 20th edition (VSN International, Hemel Hempstead, UK) while ANOVA was performed using the 17th edition of the same software. Comparisons amongst vineyard means were made using Fisher's Protected Least Significant Differences at $\alpha = 0.05$ (5 % LSD). Regression analysis was undertaken using linear regression functions in Microsoft® Excel 2013 or in Genstat 17 if a p-value was required to assess regression significance.

RESULTS

1. Seasonal weather conditions

A summary of the seasonal weather conditions in each region and season is presented in the Supplementary Information (Table S4 and Figure S2). All three study regions experienced varied weather conditions from season to season.

Otago, which is furthest south, on average experiences a cool, continental and dry climate (Supplementary Information Table S4) but this was not especially in evidence during the three seasons of study. 2017/18 was exceptionally warm, with accumulated GDD 40 % above LTA when véraison started in late January. Temperatures during the

TABLE 2. Harvest dates, accumulated growing degree days (base 10 °C) for the period from budburst to harvest and mean yield for the New Zealand Pinot noir Ideotype Vine study network for vintages 2018, 2019 and 2020.

Vineyard code	Harvest date			Growing Degree Days (10 °C)			Mean yield (kg/m)			
	2018	2019	2020	2018	2019	2020	2018	2019	2020	Average
OA	04-03-18	02-04-19	31-03-20	1	1	896	1,62 (0,38)	1,04 (0,34)	1,44 (0,32)	1,37
OB	14-03-18	08-04-19	16-04-20	1	1	943	1,49 (0,27)	1,04 (0,44)	1,26 (0,52)	1,26
OC	08-03-18	18-03-19	31-03-20	1	998	928	1,88 (0,36)	0,69 (0,49)	0,72 (0,38)	1,10
OD	17-03-18	08-04-19	09-04-20	1	1	933	2,54 (0,35)	2,59 (0,46)	2,37 (0,23)	2,50
MA	16-03-18	12-03-19	23-03-20	1	1	1	1,38 (0,34)	1,40 (0,26)	3,59 (0,38)	2,12
MB	29-03-18	12-03-19	22-03-20	1	1	1	3,28 (0,42)	1,72 (0,45)	1,97 (0,32)	2,32
MC	25-03-18	22-03-19	27-03-20	1	1	1	2,06 (0,40)	1,99 (0,33)	2,84 (0,34)	2,29
MD	31-03-18	15-03-19	27-03-20	1	1	1	1,33 (0,44)	1,05 (0,46)	1,58 (0,56)	1,32
WA	16-03-18	19-03-19	16-03-20	1	1	1	1,40 (0,28)	0,84 (0,55)	1,31 (0,39)	1,18
WB	16-03-18	19-03-19	21-03-20	1	1	1	2,09 (0,28)	1,40 (0,48)	3,65 (0,35)	2,38
WC	26-03-18	n/a	n/a	1	n/a	n/a	1,95 (0,36)	n/a	n/a	n/a
WD	n/a	10-04-19	03-04-20	n/a	1	1	n/a	0,83 (0,47)	1,63 (0,32)	n/a

Numbers in parentheses represent the Relative Standard Deviations. Abbreviation: n/a = not available.
Vineyard details are described in Table 1.

ripening period were close to LTA, albeit that the vine phenology was four weeks ahead of a typical season and therefore experienced atypical ripening conditions. The 2017/18 season in Otago represents a telling insight into the future effects of climate warming. SWB was increasingly below LTA from budburst to véraison, but high rainfall during the ripening period reversed that trend. The evolution of DV mirrored that of GDD. In 2018/19 GDD was close to LTA all through the season while SWB was unusually high in the period budburst to véraison. Conditions became drier from véraison onwards and this was associated with an increase in DV. The 2019/20 season was much cooler, with GDD falling well below LTA by harvest, which occurred in mid to late April as opposed to early March in 2017/18. SWB was close to LTA for most of the season, although December and February were wetter than normal. DV was below LTA in December.

In Marlborough 2017/18 was marked by above-average GDD all through the season coupled with high rainfall in the spring and autumn. The mid-season was characterised by a long dry period between flowering and véraison. DV was below LTA during the ripening period. In 2018/19 GDD was again above LTA but rainfall patterns were somewhat reversed, with dry periods in the spring and autumn and a wetter mid-season. DV was close to LTA all through the season. GDD in the 2019/20 season was closer to LTA but the season was very dry from fruitset to harvest.

Wairarapa broadly experienced similar rainfall and temperature patterns within each season to those of Marlborough, although above-average rainfall in the period from November to February in 2018/19 resulted in a positive deviation of SWB.

2. Harvest data

Harvest in all three seasons was undertaken within one or two days of the commercial harvest of the study block in all but one of the sites each year. Harvest dates, phenology based accumulated growing degree days (GDD) and mean yield data for each study vineyard are presented in Table 2. Yield data shown in Table 2 are expressed as kg of grapes per linear metre of vineyard row (kg/m). Within a season the differences between the highest and lowest phenology-based GDD between vineyards within a region were typically

TABLE 3. Mean bunch number and mean bunch mass per vine for the New Zealand Pinot noir Ideotype Vine study network for vintages 2018, 2019 and 2020.

Region	Vineyard	Mean bunch number per metre			Mean bunch mass per metre (g)		
		2018	2019	2020	2018	2019	2020
O	OA	9 (3,4)	10 (3,6)	14 (3,2)	186 (25)	102 (23)	104 (23)
O	OB	10 (2,2)	10 (3,0)	19 (4,7)	153 (21)	102 (23)	68 (21)
O	OC	9 (2,3)	9 (2,8)	7 (1,9)	199 (47)	81 (33)	97 (23)
O	OD	17 (4,6)	18 (6,8)	25 (4,5)	150 (26)	141 (38)	95 (9)
M	MA	10 (2,5)	15 (3,1)	22 (4,9)	142 (24)	91 (17)	165 (42)
M	MB	23 (7,1)	22 (6,2)	15 (3,4)	141 (34)	79 (21)	135 (32)
M	MC	16 (5,4)	31 (6,0)	22 (5,2)	129 (31)	63 (19)	128 (34)
M	MD	18 (5,5)	24 (6,4)	18 (7,4)	74 (18)	43 (16)	86 (31)
W	WA	14 (3,4)	13 (5,0)	17 (4,3)	103 (16)	65 (19)	77 (20)
W	WB	14 (2,8)	16 (3,9)	20 (4,0)	153 (36)	87 (33)	183 (50)
W	WC	12 (2,9)	n/a	n/a	164 (24)	n/a	n/a
W	WD	n/a	13 (4,6)	12 (2,9)	n/a	64 (18)	135 (24)

Numbers in parentheses represent the Standard Deviations. Abbreviation: n/a = not available.
Vineyard details are described in Table 1.

small, while the GDD range was generally greater between regions within a season, and greatest between seasons.

The lowest 20-vine mean yield was at vineyard OC (vineyards are described in Table 1) in 2019 (0.69 kg/m) and the highest was at vineyard WB in 2020 (3.65 kg/m). The study population minimum yield across 660 vine x season observations was 0.10 kg/m at vineyard WA in 2019 while the population maximum yield was essentially 63-fold greater (6.32 kg/m) at vineyard WB in 2020 (individual vine yield data not shown). At a single-vine level, the yield range within the study population in each season (N = 220) was 20-fold in 2018, 70-fold in 2019 and 60-fold in 2020. Within each of the vineyard study blocks the variation in yield in all three seasons was very high, with RSD > 0.23 at all sites in all years (Table 2). In a third of the vineyard x season combinations the vine to vine yield RSD within a block exceeded 0.40. The wide within-block variation allows us to study interactions between vine performance and grape composition parameters under uniform vineyard management and environmental conditions. Nevertheless the 3-year average yields per metre (Table 2) for each block were typically close to long-term winegrower yield targets (Table 1), indicating that the vine selection process also afforded a degree of representation of the wider vineyard block even though this was not the primary objective. There were two notable exceptions to the relationship between measured 20-vine yield and target block yield: vineyard MA and vineyard MB had higher 3-season average yield than the target, driven largely by higher yields in 2020. It is worth noting that both these vineyards underwent changes to key winegrowing personnel prior to the start of the 2020 season.

Mean cluster number and mean bunch mass per metre are shown in Table 3. Bunch number per metre was consistently lowest at vineyard OC and was a reflection of an intensive canopy and yield management strategy aimed at achieving 8–9 shoots per metre and one bunch per shoot. Within a season the highest bunch numbers per metre varied between vineyards MB (2018), MC (2019) and OD (2020) and were the product of low intensity yield management strategies. Bunches in Otago were typically heavier than in either Marlborough or Wairarapa in 2018 and 2019 but not in 2020. Vineyard MD consistently produced amongst the smallest bunches in all three seasons of study.

3. Shoot number

In 2018 and 2019 yield per vine was, unsurprisingly, highly correlated to vine bunch number per vine and in turn bunch number was highly correlated to shoot number (Figure 1). These results are consistent with those obtained in other New Zealand studies of manually pruned vineyards (Greven *et al.,* 2014). Yield per vine was also highly correlated with bunch number per vine in 2020 (data not shown), but COVID-19 lockdown restrictions in the lead-up to winter

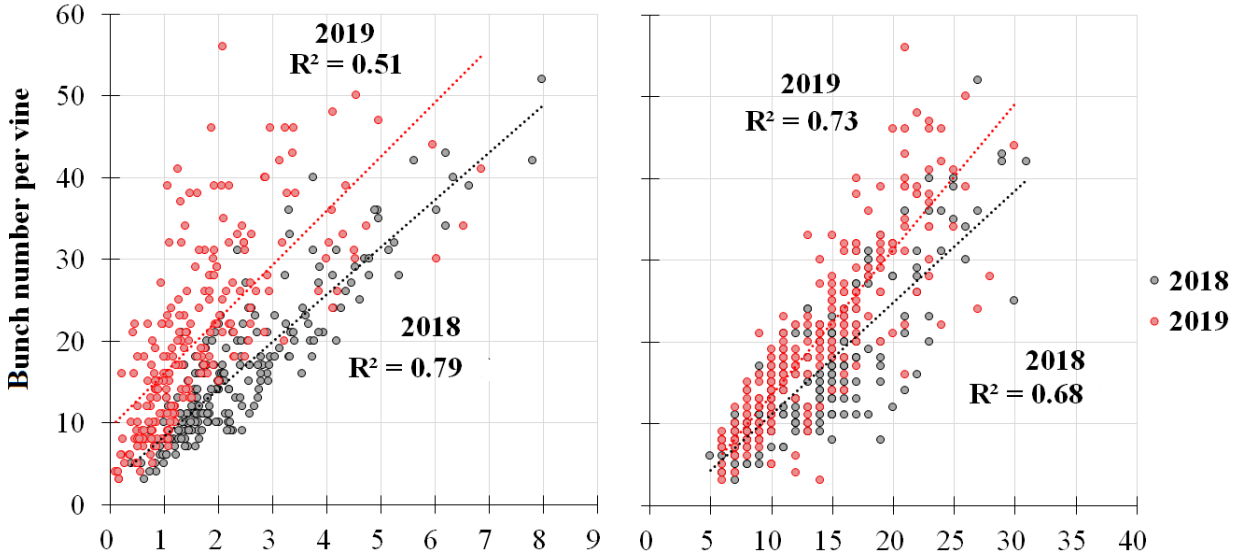


FIGURE 1. Relationships between yield per vine and bunch number per vine (left) and shoot number per vine and bunch number per vine (right) for the New Zealand Pinot noir Ideotype Vine study network in vintages 2018 and 2019.

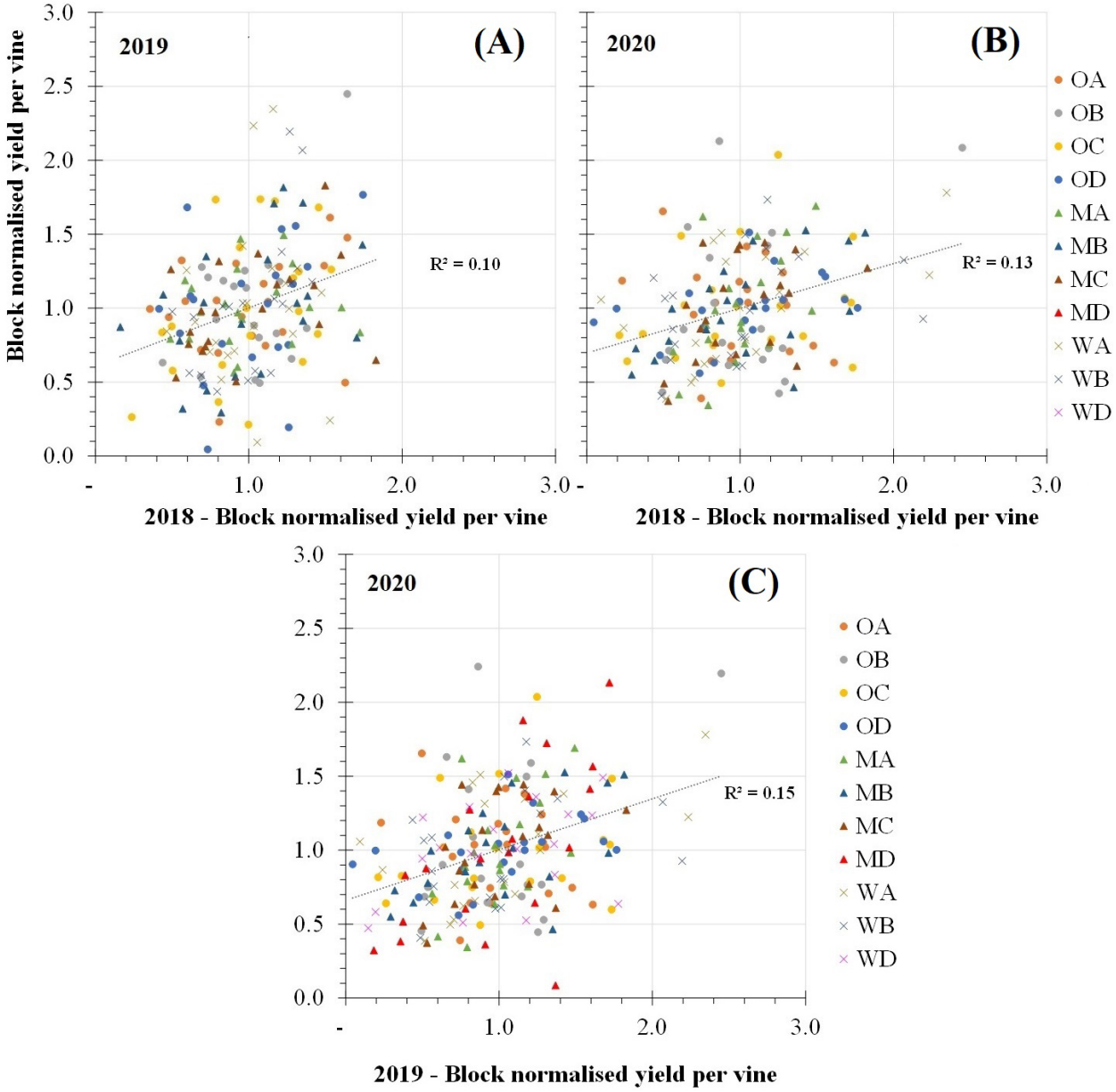


FIGURE 2. Between-season comparisons of relative yield from the same vine for the New Zealand Pinot noir Ideotype Vine study network (N = 220 vines).
In each of three vintages yield data per vine have been normalised against the block mean yield for that same year. Normalised yield for an individual vine in 2018 is compared with its normalised yield in 2019 (A), 2019 with 2020 (B) and 2018 with 2020 (C). Vineyard details are described in Table 1.

pruning prevented acquisition of shoot count data. Nevertheless it is probable that bunch number per vine was correlated to shoot number per vine.

4. Variation in yield parameters between seasons

Given the high vine to vine variation in yield within a vineyard (Table 2), a question becomes "do the same vines consistently produce above- or below-average yields each year?" To facilitate comparison of yield from a single vine between seasons, yields for each vine within a block were normalised against the block mean yield for that year. The normalised yields for each year pairing are compared in Figure 2. The relationship between relative yield in one season and relative yield for that same vine in another season was weak.

5. Grape compositional data

Berry size and composition data at harvest from 10 of 12 vineyards in 2018 and 11 of 12 vineyards in 2019 vintages are presented for information

in Table 4. For the 2020 vintage these same data were obtained from only six out of 12 vineyards and are not presented. While numerous significant differences in berry mass, TSS, TA and pH were found, there were few vineyards that were either significantly above or below the overall mean for these same parameters in both seasons. We do not discuss between vineyard differences in berry parameters in detail because our interpretation of the data is focused on deriving generalized relationships between berry parameters and vine yield.

6. Yield and berry composition interactions

Across the entire sample set, which consisted of 20 marked vines at each of 11 vineyard sites in three regions over three seasons (N = 540), there was no meaningful relationship between vine yield (expressed in kg per vine) and berry TSS when individual vine data were plotted (Figure 3). Likewise no relationship was evident whether yield was expressed as fruit mass per linear metre of row or as fruit mass per unit area of land.

When regression analysis was performed between vine yield (kg/m) and mean berry TSS on a vine by vine basis within a vineyard block, a significant negative relationship was found for only three of 27 available site x season combinations (Figure 4) despite the very high variation in yield observed between vines within a block (Table 2). In two of three cases of statistical significance, the regressions were highly leveraged by one or two outlier points (highlighted in red), but for the majority of the observations (Supplementary Information Figures S4–S6) there was no clear negative relationship between yield and berry TSS within a vineyard, which was consistent with the lack of interaction at the population scale (Figure 3).

7. Berry phenolic potential

In all three vintages berry samples were analysed for their oenological phenolic potential. The vineyard mean optical densities (OD) of the berry extracts measured at the three wavelengths (280, 320 and 520 nm) were highly correlated with

TABLE 4. Berry compositional data for the New Zealand Pinot noir Ideotype Vine study network in 2018 and 2019.

Vineyard	Berry mass (g)				Berry TSS (°Brix)				Berry TA (g/L H_2T)				Berry pH			
	2018		2019		2018		2019		2018		2019		2018		2019	
OA	1,3	b	0,9	b	22,2	de	22,7	d	6,8	ab	7,7	bc	3,38	ef	3,27	d
OB	1,1	a	0,9	b	23,9	g	23,8	e	6,9	b	6,9	a	3,38	f	3,38	e
OC	1,3	b	0,9	b	23	f	21,6	b	7	b	8,4	de	3,46	g	3,24	bcd
OD	1,4	c	1,4	d	24,3	g	22,4	cd	8,7	d	10,3	f	3,27	bc	3,24	bcd
MA	1,3	b	0,9	b	22,1	de	22,1	bc	8	c	7,8	bcd	3,23	ab	3,19	ab
MB	1,5	c	1,1	c	20,4	a	20,9	a	9	d	8,3	cde	3,21	a	3,2	abc
MC	1,5	c	0,9	b	20,6	a	21,9	bc	8,6	d	8,6	e	3,19	a	3,16	a
MD	n/a		0,7	a	n/a		21	a	n/a		7,6	b	n/a		3,4	e
WA	1,1	a	0,9	b	22,4	ef	22,8	d	6,7	ab	8,5	e	3,31	cd	3,25	cd
WB	1,6	c	1	c	21,4	bc	23,6	e	7,1	b	8,8	e	3,33	de	3,26	d
WC	1,5	c	n/a		21	ab	n/a		7,9	c	n/a		3,22	ab	n/a	
WD	n/a		0,9	b	n/a		23,7	e	n/a		8,5	e	n/a		3,27	d
Mean	1,34		0,96		22,09		22,4		7,56		8,3		3,31		3,26	
LSD	0,11		0,62		0,62		0,53		0,44		0,61		0,05		0,06	
P value	< 0.001		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001	

Values followed by the same letter down a column are not significantly different (α = 0.05). Abbreviations: TSS = Total soluble solids; TA = Titratable Acidity; H_2T = Tartaric acid; n/a = not available; LSD = Least significant difference (α = 0.05).
Vineyard details are described in Table 1.

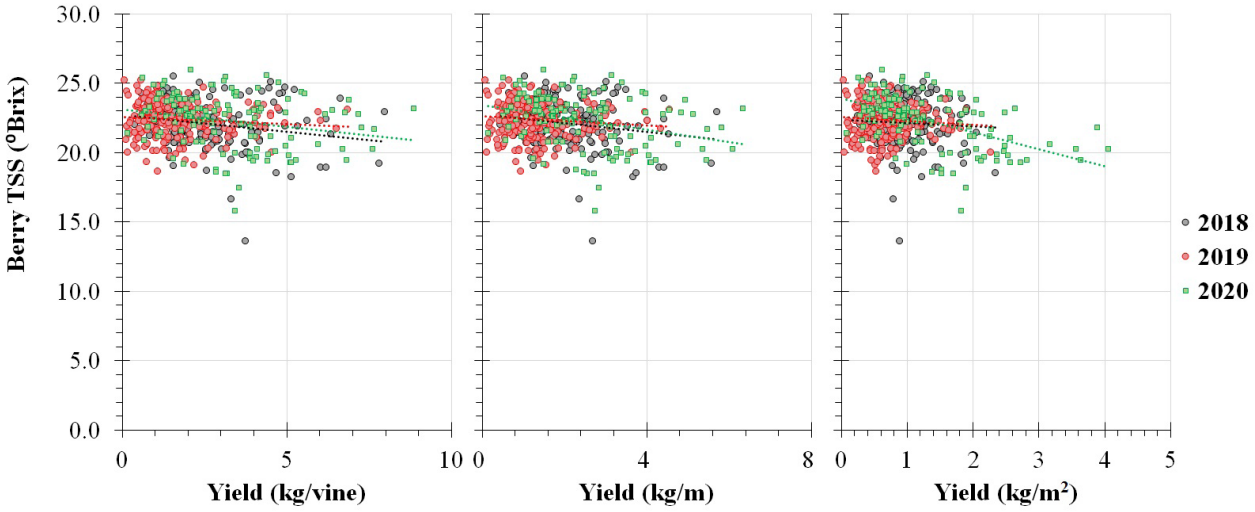


FIGURE 3. Relationship between yield per vine (left), yield per metre of vine row (centre) and yield per m^2 of land area (right) and mean berry total soluble solids (TSS) of the New Zealand Pinot noir Ideotype Vine study network in 2018, 2019 and 2020.

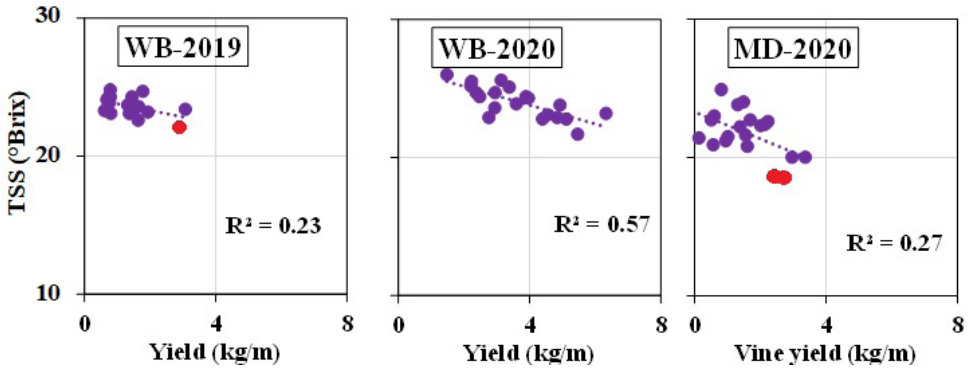


FIGURE 4. Statistically significant ($P < 0.05$) negative relationships between yield (kg/m) and berry Total Soluble Solids (TSS) of the New Zealand Pinot noir Ideotype Vine study network in 2018, 2019 and 2020 (i.e. three vineyard x season combinations only).

The full set of vineyard x season graphs (N = 27) can be found in the Supplementary Information (Figures S4–S6).

each other (data not presented). Optical densities, in particular the OD_{520} of the berry extracts, were correlated with vineyard mean berry mass (Figure 5). Berry phenolic potential was also negatively correlated with vine yield although this was, in part, because vine yield was affected by berry mass. We therefore calculated berry number per metre (bunch number per metre x berry number per bunch) in an effort to represent yield without a berry size factor. Correlation coefficients (all regressions $P. < 0.001$) for the relationship between berry OD_{520} and berry number per metre were consistently lower than for the corresponding berry mass relationships, suggesting that berry mass was more strongly related to colour potential than berry number per metre (i.e. the adjusted yield).

8. Principal Component Analysis

The available single-vine vine and grape parameter data were consolidated for the 2018, 2019 and 2020 harvests. Principal Component Analysis (PCA) was undertaken using yield per vine (kg) categories as a clustering variate as shown in Figure 6. Two Principal Components (PCs) represent 67.4 % of the variation in the dataset, with 43.6 % and 23.8 % explained by PC1 and PC2, respectively. The left biplot of Figure 6 shows the PC scores of vine and berry parameters categorised by yield. The centre biplot shows the vector loadings of the measured physiological and chemical parameters and the right biplot shows the PC scores of vine and berry parameters categorised by year.

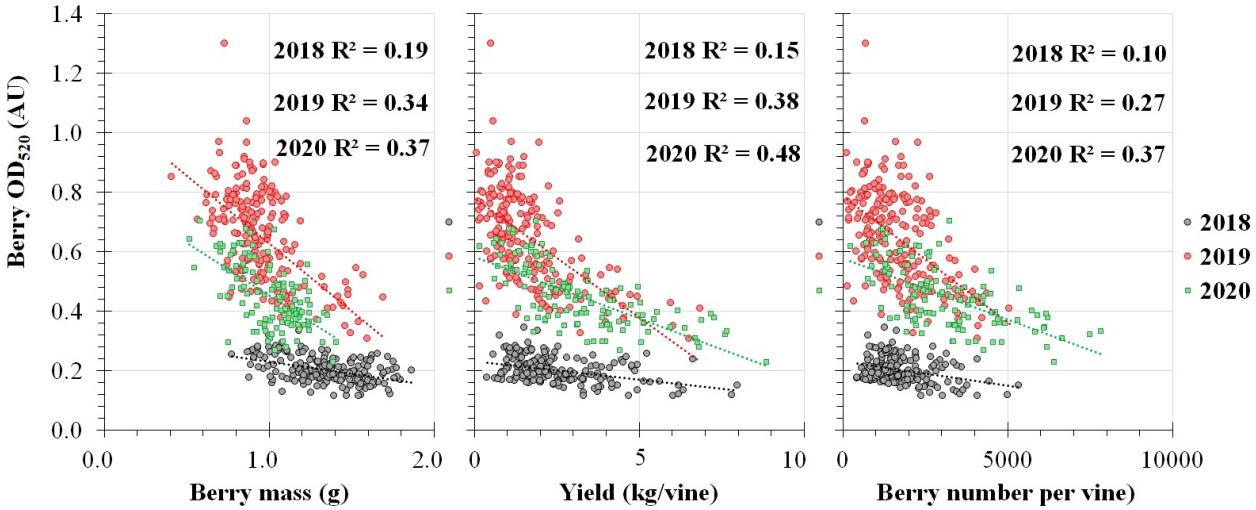


FIGURE 5. Relationship of berry mass (left), yield (centre) and berry number per vine (right) with berry colour potential as represented by the OD_{520} of the homogenate extracts of the New Zealand Pinot noir Ideotype Vine study network in 2018, 2019 and 2020.
All regressions are statistically highly significant (F Pr. < 0.001).

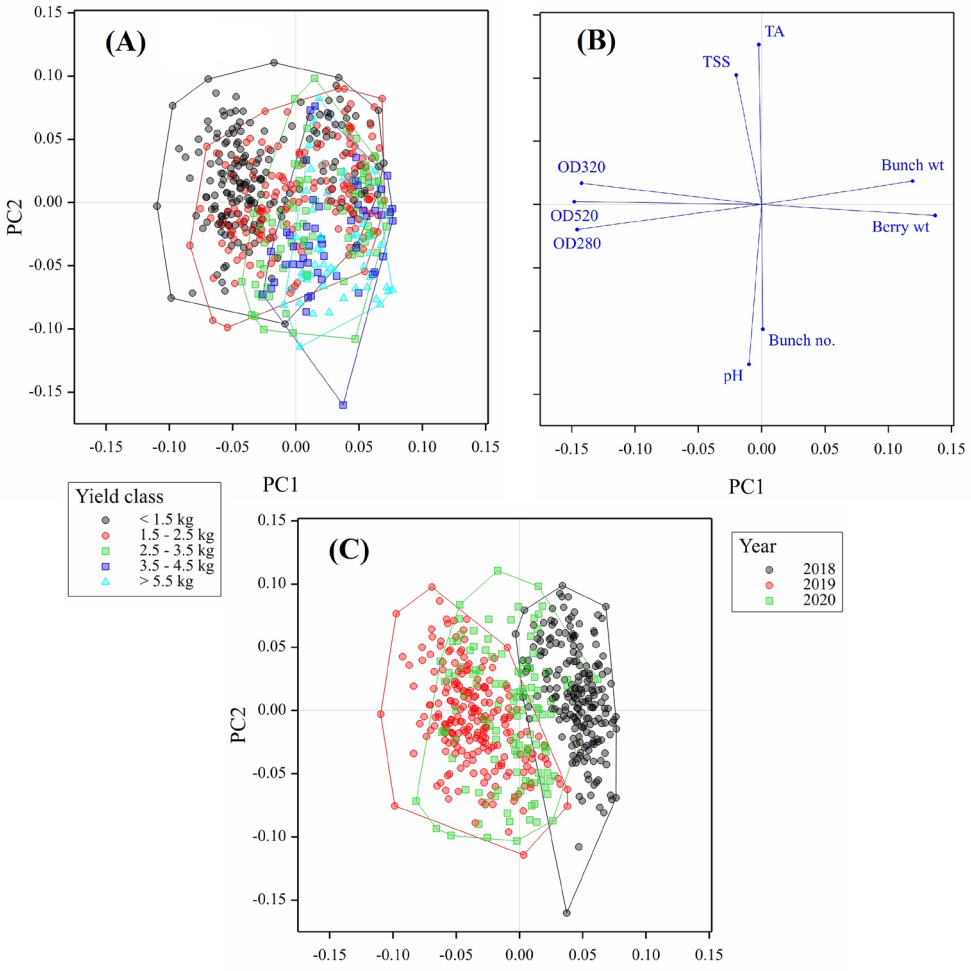


FIGURE 6. Principal Component Analysis (PCA) of vine and berry parameters of the New Zealand Pinot noir Ideotype Vine study network in 2018, 2019 and 2020.
Biplot (A) shows the scores of vine and berry parameters categorised by yield. Biplot (B) shows the vector loadings of the measured physiological and chemical parameters and biplot (C) shows the scores of vine and berry parameters categorised by year.

TABLE 5. Statistics and target specification ranges for grape berry size and basic berry composition parameters of the New Zealand Pinot noir Ideotype Vine study network in 2018, 2019 and 2020**.**

Year		Berry mass (g)	TSS (°Brix)	TA (g/L H_2T)	pH	OD_{280} (AU)	OD_{520} (AU)
	Mean	1,3	22,4	7,2	3,33	1,35	0,21
	Max.	1,8	24,7	9,3	3,67	2,11	0,34
	Min.	0,8	18,7	4,9	3,14	0,64	0,11
2018	Median	1,3	22,5	7,1	3,31	1,40	0,20
	SD	0,2	1,2	0,9	0,11	0,34	0,04
	Upper	1,5	23,9	8,3	3,47	1,77	0,27
	Lower	1,0	21,0	6,1	3,19	0,92	0,16
	Mean	0,9	22,5	8,0	3,28	1,97	0,73
	Max.	1,2	25,2	11,0	3,63	2,59	1,30
	Min.	0,4	18,6	5,6	3,02	1,33	0,43
2019	Median	0,9	22,6	8,0	3,27	1,98	0,73
	SD	0,1	1,3	1,0	0,12	0,23	0,12
	Upper	1,0	24,1	9,2	3,43	2,26	0,88
	Lower	0,7	20,9	6,7	3,14	1,68	0,57
	Mean	0,9	22,6	7,9	3,42	1,98	0,55
	Max.	1,2	25,4	10,2	3,87	2,53	0,68
	Min.	0,5	18,5	6,3	2,84	1,54	0,33
2020	Median	0,9	22,7	7,7	3,47	1,95	0,56
	SD	0,2	1,6	0,8	0,22	0,25	0,08
	Upper	1,1	24,6	8,8	3,69	2,30	0,65
	Lower	0,7	20,6	6,9	3,15	1,66	0,44

The Upper and Lower ranges of the specification are equal to the mean ± 1.25s. Abbreviations: TSS = Total Soluble Solids; TA = Titratable Acidity; H2T = Tartaric Acid; OD280 = Optical Density @ 280 nm; OD520 = Optical Density @ 520 nm; AU = Absorbance Units; SD = Standard Deviation.

Yield per vine (Figure 6) categories were unable to differentiate the samples, such that the groupings were essentially superposed albeit that lower yield classes had more data points and were more dispersed across PC1. The PC1 loadings show opposing vectors for berry and bunch size in relation to berry colour and phenolic indices, while PC2 shows opposing loadings between TSS and bunch number. TA and pH are, as expected, also opposed for PC2.

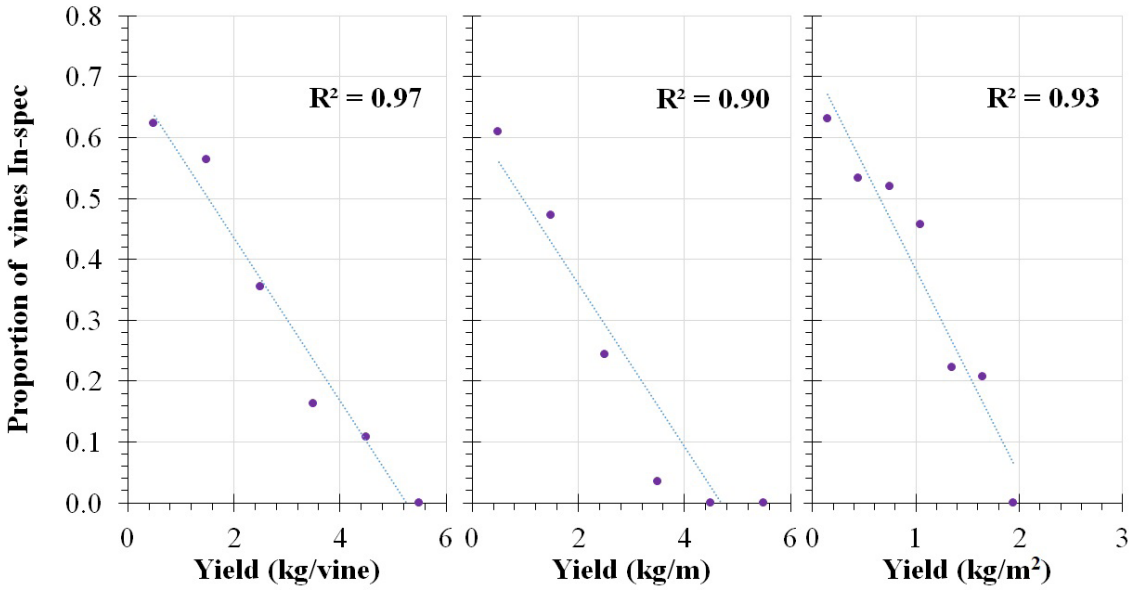
9. Grape parameter benchmarking

Where data were available from the vine x season observations from Icon vineyards (N = 300) we have sought to establish benchmark specification ranges for the following six grape parameters: berry mass; TSS; TA; pH, OD_{280} and OD_{520}. Because of the strong effect of the season on the grape parameters, as previously shown in the PCA analysis (Figure 6), we established specification ranges for each parameter specific

to each season. The specification range for each berry parameter was calculated from the Icon vine population as the mean ± 1.25SD. In this way each parameter specification range captured approximately 80 % of the Icon vine population values each season. Care was taken to ensure that the specification ranges were also reasonably aligned with established oenological berry composition targets for red table wine production (Iland *et al.,* 2000; Iland *et al.,* 2004). The calculated ranges and population statistics are presented in Table 5.

In parallel, the full single-vine x season dataset (N = 540) which included both Icon and Affordable vines was classified by yield into arbitrary and equal weight classes (Figure 7). The classifications were done by yield per vine (kg/vine), yield per linear metre of vine row (yield/m) and yield per unit area of land (kg/m^2), to take into account differences in planting densities of the vineyards.

The berry parameters for the full dataset were in turn classified according to the parameter ranges established for the Icon subset. The classification was a simple "yes/no" depending on whether the measured parameter was within range or not. Vines were considered to be within an overall specification "In-Spec" if their berry size and basic berry composition parameter values fell within their corresponding range for at least five out of six parameters. The frequency of In-Spec vines was then calculated for each yield class. Results are presented graphically in Figure 7. Highly significant negative linear relationships were established between vine yield class and the frequency of In-Spec vines. Simply put, the lower



(kg/vine)		(kg/m)		(kg/m^2)	
Class	**mid-point**	**Class**	**mid-point**	**Class**	**mid-point**
0 <=> 1.0	0.5	0 <=> 1.0	0.5	0 <=> 0.3	0.15
1.0 <=> 2.0	1.5	1.0 <=> 2.0	1.5	0.3 <=> 0.6	0.45
2.0 <=> 3.0	2.5	2.0 <=> 3.0	2.5	0.6 <=> 0.9	0.75
3.0 <=> 4.0	3.5	3.0 <=> 4.0	3.5	0.9 <=> 1.2	1.05
4.0 <=> 5.0	4.5	4.0 <=> 5.0	4.5	1.2 <=> 1.5	1.35
5.0 <=> 6.0	5.5	5.0 <=> 6.0	5.5	1.5 <=> 1.8	1.65
				1.8 <=> 2.1	1.95

FIGURE 7. Proportion of vines in the New Zealand Pinot noir Ideotype Vine study population (N = 540) for which their berry size, TSS, TA, pH, OD_{280} and OD_{520} values were within their corresponding range for at least five out of six parameters "In-Spec" plotted against the mid-point of the vineyard yield class expressed as yield per vine (left), yield per linear metre of vine row (centre) and yield per unit of land area (right), to take into account differences in planting densities of the vineyards.
Abbreviations: TSS = Total Soluble Solids; TA = Titratable Acidity; OD_{280} = Optical Density @ 280 nm; OD_{520} = Optical Density @ 520 nm.

the yield, the higher the proportion of vines in the vineyard that met the benchmark specification established for Icon vines.

DISCUSSION

Our experimental approach in this "Ideotype Vine" study controls variables such as clone, region and vineyard by studying within-block differences in vine performance across multiple vineyards. Our aim is to derive generalisable relationships between vine performance attributes (e.g. yield) and grape composition parameters. All three study regions experienced contrasting weather conditions between seasons, providing the study with valuable climatic diversity. The 2017/18 season was warm and relatively wet during the period from véraison to harvest while overall 2018/19 and 2019/20 were drier and cooler. The early season was wet and the mid-late season dry in 2018/19 while the dry period was more extended in 2019/20. In general terms the harvest conditions in 2017/18 were relatively humid, with botrytis bunch rot infection periods (Agnew *et al.,* 2018) strongly influencing harvest timing decisions. The very dry conditions and low disease pressure in 2018/9 and 2019/20 (Agnew and Raw, 2019) allowed winegrowers to schedule block harvests with a freedom rarely encountered in New Zealand. Between vineyards there was no obvious pattern between mean 20-vine yield and the commercial harvest date or the budburst to harvest GDD (Table 2). Within-season and within-region differences in commercial harvest date often appeared a result of winegrowers using fruit hang-time to achieve a desired and somewhat subjective grape maturity target. This is an important consideration in the interpretation of the yield and grape composition results obtained.

1. Vine Yield

Within-vineyard block variation in yield was always very high and in a third of the vineyard x season combinations the between vine yield RSD exceeded 40 %. These variations in yield between vines within a vineyard block occurred irrespective of whether the vineyard was managed to produce high-priced single vineyard Pinot noir wine or targeted to the production of a more affordable wine.

On a vine by vine basis normalised yields did not correlate among seasons; in other words, yield in one season had no meaningful effect on yield in any other season (Figure 2). The extent of the variation in performance of the same vines between seasons largely excludes factors that are stable between seasons as primary causes. For example, factors such as within-block differences in meso-climate (Sturman *et al.,* 2017), soil physical properties (Bramley *et al.,* 2011; Trought and Bramley 2011; Bramley *et al.,* 2019), long-term plant health status (virus, trunk disease) (Mundy *et al.,* 2009) and plant genetics can probably be ruled out. Variations in management or environment x management (E x M) interactions of the same vine from year to year seem the most likely contributors to variation.

In manually pruned vineyards shoot number per vine is largely a managed attribute, being a function of the node number retained after winter pruning and eventual shoot thinning operations. Established viticulture theory and practice dictates that retained node number and therefore shoot number per vine (and the associated yield) should be balanced with the capacity of the individual plant (Ravaz 1903; Jackson *et al.,* 1984; Carbonneau, 1993). The capacity of a mature, healthy vine is relatively constant from year to year (Carbonneau, 1993) and has been assessed using pruning weights (Ravaz 1903) and through the effective shoot number method (Greven *et al.,* 2014). It therefore follows that targeted shoot number, at an individual vine level, should ideally be relatively constant from year to year. Our data have shown that differences in shoot number per vine were the primary cause of differences bunch number per vine and, in turn, bunch number per vine was the major driver of yield differences (Figure 1). This result is in agreement with those of Greven *et al.* (2014) who found a proportional relationship between retained node number and vine yield in the first season following the application of a differing node number.

2. Yield-quality interactions

Winegrowers often use a combination of experiential knowledge (Parr, 2019) and objective measurement to assess the relative quality of grape or wine lots. For the most part an overall opinion of wine quality is not formed until after the completion of primary fermentation, typically at a time when initial grading tastings occur. At this point in the winemaking process the smallest production unit in the winery is either a tank or a vineyard block, depending on respective sizes. In this way the winegrower tends to form a single view of tank or vineyard block quality whereas the biological reality is that the production unit is comprised of thousands of vines with, as we have shown, a high degree of variability in performance

between plants. Objectively vineyard block quality is the cumulative effect of a high number of differing individual vines, each with its own quality, whereas subjectively it is viewed as a single integrated characteristic.

Across the entire sample set there was no general relationship between vine yield and berry TSS irrespective of whether yield was expressed per vine, per metre of row or per square metre of land. Likewise there was little evidence of a within-block effect of yield on berry TSS (Figure 4 and Supplementary Information Figures S4–S6). The inference is that, across the study, yields were mostly within a range that allowed basic berry maturity in Pinot noir to be achieved in the majority of vineyard x season scenarios. This result is consistent with that of Mawdsley *et al.* (2019) who found that that yield reduction had no measurable effect on Pinot noir ripening rate or harvest grape composition when starting yields were not excessive. A key point to note is that our study has obtained grape composition data at or very near to commercial harvest. Trought & Bramley (2011) reported decreasing within block variability of key berry composition parameters as ripening advanced. The general lack of an effect of yield on berry TSS can therefore be partly attributed to the winegrower waiting a sufficient length of time to enable the higher yielding vines to reach a similar TSS to the lower yielding vines in the same vineyard block. There were a few exceptions in our study (notably vineyards WB and MC in 2020) where the negative effect of yield on berry TSS was significant (Figure 4) but which can be traced to a somewhat premature harvest immediately prior to the COVID-19 lockdown. These results highlight the role the timing of a harvest decision can play in determining a research finding, and remind us that extended ripening can carry additional, and in the case of COVID-19, totally unforeseen risk.

There was a striking difference in phenolic content of the berries between the vintages. The OD_{520} was, on average, three-fold higher in 2019 than in 2018 while berry colour in 2020 was intermediate. Although yields were generally lower in 2019, at the same fruit yield berry colour potential was much higher in 2019, especially compared with 2018. These vintage-related differences were an order of magnitude greater than any effect that targeted management such as leaf or crop removal might induce (Kemp *et al.,* 2011; Lee and Skinkis, 2013; Lemut *et al.,* 2013; Mawdsley *et al.,* 2019). Berry colour indices were negatively correlated with vineyard mean berry mass and, in a related way, with vine yield, although the data suggested that berry mass was more strongly correlated to yield than berry number per vine. PCA analysis of the data also showed that vintage was an effective clustering category, while yield per vine was unable to differentiate the samples such that the groupings were essentially superposed. The vintage effect dominated compositional effects that might be associated with yield per vine, region and vineyard, albeit that vintage by vineyard interactions were in evidence.

3. Quality benchmarking

The wines produced from the study network of 12 commercial vineyards comprise eight single-vineyard "Icon" wines and four multi-vineyard blend "Affordable" wines (Table 1 and Supplementary Information Table S3). Three of the Icon vineyards are each located in Otago and Wairarapa and two are in Marlborough. Of the eight Icon wines, several are considered to be among New Zealand's best examples of Pinot noir (Jukes and Stelzer, 2019; Parr *et al.,* 2020). These Icon wines range in current retail price from $NZ44 to $NZ140 per bottle, with an average price of approximately $NZ75 compared with an average bottle price of approximately $NZ24 for the Affordable wine group. In the context of this study we have assumed that the population of vines that directly contribute to the production of these Icon wines are a reasonable ideotype population from which to derive benchmark grape berry size and basic berry composition parameters (Table 5), albeit that within each Icon vineyard site there was vine to vine variation in performance characteristics.

From the berry quality benchmarking and yield classification process we have derived highly significant negative linear relationships between vine yield class and the proportion of vines that were within specification, demonstrating a reduction in grape quality potential as yield increases. This result provides evidence of the quality risk associated with higher yield. Our results also support the view that the viticultural practices generally used by New Zealand's top-end Pinot noir producers, especially with regard to yield management, provide an effective means of ensuring a high proportion of vines meet an arbitrary grape parameter specification based on berry mass: TSS; TA; pH, OD_{280} and OD_{520}. Perhaps more importantly however, the results also demonstrate that a considerable proportion of In-Spec vines that are present in the both Icon

and Affordable vineyards are also able to meet the same grape parameter specification at relatively higher yields. Specifically, of the vines yielding in the range of 1–2 kg/m from both the Icon and Affordable vineyards, 48 % (74/153) met the Icon vine benchmark specification. The proportion of In-Spec vines was, however, higher in Icon vineyards (54/80 = 68 %) than in the Affordable vineyards (20/73 = 27 %) suggesting that site selection and/or vineyard management (i.e. E x M) factors may also play a role. In the authors' opinion, however, the most important finding of this study is that 15 % (14/92) of vines yielding > 2.0 kg/m in the Affordable vineyard category achieved the Icon quality specification without the application of intensive shoot and crop thinning regimes. These vines could be considered the outstanding performers or "Ideotype" vines within the study population. Inspection of the individual vine data from this ideotype population also revealed that it was not the same vines each year that performed optimally, confirming the need for more in-depth study to determine factors that enable a favourable convergence of a low intensity yield management with high grape quality.

CONCLUSIONS

In this work we have made progress in reconciling objective and subjective perspectives of quality by measuring the proportion of vines within a diverse population that meet a defined quality specification. We have shown that independently of season, region, site or vineyard management there is a statistically significant negative relationship between vine yield and the proportion of vines in a block that attain a common grape quality specification. While this result supports the subjective view of a yield quality paradigm, at an individual vine level the result also confirms that a small proportion of vines in the study achieve both high quality and higher yield under an Affordable vineyard management regime.

Our intention for the remainder of this programme, and beyond, is to more intensively study the vine ideotypes within our overall study population that produce In-Spec berries at profitable commercial yields (> 2.0 kg/m). Our challenge is to understand why, in some seasons, these vines are able to meet specification at higher yields. We are confident that, in future, our experimental approach will deliver important insights to allow the development viticultural management strategies to coax a greater proportion of vines with higher yields to consistently reach the same quality standard as the lower-yielding Icon vines.

For three contrasting vintage conditions, our data support our hypothesis, which states that it is possible to break the yield-quality paradigm. We are currently in a position to advance our programme, confident in the knowledge that factors such as vine yield, region or vineyard are, in themselves, unlikely to be immovable drivers of key grape quality parameters in New Zealand Pinot noir. That is not, however, to say that fine differences in grape or wine composition are not also extremely important in determining the style, quality and price of Pinot noir wine.

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