Department of Environment and Agriculture

An Economic Analysis of Precision Viticulture, Fruit, and Pre-Release Wine Pricing across Three Western Australian Cabernet Sauvignon Vineyards

Hayley Del Maynard

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Name ________________________________ Date_______________________________

Acknowledgments

I'm not sure "Acknowledgments" is an appropriate heading for this section; perhaps "Infinite Thanks and Gratitude" would be more apt. I don't wish to acknowledge these people so much as shout my appreciation from the mountains and shower them with flowers and chocolates. But I suppose this brief page will have to suffice.

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Abstract

In this thesis, the effects of Precision Viticulture (PV) technologies on intrinsic properties of Cabernet Sauvignon fruit and wine, quality, and price were spatially analysed through case studies and an overarching levelised cost model. Relationships between Plant Cell Density (PCD a vegetation index derived from near infrared:red reflectance that is often used as an input for PV technologies) and vine attributes (trunk circumference and canopy surface area measurements) were verified, before PCD imagery was used to delineate high and low vine vigour zones at three different vineyards in three climatically distinct wine regions of Western Australia (Geographe, Margaret River, and Great Southern). Wines were made from each zone, in addition to a uniform control (proportional blend of low and high vigour zones) over two vintages. Wine sensory and chemistry analyses were undertaken to examine the effects of vigour on specific organoleptic and volatile properties of the wines and how these effects translate to price and quality. A levelised cost model was created, incorporating the data collected from each of the case studies and using industry-derived cost values and response function observations from the existing literature in the field.

Remotely sensed PCD and manually sampled vine measurements share a weak positive linear relationship. However, when vines are targeted based on high and low vigour zones (as opposed to grid sampling), the relationship strengthens significantly. These results verify the utility and economic efficiency of PCD imagery compared with on-the-ground data collection. However, when PCD was compared with berry chemistry values (pH, titratable acidity, and total soluble solids), consistently significant linear relationships were not found across sites. This result suggests that PCD imagery should be used as a tool to distinguish between vigour zones in a vineyard, however, under the conditions of this study it had limited use in the prediction of variation of berry composition.

Management of variations in vine vigour using a zonal vineyard management approach has the potential to decrease operating expenses through targeted use of inputs and more efficient management practices and increase revenue through product differentiation or homogenization. PCD imagery, canopy surface area measurements, trunk circumference data, input from the viticulturist and winemaker, in additional to logistical issues were used to identify and define vigour zones and enabled differential management of low and high

vigour zones at each site. Two of the three sites realised increased total profit/ha through decreased operating expenses and increased fruit price. The only site not to achieve any benefits from PV was the smallest site (0.27 ha), suggesting that a minimum vineyard block size is required to realise a return on investment from PV.

Small batch wines were demonstrated to be representative of their commercial scale counterparts. A semi-trained panel determined the overall quality of small batch experimental wines is of equal or greater quality than commercial scale wines through paired discrimination sensory analysis. This result supports and justifies further use of the small batch wines in sensory and chemistry analysis for studies of this nature.

Site and regional meso-climate effects are the primary drivers of wine quality and price. However, vine vigour is also of significant importance. Quantitative descriptive analysis and targeted and untargeted gas chromatography mass spectrometry analysis (GC/MS) was undertaken to examine the effects of vintage, site, and vine vigour on each of the experimental wines. Balance, complexity, ethyl 2-methylpropanoate, and ethyl acetate were determined to be the main drivers of price. It was found that wines made from low vigour vines tended to be associated with red berry, dark fruit, jam, balance, complexity, and ethyl propanoate, whereas wines made from high vigour vines were grouped with canned vegetable, bitter, ethyl decanoate, 2&3-methylbutyl acetate, and 2&3-methylbutanol. Overall, a general inverse relationship was found between vine vigour and quality, suggesting that for Cabernet Sauvignon grown in the Western Australian wine regions used in this study low vigour vines produce wines of higher quality and high vigour vines produce wines of lower quality.

Intrinsic quality of fruit and wine does exist and can be measured. This study has utilised a novel approach through the creation of a levelised cost model that includes total cost (operating, overheads, and capital)/tonne of fruit over the lifetime of the vineyard. Applying the first principles assumption that fruit price equals total cost/unit plus a profit margin (normally 20%), a unique dollar value assessment of quality was achieved. While this thesis does not attempt to further qualify the individual drivers of quality, the analysis verifies the existence of intrinsic quality attributes.

The ability of PV technologies to maximise economic return are subject to size, and recommended adoption rates vary with producer size. Using PV response functions developed from input from subject matter experts, findings of previous research, and data collected from case studies in this thesis, levelised cost/tonne was calculated for each step of PV adoption for each producer size. It was found that producers (with reference to overall producer size, not individual vineyard block size) of less than 15 ha are not encouraged to adopt PV technologies, whereas all other producers are encouraged to adopt all three technologies (remote sensing, soil sensing, yield monitoring).

Spatial variability within a vineyard is an inherent issue faced by all growers. In this study, PV technologies enable targeted management to maximise economic return from a vineyard through vigour zone identification and ultimate quality manipulation (through product differentiation or homogenisation). Vine vigour shares an inverse relationship with quality: low vigour zones produce higher quality wines than do high vigour zones. Verification of this relationship enables the development of response functions which determine the overall economic potential of PV technologies. Furthermore, by assigning a dollar value to quality, it is possible to directly analyse the economic effects of PV technologies on vineyard profitability.

As the wine industry currently lacks a universally acknowledged measurement scale for quality, the levelised cost analysis used in this research fills this knowledge gap by enabling fruit quality to be assessed through the cost/price differential. Understanding the relationship between fruit quality and vine vigour further allows the effects of PV technologies to be quantified and economically analysed.

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Chapter 1 Introduction

It is readily acknowledged that spatial variability drives vine vigour differences which in turn produce fruit of divergent quality (Arnó et al. 2009, Bramley 2005, Cook and Bramley 1998, Proffitt et al. 2006). Vine vigour can be measured by canopy size (Boshoff 2010), trunk circumference (Trought et al. 2008), by remote sensing techniques (Proffitt et al. 2006), leaf area index (Hall et al. 2008), pruning weight (Dobrowski et al. 2003), among other indices. However, significant knowledge gaps exist when determining how vigour variations influence overall fruit quality and price (Cook and Bramley 2001). Additionally, the economic benefits of managing vigour differences through Precision Viticulture (PV) technology are poorly described and largely unknown (Cook and Bramley 2001, Cook et al. 2000). Previous research has shown that variation in vigour can have an effect on quality (Proffitt et al. 2006, Scollary et al. 2008); in general the findings have shown that low vigour vines produce fruit and resultant wine of higher quality than do vines of higher vigour (Bramley et al. 2011). However, the specifics of this relationship are poorly understood and are inconsistent (Bramley et al. 2011, Proffitt et al. 2006, Trought et al. 2008).

Before the development of PV technologies, spatial variability, especially variation in vine vigour, within a vineyard was a difficult management problem due to the lack of an adequate means of measuring within-paddock variation (Cook and Bramley 1998). Profitability in the vineyard is maximised when uniformly high quality fruit is produced, and an opportunity is lost when high quality fruit bulked with low quality fruit due to a lowering of the price paid for the product (Bramley 2005, Bramley et al. 2005, Bramley and Hamilton 2004, Bramley and Hamilton 2007). Understanding vigour zones within a paddock can allow a producer to selectively harvest based on vigour and quality, or to manage differentially (zonal vineyard management) to homogenise the final product (Arnó et al. 2009, Cook and Bramley 1998, Proffitt et al. 2006).

While the potential advantages to zonal management have been demonstrated across a range of environments (Bramley et al. 2003, Bramley et al. 2005, Bramley et al. 2011, Bramley and Hamilton 2005, Proffitt and Malcolm 2005, Proffitt et al. 2006, Scollary et al. 2008), the adoption rate by industry has been slow (Arnó et al. 2009, Bongiovanni and Lowenberg-DeBoer 2001, Llewellyn 2007). One of the main reasons cited for the slow adoption is a lack of clear and detailed economic analysis of the costs and benefits associated with PV technologies (Adrian et al. 2005, Ancev et al. 2004, Baumgart-Getz et al. 2012, Lamb et al. 2008, Lowenberg-DeBoer 2003).

One of the main limitations is the lack of an objective measurement scale for both fruit and wine quality. Hence, analysing quality and its relationship with price has proven difficult.

The wine grape market is one of the only agricultural commodities to not have a uniform measurement scale for quality (Heien 2006). Previous research has attempted to measure intrinsic fruit and wine quality through simple berry chemistry parameters such as pH, titratable acidity, and total soluble solids (Jones and Storchmann 2001, Trought and Bramley 2011). However, it has been shown that these measures are only basic harvest indicators and share no direct relationship with fruit or wine quality or price (Iland et al. 2011, p. 167, Jackson and Lombard 1993, Jackson and Lombard 1993, Jackson 2008, p. 212). So, while vigour may drive quality, the actual ramifications and quantifications of this relationship, and the overall fruit price and quality relationship have stalemated economic analysis of PV.

The main objectives of this thesis were (Figure 1.1) to:

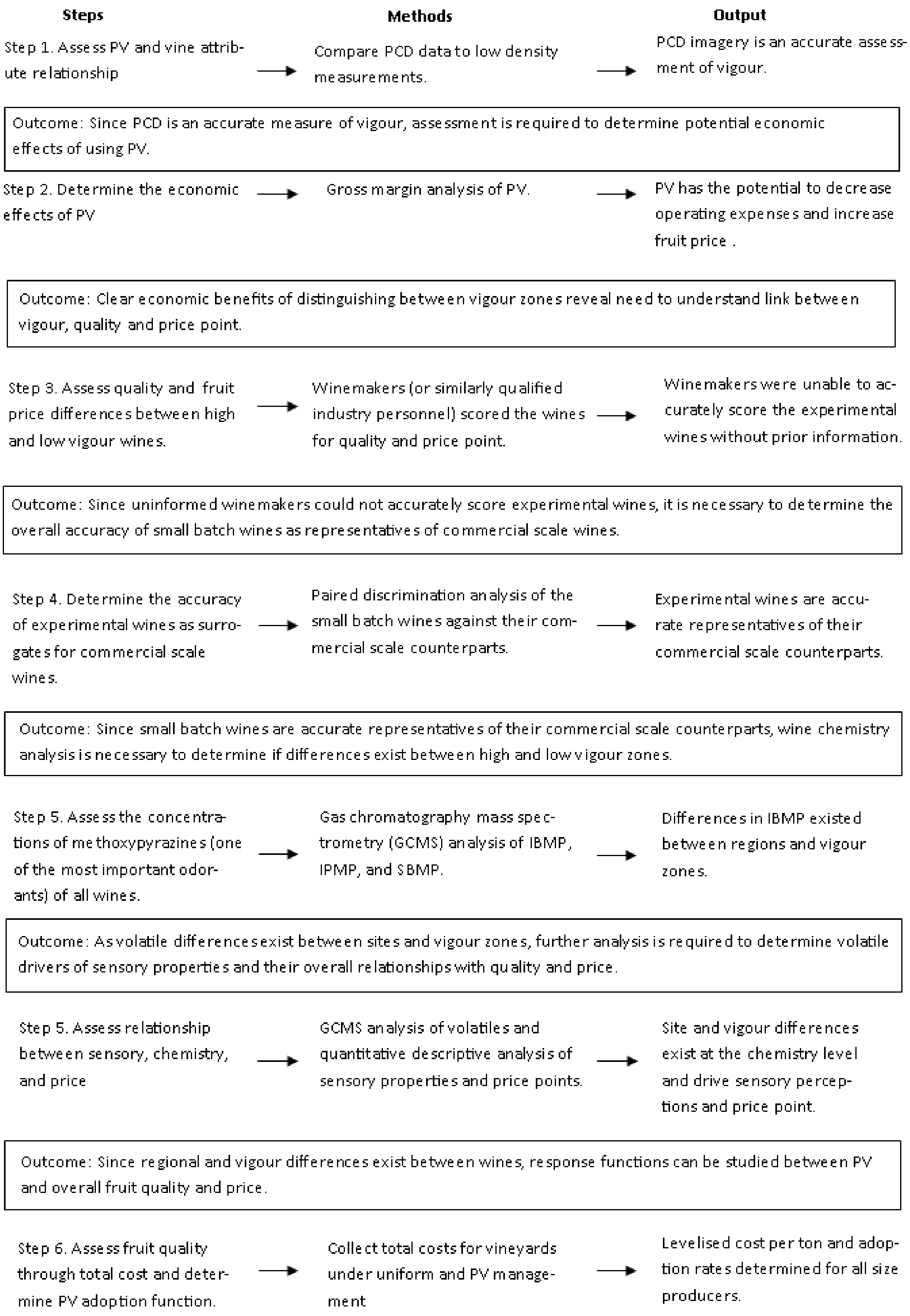
1. Establish a link between remotely sensed Plant Cell Density (PCD) imagery and on-the-ground measurements of grapevine vigour,
2. Calculate gross margin effects of PV at multiple sites across Western Australia,
3. Assess the relationship between vigour and wine quality for 3 sites from multiple wine growing regions (Geographical Indicator's) across Western Australia,
4. Determine the applicability of experimental wines as representatives of their commercial scale counterparts,
5. Analyse the relationship between wine chemistry, organoleptic properties, vigour zone, region, and price,
6. Assess fruit quality as a measure of levelised cost/tonne,
7. Determine a PV adoption function for producers of all sizes.

This research asked: What is the relationship between vigour, quality, and price? What specific volatile and sensory attributes drive quality? What are the intrinsic drivers of price? How can we efficiently manage vigour to maximise economic return from fruit and wine?

The hypotheses were:

That:

1. PCD is an accurate measure of vine vigour,
2. PV technologies (especially PCD) can be used to assess and manage vigour and increase gross margin through fruit price increase and operating cost decrease,
3. Low vigour vines yield wine of higher quality than high vigour vines,
4. Experimental wines are representative samples of their commercial scale counterparts,
5. Vigour variation within a vineyard drives different wine chemistry which in turn drives sensory perceptions. Overall, wines produced from low vigour vines are associated with positive sensory attributes, high quality scores, and higher overall price points than wines produced from high vigour vines,
6. Levelised cost/tonne decreases with increasing vineyard size,
7. PV management practices are recommended for most producers; however, there is a minimum size threshold for positive return on investment.



Steps	Methods	Output
Step 1. Assess PV and vine attribute relationship	Compare PCD data to low density measurements.	PCD imagery is an accurate assessment of vigour.

Outcome: Since PCD is an accurate measure of vigour, assessment is required to determine potential economic effects of using PV.

Steps	Methods	Output
Step 2. Determine the economic effects of PV	Gross margin analysis of PV.	PV has the potential to decrease operating expenses and increase fruit price .

Outcome: Clear economic benefits of distinguishing between vigour zones reveal need to understand link between vigour, quality and price point.

Steps	Methods	Output
Step 3. Assess quality and fruit price differences between high and low vigour wines.	Winemakers (or similarly qualified industry personnel) scored the wines for quality and price point.	Winemakers were unable to accurately score the experimental wines without prior information.

Outcome: Since uninformed winemakers could not accurately score experimental wines, it is necessary to determine the overall accuracy of small batch wines as representatives of commercial scale wines.

Steps	Methods	Output
Step 4. Determine the accuracy of experimental wines as surrogates for commercial scale wines.	Paired discrimination analysis of the small batch wines against their commercial scale counterparts.	Experimental wines are accurate representatives of their commercial scale counterparts.

Outcome: Since small batch wines are accurate representatives of their commercial scale counterparts, wine chemistry analysis is necessary to determine if differences exist between high and low vigour zones.

Steps	Methods	Output
Step 5. Assess the concentrations of methoxypyrazines (one of the most important odorants) of all wines.	Gas chromatography mass spectrometry (GCMS) analysis of IBMP, IPMP, and SBMP.	Differences in IBMP existed between regions and vigour zones.

Outcome: As volatile differences exist between sites and vigour zones, further analysis is required to determine volatile drivers of sensory properties and their overall relationships with quality and price.

Steps	Methods	Output
Step 5. Assess relationship between sensory, chemistry, and price	GCMS analysis of volatiles and quantitative descriptive analysis of sensory properties and price points.	Site and vigour differences exist at the chemistry level and drive sensory perceptions and price point.

Outcome: Since regional and vigour differences exist between wines, response functions can be studied between PV and overall fruit quality and price.

Steps	Methods	Output
Step 6. Assess fruit quality through total cost and determine PV adoption function.	Collect total costs for vineyards under uniform and PV management	Levelised cost per ton and adoption rates determined for all size producers.

Figure 1.1 The steps, methods, outputs, and outcomes for each phase of this research. The steps are the objectives, the methods are the resources and techniques used for analysis,

and the outputs are the results. The boxes are the outcomes which summarise the results and provide justification for the next step.

Chapter 2 Literature Review

This research is a multidisciplinary project that extends from grape growing and wine economics to consumer behaviour perceptions and analysis. Literature on wine economics and consumer involvement, price, and quality issues relevant to wine are reviewed. This project centres around the concept of fruit and wine quality - how best to achieve it (economically and environmentally efficiently), how to assess it (sensory and chemistry analysis), and its overall relevance in an economic application. Key studies and milestones in the field of wine economics and econometrics are reviewed. However, due to the limitations of the past studies this thesis introduces the topic of levelised cost analysis for viticulture - a model that accounts for all costs (hidden capital and operating) pertinent to grape production and the technology (required in today's economic climate) to farm vineyards efficiently.

Wine Economics

Wine has fascinated economists for decades as many market dynamics are not applicable in this commodity. For example, fundamental economic assumptions, like producers always wanting to maximize profit and minimize cost, are not always true in wine. Some producers will sacrifice profit in pursuit of better quality or higher accolades and sometimes a downward shift in price may actually *decrease* demand. It is these paradoxical situations, these behavioural anomalies, which have stimulated interest and growth in the field of wine economics (Storchmann 2011, Thornton 2013).

The apparently erratic nature of the wine market, the elusive definition of quality, the unpredictable behaviour of producers and consumers, all drive interest into this field (Storchmann 2011, Storchmann 2012, Thornton 2013). Previously developed hedonic pricing models have attempted to explain wine market anomalies (Oczkowski 2006, Oczkowski 2014); however, these models have produced contradictory results. At this new and exciting crossroads, there is an apparent need for a more traceable approach to the analysis of wine quality and its relationship with price.

As the wine grape market is composed of buyers possessing a relatively high competence and knowledge of the product, price can be a variable indicator of quality as no direct measurement scale exists (Fraser 2003, Jackson 2008). However, as a commodity progresses through its lifecycle and moves from a raw good into a finished product, it becomes more difficult to understand and evaluate (Scitovsky 1944). The wine grape market is one of the only agricultural commodity markets to not have a measurement scale for such factors (Heien 2006). This contradicts the grain industry, for example, where protein content is used to grade quality and therefore determine price (Willams and Wright 1991). So, while a grape buyer may be an educated industry professional, the scale with which he or she measures is largely subjective (Dodds and Monroe 1984, Garvin 1983, Holbrook and Corfman 1985, Jacoby and Olson 1985, Parasuraman et al. 1985, Zeithaml 1988). Advances in sensory and chemistry sciences have enabled a more in-depth analysis of potential quality drivers (Robinson et al. 2014), however, the "Holy Grail" of viticulture - this quest for a uniform quality scale - is ongoing.

When a grape is processed into wine, the finished product becomes more difficult to directly compare with other wines (Costanigro et al 2007), and quality becomes an even harder entity to quantify and define (Jacoby et al. 1973, McConnell 1968, Robinson et al. 2014, Shapiro 1973, Steenkamp 1990, Zeithaml 1988). "Quality can be defined broadly as (technical) superiority or excellence," while *perceived* quality is the consumer's *perception* of quality (Lichtenstein and Burton 1989, Steenkamp 1989, Zeithaml 1988). It should be noted that studies have shown that winemakers' perceptions of quality and consumers' preferences of quality are often not in alignment (Blackman et al. 2010, Lattey et al. 2010, Lesschaeve 2007). Due to constantly evolving consumer preferences, winemakers are continually challenged to respond to different market preferences (Blackman et al. 2010, Lesschaeve et al. 2002, Lesschaeve 2007). Wine contains a larger number of volatile compounds than grapes, due to vinification and winemaker manipulation (Jackson 2008), thereby complicating sensory and chemical analysis. Additionally, what a consumer perceives organoleptically may not directly (or easily) translate into the wine's chemical profile (Jackson 2008, Preston et al. 2008, Robinson et al. 2014).

In addition to the increased sensory and chemical complexity, the market dynamics of wine are completely different. While grape buyers are industry knowledgeable individuals normally operating within a contract (Heien 2006), the wine market is composed of buyers with varying degrees of knowledge and information (Hall et al. 2001, Costanigro et al. 2007).

The finished wine market is therefore subject to greater information asymmetry and extrinsic variables than the wine grape market (Ashenfelter 2010, Ling and Lockshin 2003, Thornton 2013). Costanigro et al. (2007) found that the finished wine market is composed of different product classes as specified by price. This is in line with industry research (Ernst and Young Entrepreneurs 1999) and consumer research (Hall et al. 2001) which determined that both industry and consumers segment the wine market based on price. In a market with varying consumer knowledge and quality perceptions, it is difficult to find a gauge for quality, and separately for value (Schewfelt 1999, Zeithaml 1988). It is difficult to understand inherent quality differences between products of similar or differing price numerals (Ashenfelter et al. 2010, Jones et al. 2010). So, how then do consumers gauge wine quality?

Evidence has been found in markets where the consumer has little knowledge, or the quality parameters are abstract, that “nonlinear price-perceived quality relationships” do exist (Gardner 1971, McConnell 1968, Peterson 1970). Both Crosby (1979) and Zeithaml (1988) noted that quality and value are often misinterpreted by the consumer. As a finished good with a high elasticity of demand and low overall consumer quality information, quality may be based on more *extrinsic* factors (Zeithaml 1988). Studies have shown that “many consumers use the price cue as a signal to indicate product quality” (Alston et al. 1983, Lichtenstein et al 1993, Olson 1977, Tellis and Gaeth 1990). In this way, price can act as a positive indicator of quality to a consumer who lacks absolute knowledge as to a product’s actual value. As it is difficult to facilitate a quantitative approach to analysing or defining quality of wine (Jackson and Lombard 1993, Jackson 2008), the overall quality information available to the consumer is low. This can lead to price-seeking on the part of the consumer, and often price stimulus will incur a positive response (Tellis and Gaeth 1990). Price is then used to determine quality (Hall et al. 2001, Olson 1977, Olson 1978). Instead of price being the dependent variable on quality, the reverse holds true, with the result being consumers using price cues to understand quality of the commercial wines. However, the question of how exact these price cues are to actual “quality” parameters arises.

Research has been undertaken to better understand the link between consumer perceptions and wine quality. Corduas et al. (2013) found that intrinsic characteristics of a wine are significant purchase drivers. Schnabel and Storchmann (2010) found that “price signals respond positively to wine quality and negatively to increasing information." This research upheld the Bagwell and Riordan (1991) theory which postulated that low information goods tend to be subject to "high and declining price signals." That is, the product is introduced to the market at a price above the full-information, profit-maximizing price and then diminishes over time as the consumer base reaches full information. Palma et al. (2013) found that price plays a large role in determining *expected* quality *before* consumption (or the achievement of full-information) (Olson 1977). However, the issue with analysis of wine quality is the same issue found in analysis of grape quality - no objective scale or direct relationship has been found (Cardello 1995, Jackson and Lombard 1993, Jackson 2008). The reader must be aware that "quality" as expressed or analysed by different researchers, consumers, or producers may take on a completely different context (Zeithaml 1988). This is in line with research by Charters and Pettigrew (2006) which used qualitative methods to determine that "quality is a multidimensional construct and that consumers engage with it depending on their varying involvement levels with the product." This further demonstrates the inability of the surrogate measures used in most research (like winery ratings, critic scores, or dummy variables) to predict actual wine quality.

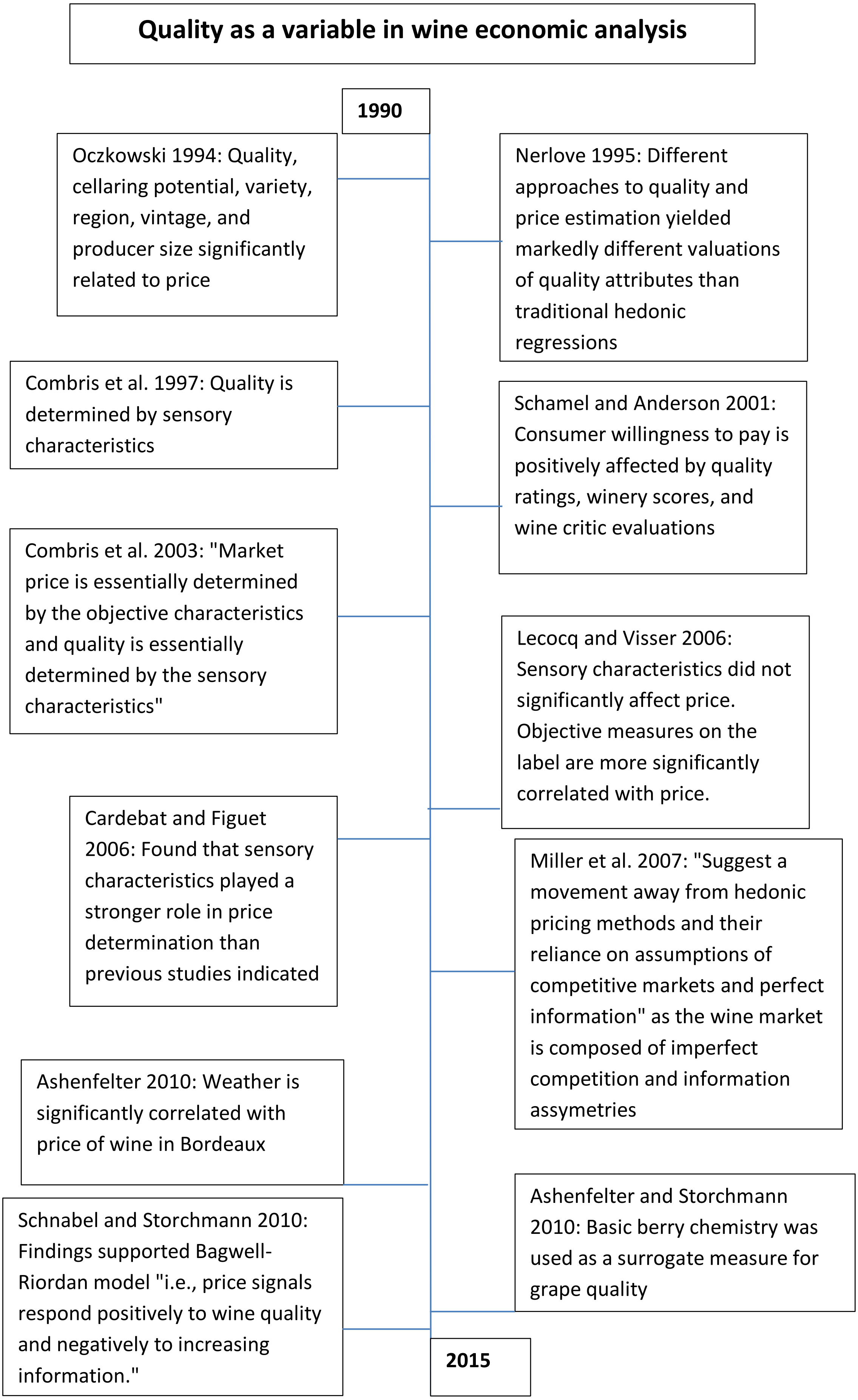
This research operates on the assumption that wine quality, as determined by intrinsic factors, does exist, even though the industry has yet to find a direct scale with which to measure it (Jackson 2008). Benhabib and Day (1981) found

> "that rational choice in a stationary environment can lead to erratic behaviour when preferences depend on experience…(and) one would therefore expect the possibility of erratic behaviour for a wide variety of dynamic economic models involving rational decision-making with feedback."

While extrinsic factors may inflate or deflate perceived quality (Dodds and Monroe 1985, Garvin 1983, Olson 1978), the basis of this assumption is that the wine consumer market is composed of rational consumers. Perhaps the reason previous models have shown the wine market to be so erratic, and indeed, irrational, is due to an inability to successfully account for intrinsic qualities and behavioural elements of the product, the consumer, and the wine market as a whole (Lawless 1995, Thaler 1980). Unwin (1999) noted that hedonic price regression is "flawed for four main reasons: difficulties in identifying the most appropriate variables to use; uncertainty over the aims of such methods; problems in the definitions of wine quality; and internal inconsistencies." Unfortunately, consumer perceptions have been largely ignored in subsequent research, as the difficulties in isolating and studying this facet of wine economic analysis have proven difficult (Cardello 1995, Jackson 2008, Lawless 1995, Verdú et al. 2004).

The principle study of the price/quality relationship in wine has grown significantly since the 1990s. Most research in the field has endeavoured to examine this relationship through hedonic regression, a form of analysis that involves categorizing a dependent variable (price) into its constituent features (i.e. region of origin, grape variety, berry chemistry, quality). Results from this body of work have been somewhat contradictory. Figure 2.1 is a timeline of some of the major papers discussed.

Researchers have oscillated in their opinion of the strength of the relationship between intrinsic wine quality and price. Oczkowski (1994) was one of the first researchers to employ a hedonic price function to try and explain differences in wine pricing. He found six attributes to be statistically significant: quality, cellaring potential, grape variety, region, vintage, and producer size. Nerlove (1995) used quantity of wine sold as the independent regressor and price and quality attributes as the dependent variables in his hedonic price function. His study, using the Swedish wine market, demonstrated that a different approach to quality and price estimation yielded markedly different valuations of quality attributes than the more traditional hedonic regressions. However, Landon and Smith (1998) developed a model employing price as a function of current and expected quality (reputation). It found a much higher correlation between reputation and price than current quality and price, indicating a premium would be paid for reputation. Oczkowski (2001) went on to find that inappropriate use of ordinary least squares (OLS) regression distorted the findings and overall importance of measured attributes. The author used factor analysis and 2 Stage Least Squares regression analysis to evaluate hedonic pricing of wines. It was noted that reputation had a significant effect, but quality's effects were not significant. Schamel and Anderson (2003) found that quality, as measured by James Halliday's and Winestate magazine's sensory quality ratings, was significantly correlated with price. Subsequently, Combris et al. (2003) used hedonic pricing applied to a data set from an



Quality as a variable in wine economic analysis

1990

Oczkowski 1994: Quality, cellaring potential, variety, region, vintage, and producer size significantly related to price

Nerlove 1995: Different approaches to quality and price estimation yielded markedly different valuations of quality attributes than traditional hedonic regressions

Combris et al. 1997: Quality is determined by sensory characteristics

Schamel and Anderson 2001: Consumer willingness to pay is positively affected by quality ratings, winery scores, and wine critic evaluations

Combris et al. 2003: "Market price is essentially determined by the objective characteristics and quality is essentially determined by the sensory characteristics"

Lecocq and Visser 2006: Sensory characteristics did not significantly affect price. Objective measures on the label are more significantly correlated with price.

Cardebat and Figuet 2006: Found that sensory characteristics played a stronger role in price determination than previous studies indicated

Miller et al. 2007: "Suggest a movement away from hedonic pricing methods and their reliance on assumptions of competitive markets and perfect information" as the wine market is composed of imperfect competition and information assymetries

Ashenfelter 2010: Weather is significantly correlated with price of wine in Bordeaux

Ashenfelter and Storchmann 2010: Basic berry chemistry was used as a surrogate measure for grape quality

Schnabel and Storchmann 2010: Findings supported Bagwell-Riordan model "i.e., price signals respond positively to wine quality and negatively to increasing information."

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Figure 2.1 Chronological ordering of significant papers in wine economics experimental study where juries were asked to evaluate and grade a number of Bordeaux wines. They found that "market price is essentially determined by the objective characteristics and quality is essentially determined by the sensory characteristics."

Further exploration into potential drivers of price led to exploration of other extrinsic variables and a lesser emphasis was placed on intrinsic quality determinants. Schamel and Anderson (2001, 2003) used hedonic price functions to determine that wine critic scores, Halliday's winery ratings, and classic wine designations are significantly correlated with price and consumers' willingness to pay. Ashenfelter and Jones (2000) found that expert opinion that is orthogonal to inherent wine quality is still a significant determinant of wine price. In 2006, Lecocq and Visser published their findings that sensory characteristics did not significantly affect price. Rather, objective measures on the label were more significantly correlated with price. At this same time, Cardebat and Figuet (2006) used hedonic pricing to look at price determinants. They found reputation to be strongly linked to price. Additionally, they found that sensory characteristics also played a stronger role than previous studies indicated, noting that increased "competition and reductions in information asymmetries" could be responsible for their findings. Due to clear contradictions in the literature, Miller et al. (2007) recommended a move away from hedonic pricing whose assumptions are based on competitive markets and perfect information; and instead suggest that future work account for the imperfect competition and imperfect, asymmetric nature of the wine market.

At this point, wine economic research shifted its focus from a price/quality relationship to a study of price/weather correlation. Ashenfelter (2008) found that seasonal weather (temperature during ripening and rainfall) can predict cellaring value of Bordeaux wines due to typical weather of the region being so varied. This analysis is continued in Ashenfelter (2010) where it is demonstrated that most young wines at auction are introduced at an artificially high price. As they age, their prices will fall to their relative value. Wines from vintages of specific weather patterns, however, will continue to grow in value. This research used econometric modelling to analyse market inefficiency and demonstrated that weather patterns were drivers of price variability in Bordeaux wines. It should be noted that Bordeaux experiences different weather patterns than Western Australia. Low pressure weather systems inherent to that region create varied vintages, whereas the high pressure weather patterns common to Western Australia and other New World countries generate consistently good vintages (Ashenfelter 2010). Ashenfelter and Storchmann (2010) used hedonic pricing to estimate economic effects of climate change. This study was conducted in the Mosel Valley in Germany which is different to the rest of the world with regard to fruit pricing valuation. In this particular region, due to its Northern aspect, ripening can be difficult, and therefore more money is paid for fruit with higher sugar content. The study used the Mosel quality classification system for estimating quality, a measure that in most premium wine growing regions this is considered inadequate and irrelevant.

A closer inspection of this research begs the question of quality's definition. What exactly is wine quality? Wine critics like James Halliday have developed individual scales that have been widely regarded as objective measures of quality. However, these scales are specifically calibrated to an individual's palette. The "quality" variables used in the previous research, have been measured using a variety of devices. Some studies used published wine scores, others used judges' or critics' evaluations, while still others used a dummy (proxy) variable as a surrogate measure for quality.

As suggested before and upheld by Miller et al. (2007) and Unwin (1999), the key issue of econometric models is that their fundamental structure is flawed. Too often the intricacies of the product and market are overly simplified, in favour of models more in line with Occam's razor. For example, take the structure from Jones and Storchmann (2001) in Figure 2.2.

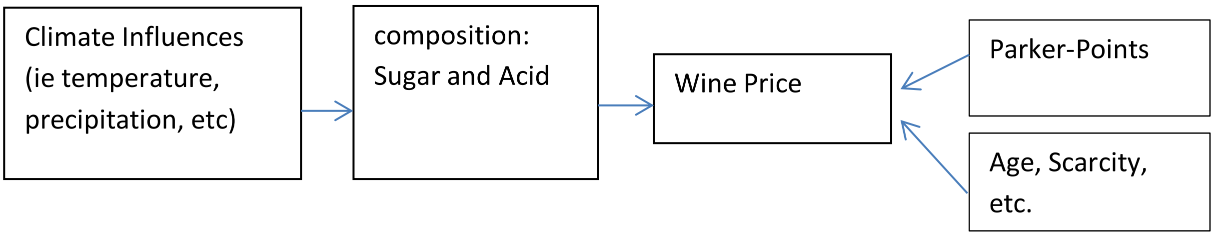


Figure 2.2 Structure of a model that uses basic measures to attempt to analyse wine quality and price (Jones and Storchmann 2001).

Wine is a multidimensional product that is composed of hundreds of known volatile compounds that contribute to sensory perceptions with sugar and acid used as merely "base-line" harvest indicators (Jackson 2008, Iland et al. 2011). These measures are not direct objective measurements of quality, but rather used as a minimum standard to gauge berry ripeness (Iland et al. 2011). Their direct role in price point assignment, as proved through this research, is negligible. Simple berry chemistry is not an accurate view of wine quality parameters (Iland et al. 2011). Climate influences definitely play a role in wine quality and price, however, depending on the specific region this variable may be more or less influential (Ashenfelter 2010, Iland et al. 2011). As discussed earlier, regions in France are more susceptible to weather influences than California or Australia. Extrinsic factors such as wine critic scores, age, scarcity, and reputation are all important factors to consider (Ling and Lockshin 2003). However, it should be noted that while extrinsic factors play a major role in first purchase behaviour, their role in subsequent purchases may be limited. It can be argued that once the consumer has obtained full information of the product (i.e. the consumer has imbibed the beverage) he or she is able to decide if the *intrinsic* quality characteristics of the wine (aroma and taste) are of the standard that would merit a repeat purchase (Olson 1977, Olson and Jacoby 1972). This logic follows the principles of rational consumer behaviour - that a consumer will continue to purchase a product if he or she decides the quality is worth the price (Olson 1977, Thaler 1980). A person will not continue to buy a wine that is not desirable or enjoyed. This argument supports the main assumption of this research: that the wine market is composed of rational consumers.

Wine made in Europe, especially France, is subject to more regulation than the rest of the world. Viticultural and oenological regulations and methodologies are strictly outlined and upheld (Jackson 2008, Stanziani 2004). The production and market regulations of Europe are summarised by Meloni and Swinnen (2013):

> "The European Union is the largest global wine-producing region and the main global wine importer and exporter. It is also a highly regulated market. Government intervention has taken many forms. Regulations determine where certain wines can be produced and where not, the minimum spacing between vines, the type of vines that can be planted in certain regions, yield restrictions, and so on. In addition, public regulations determine subsidies to EU producers and wine distillation

> schemes. The EU also determines public subsidies to finance grubbing up programs to remove existing vineyards, and imposes a limit on the planting of new vineyards."

New World countries, like those of North and South America, Australia, and New Zealand are not subject to the same level of regulations (Rose 2006). As most of the previous econometric analysis has been based on the prices of cellared wines from France and Europe, it is important to remember that the weather patterns, winemaking regulations, and wine markets are distinctly different in other countries. Furthermore, there is no evidence to show that wine expert scores or ratings "can predict consumer liking scores or market success" (Lesschaeve 2007), and therefore consumer perceived quality. The complexity of wine and the inherent heterogeneity of consumers' preferences (Palma et al. 2013) create modelling difficulties.

This research proposes a completely different approach to the analysis of wine quality. While previous papers circumnavigated cost by examining price in markets with different conditions, this research will use cost to directly examine wine quality via the process of levelised cost analysis. This technique uses the basic commodity pricing equation: price equals cost plus a nominal 20% profit margin, which is a modest requirement for a business subject to climate and market variability. Any discrepancy between modelled price and observed price can be classified as quality. This research does not attempt to classify the number and direct proportionality of quality drivers, but rather, attempts to segregate an objective value for quality, something that has not been done before. Furthermore, this research will use levelised cost analysis as part of an assessment of the role of PV in grape production for Cabernet Sauvignon wines.

Precision Viticulture

Land is inherently variable. This "spatial variability" as it is termed in agriculture, is a global issue for farmers (Bongiovanni and Lowenberg-DeBoer 2004, Bramley 2001). The variation in a field can be attributed to one of three elements: endogenous (i.e. edaphic or topographic), exogenous (i.e. weather), or controllable (i.e. inputs) (Hatfield 2000). A spectrum of approaches exists with regard to managing this variability. Conventional farming is the most generic, whereby in the case of grape production a vineyard block is treated homogenously, regardless of any topographic or edaphic differences (Pacini et al. 2003). Historically, this approach has been the most common, as the technology and means to identify, quantify, and develop management strategies to account for within-land variation has not been commercially available. This management style has a wide range of implications, not the least of which are environmental and economic (Bongiovanni and Lowenberg-DeBoer 2004, Pacini et al. 2003, Robertson et al. 2007). For example, soil at the top of a hill tends to be less rich in organic matter due to water run-off and soil erosion. Conversely, soil at the bottom of the hill tends to be high in organic matter and well-irrigated. A farmer who irrigates the top of the hill and the bottom of the hill with equal measures of inputs (i.e. water, fertilizer, compost, etc.) would be an example of conventional farming or "uniform management." There are benefits to uniform management. These include less time and resources spent collecting information on which to make a decision, and the added time and cost savings of implementation of only one management practice (Anderson et al. 1977).

The next step in the management tree is Differential or Site Specific Management. Site-specific management (SSM) is the management of agricultural crops at a spatial scale smaller than that of the whole field, or in more general terms "doing the right thing, at the right place, at the right time" (Bongiovanni and Lowenberg-DeBoer 2004). Widespread farmer adoption of SSM practices is contingent on its economic advantage.

> "Three criteria that must be satisfied in order for SSM to be justified are, (1) that significant within-field spatial variability exists in factors that influence crop yield, (2) that, causes of this variability can be identified and measured, and (3) that, the

> information from these measurements can be used to modify crop management practices to increase profit or decrease environmental impact" (Plant 2001).

Differential management incorporates a more knowledge-based approach, basing vine management decisions on existing differences within the vineyard (Lowenberg-DeBoer 2003). This form of management practice may seem to be one of "common sense." At a base level, it involves no form of technical or intensive data collection (Bongiovanni and Lowenberg-DeBoer 2004, Hartwick 1978). Management decisions are weighed holistically and environmentally and based on the farmers' intimate knowledge of his land (Caffey et al. 2001, Pacini et al. 2003, Pannell and Glenn 2000, Solow 1974). As differential management becomes more involved, a more intensive form of data collection is required and fine-scale, economically sound decision making becomes possible.

Precision Agriculture (PA) operates on the end of this management spectrum, sharing an indistinct boundary with differential management. PA involves the use of technologies, like soil sensing and remotely sensed imagery, to respond to an increased need for more detailed and sensitive vineyard information to enable more-informed decision making (McBratney and Whelan 2001, Shibusawa 1998). The list of technologies is ever increasing, however, the main technologies used in commercial applications are Global Positioning Systems (GPS), Geographical Information Systems (GIS), proximal and remote sensing, yield monitoring, soil sensing, autosteer, Variable Rate Application (VRA), and advancements in data processing and telecommunications (Gibbons 2000).

PA technologies have been evolving since the early 1990s (Bramley 2009). This growing field has sprouted interest in many broad-acre crops and has slowly expanded into other specialised agricultural commodities. Its applicability has spread to higher value specialised crops, like wine grapes, in recent years (Cook and Bramley 1998, Panten et al. 2010, Proffitt et al. 2006).

Spatial variability within vineyards, like broad-acre crops, is an inherent characteristic of all vineyards. Vineyard managers and winemakers have been aware of its existence since the beginning of domesticated grape production; however they had no adequate means of measuring and managing this variability (Cook and Bramley 1998, Proffitt et al. 2006, Stafford 2000). Precision Viticulture, "defined as the methodologies that allow site-specific vineyard monitoring and management" (Mazzetto et al. 2010), is the specific application of PA in vineyards. These technologies provide the means to acquire high density data; however, it is the use of this information in the decision making process that produces positive economic returns.

There are a host of PV technologies available to the modern grapegrower that have different purposes and associated benefits. These include: "crop sensors and yield monitors, proximal and remote sensors, Global Positioning Systems (GPS), VRA (Variable-Rate Application) equipment and machinery, Geographic Information Systems (GIS) and systems for data analysis and interpretation" (Arnó et al. 2009). Benefits gained from PV include cost savings from the appropriate management of inputs (irrigation, compost, fertilisers), potential increase in revenue from the identification and differentiation of grapes of contrasting qualities, and greater accuracy and precision of vineyard sampling, management, and crop yield prediction (Bramley 2001, Bramley and Lamb 2003, Proffitt and Hamilton 2001). Additionally, these technologies provide an array of spatial information including vine vigour imagery (collected via remote sensing technology), digital terrain models/topographical maps (collected via soil sensing technology), apparent electrical conductivity maps (collected via soil sensing technology), and yield maps (collected via yield monitoring technology) (Cook and Bramley 1998, Proffitt et al. 2006, Trought et al. 2008).

Existing research in PV has shown that vines of a higher vigour tend to yield fruit of lower quality (Bramley 2005, Bramley et al. 2005, Cortell et al. 2005, Lamb and Bramley 2001, Lamb and Bramley 2002, Proffitt et al. 2004, Proffitt and Bramley 2010, Scollary et al. 2008, Trought and Bramley 2011). It should be noted that each of these studies relied heavily on varying quality definitions. Bramley et al. (2005), Proffitt et al. (2004), and Scollary et al. (2008) used fruit price received to denote quality, while Cortell et al. (2005) used proanthocyanidin concentration. Additionally, not all studies used Cabernet Sauvignon fruit. Cortell et al. (2005) was a study of Pinot Noir, while Proffitt et al. (2006) and Bramley et al. (2005) present a number of case studies using multiple varieties. The identification of this relationship has opened the door to remote sensing and variable rate applications. Grapegrowers can easily identify and manage zones of contrasting vigour, thereby potentially decreasing cost of inputs and increasing revenues through differentiation of fruit of varying quality and price values (Bramley et al. 2005, Proffitt et al. 2006, Smart 2005).

While PA technologies have been around since the early 1990s, they have experienced a slow adoption rate (Bongiovanni and Lowenberg-DeBoer 2001, Llewellyn 2007), as farmers are uncertain of whether to adopt PA technologies (Zhang et al. 2002). This is due to a number of reasons. The primary reason cited for a lack of adoption is cost and perceived net benefit (Adrian et al. 2005, Ancev et al. 2004, Baumgart-Getz et al. 2012, Lamb et al. 2008, Lowenberg-DeBoer 2003). Daberkow and McBride (2003) noticed that high input crops tend to experience a faster adoption rate due to greater perceived economic return. Availability and apprehension of technology are also key obstacles to adoption (Lamb et al. 2008, Lowenberg-DeBoer 2003, Orr et al. 2001). New technology can be intimidating to a farmer, especially if he or she has minimal computer skills. Orr et al. (2001) saw that adoption of technology is affected by its pertinence to decision-making and relative complexity of the specific technology. These obstacles highlight the need to address adoption rate in the industry and identify pathways to improve the slow rate.

Adoption of PV technologies, as in the case of PA technologies, has been similarly limited (Arnó et al. 2009) even though Scholefield and Robinson (1999) advocated the potential to "improve production systems by looking over the fence at what other industries are doing." Therefore, despite numerous studies and reports that advocate the use of PV technologies to enhance the decision making process (Arnó et al. 2009, Bramley et al. 2011, Cook and Bramley 1998, among others), the adoption of PV technologies has been both slow and partial, as distinct from full and complete. Slow and partial signifies the use of only one or two of the commercially available technologies, and full and complete indicates the use of all commercially available technologies and their applications in the decision making process. It is known that early adopters of technology tend to benefit from adoption (Anderson et al. 1977); however a number of factors could be contributing to this lack of adoption. Lamb et al. (2008) cited cost in addition to a lack of knowledge at the consultant level as contributing factors. However, as farmers overall tend to be slightly risk averse (Abadi Ghadim et al. 2005, Bardsley and Harris 1987, Binswanger 1980, Bond and Wonder 1980, Pringle 2012), communication among farmers is also a factor (Kutter et al. 2011). Abadi and Pannell (1999) noted that a farmer is more likely to adopt a new technology if he or she is near to and frequently contacts an adopter. It has been shown that a knowledge gap, and perhaps a level of mistrust, exists between farmers and researchers (Cook and

Bramley 1998, Lamb et al. 2008). Lindner (1987) noted that a producer's conclusion to adopt or reject an innovation is determined by his/her "self-interest" and perceived benefits. This concept of innovation can be extended to PV as a range of technologies.

In addition to these obstacles, the existence of a flat pay-off function for agricultural decision making is also a major impediment to PV implementation. Pannell (2006) showed the existence of a flat payoff curve in decision-making analysis, indicating that "even large deviations from optimal decisions make little difference to the payoff." The repercussions of this show:

> "a. decision makers often have a wide margin for error in their production planning decisions, and flexibility to pursue factors not considered in the calculation of payoffs; b. optimizing techniques are sometimes of limited practical relevance for decision support; c. the value of information used to refine management decisions is often low; and d. the benefits of using "precision farming" technologies to adjust production input levels are often low" (Pannell 2006).

With this slow adoption rate, a number of challenges are facing PV implementation. Most importantly is the lack of economic analysis and in this instance technology has outpaced relevant economic analysis and researchers have failed to adequately demonstrate the benefits of PA (PV) (Lowell 2004, Zhang et al. 2002). This is discussed further in the following section (Previous economic and econometric analysis of Precision Agriculture/Viticulture).

It is important to note that the purpose of Precision Agriculture (Viticulture) is to generate more informed management decisions. Lowenberg-DeBoer and Boehjle (1996) claimed that information from PA leads to more informed decision making which can potentially generate benefits. However, information alone (without appropriate ground truthing and implementation) is not valuable. "Precision Agriculture is not a single technique but a range of methodologies which aim to increase the precision of agricultural management" (Cook and Bramley 1998). Figure 2.3 is a reproduced diagram from Cook and Bramley (1998) that describes that continuous information processing cycle of observation, interpretation, evaluation, and implementation. Precision Agriculture offers the tools to more accurately, efficiently, and economically manage variation (Arnó et al. 2009, Proffitt et al. 2006, Iland et al. 2011), however, information is of no real value on its own (Cook and Bramley 1998, Lowenberg-DeBoer and Boehjle 1996, Pierce and Nowak 1999).

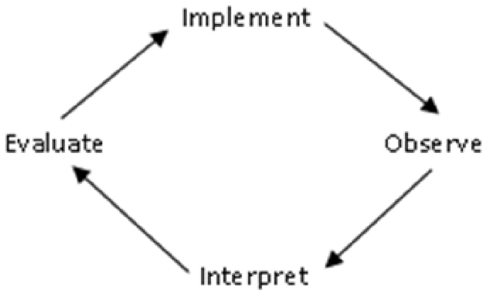


Figure 2.3 Precision Agriculture information processing diagram. Reproduced from Cook and Bramley (1998), it shows the Precision Agriculture continual cycle for information processing to generate more informed management decisions.

The implications of this cumulative knowledge highlight a need for a traceable view of quality. The shortcomings of econometric modellings are evidenced in the slow adoption rate of technology. Farmers want to see actual evidence of success before adoption (Lamb et al. 2008). As every parcel of land is unique, so too will be the benefits of PV application (Robertson et al. 2007).

Previous economic and econometric analysis of Precision Agriculture/Viticulture

One of the main reasons for this slow PA/PV adoption rate is a lack of corresponding agronomic research into the benefits or otherwise of Precision Viticulture. However, some information does exist. For example, Godwin et al. (2003) found that interactions between parcel size, spatial variability, yield, and cost of PA technologies determine the overall benefit of PA. However, as every parcel of land is different, quantification of economic benefits of PA has proven difficult (Lowenberg-DeBoer 2003, Lambert and Lowenberg-DeBoer 2000, Godwin et al. 2003, Lowell 2004). In a comprehensive study, Lambert and Lowenberg-DeBoer (2000), found that out of 108 studies examining profitability of PA, 63% saw a positive net return and 11% experienced negative net returns. The other 26% showed mixed results.

Agronomic analysis of Precision Agriculture has been explored more comprehensively than Precision Viticulture. Table 2.1 is a summary of important papers from the PA literature.

Table 2.1 Prominent papers from the Precision Agriculture economics literature are listed along with relevant overviews, methodologies, and findings.

Paper	Overview	Economic Analysis	Key Findings and Conclusions
Robertson et al. 2007	Gross margin analysis of required return of PA to make it economically viable	Used investment analysis to describe how much benefit is required of PA technology	Barriers to adoption are: lack of economic evidence, technical support, equipment compatibility, and training for farmers and consultants.
Lowenberg-DeBoer and Boehlje 1996	Partial budgeting studies of precision farming	Used partial budgeting and cost analysis to examine economic effects of PA techniques and technologies	Lack of crop response information devalued partial budgeting. Profitability of PA is hard to measure, could be improved by incorporating more "data in more complete systems."
Godwin et al. 2003	Cost benefit analysis of PA	Economic costs were evaluated based on area of farm with benefit potential. Capital and associated costs were traced for yield and spatial application of fertilizers and seeds	1. Benefits of VRA of nitrogen outweigh costs for cereal farms greater than 75 ha for systems costing Great British Pound (GBP) 4500. "2. This area increases in size in proportion to capital cost." "3. Environmental benefits should improve long term sustainability" of farm. 4. Historical yield records are not accurate basis for variable application of nitrogen decision making.
Godwin et al. 2003	"Cost benefit analysis of spatial nitrogen application compared to costs of precision farming technology"	Cost benefit analysis of potential return achieved through PA	Benefits of PA outweigh costs. However, return is variable dependent on size and inherent variability of farm.

Table 2.1 (continued)

Paper	Overview	Economic Analysis	Key Findings and Conclusions
Brennen et al. 2007	Economic analysis of VRA	Continuous linear function comparing yield and protein. Model was compared with observed values. Includes only OPEX costs in gross margin analysis	VRA is economically viable and indicates higher return than uniform management. "However, recognises existence of flat pay-off curve near maximum."
Pannell 2006	Overview of flat payoff functions in economic decision making	Examples and analysis show flat payoff curve near the maximum of the function	In the agricultural decision making process, "a large margin of error is possible without incurring financial hardship." This suggests that PA (PV) technologies may have a wide margin of error with regard to return on investment.
Robertson et al. 2012	Survey of national and regional adoption of VR	Uses adoption theory to analyse constraints	Subjects indicated a belief in economic return of VRA. "Constraints to adoption were technical issues with equipment and software access to service provision and the incompatibility of equipment with existing farm operations."

The main methodologies of most of these studies were cost-benefit analysis (CBA) and gross margin analysis (Table 2.1). However, no study included full cost analysis incorporating operating, overhead, and capital costs. Brennen et al. (2007) discussed the importance of including total costs (capital, overheads, and operating) to fully evaluate benefits of PA in an economic analysis.

Past econometric modelling has demonstrated positive benefits of Precision Agriculture at a limited scale, but lacks the fundamental grounding of a full cost analysis. These models have had limited success in demonstrating significant benefits from adoption of PA (Anselin 2002, Florax et al. 2002). However, farmers are more likely to adopt PA technologies after witnessing successful trials and examples (Abadi and Pannell 1999). Analysis derived from econometric models also benefits from *ex-post* (based on observed results) information such as growing season weather (Anselin et al. 2004, Brennen et al 2007, Bullock and Bullock 2000). This knowledge is unrealistic and does not adequately portray the *ex-ante* (based on forecasts) decision-making situation. This research is the first of its kind in viticulture to attribute key management practices that determine quality of fruit and the costs associated with doing so.

Conceptual framework of analysis of impact of Precision Viticulture as an innovation

Investors and owners of vineyards, like any other profit maximising decision makers, allocate their funds to their production systems in order to finance not only annual operating inputs such as labour, fertilizer, pesticides, and fuel, but capital assets such as land, machinery, buildings, and technology.

At the core of economic evaluation of adoption of innovations is the decision problem in the context of marginal analysis of the “with and the without scenario” concerning the innovation. First the grower has to be considered to be an economic agent capable of making independent decisions after investigating the benefits and costs of the innovation such that she chooses the innovation if it is in her “best interest”. Through this assumption we can assert that the grower wants to improve his or her welfare by having a more profitable farm. It is acknowledged that profit is only one motive, but it is a strong one (Abadi and Pannell 1999, Lindner 1987).

A benefit cost analysis (BCA) enables estimation of the net benefits of investing a firm's resources (funds, lands, labour) in a specific potential project or innovation. It then allows the net benefits of the proposed project to be compared with the benefits of an existing system (Business As Usual scenario: BAU) or a hypothetical project that would be displaced if the project or innovation being assessed was to be adopted and implemented. The displaced project or the BAU is often referred to the counter-factual referring to continued use of an existing system of production. Note that the counter-factual or BAU is not changeless through time. It may be that in the BAU some elements of the production may change over time as the resources or production unit may be subject to declining productivity (Boardman et al. 2006).

Typically there are several steps in BCA. Broadly it starts with specifying the set of alternative projects (i.e. adoption of an innovation) that are to be evaluated. This requires decisions to be made on the relevant benefits and costs to be accounted for in the analysis. Then it is necessary to catalogue and categorise the impacts arising out of the "with the project incorporating an innovation" and the without the innovation scenario (BUA or *status quo*), as they would occur over the life of the project. Next the analyst must select the indicators and their units that will be used to measure impact of alternatives. Then it is necessary to predict the magnitude of the impacts over the life of the project. What follows is an estimate of the monetary values of all the impacts. Then the benefits and the costs are "discounted" to obtain their present values. The net present value of each of the alternative scenarios is then computed. Sensitivity analysis must be performed on the key drivers or assumptions that are likely to cause the outcome of evaluation to change significantly. The outcome of the analysis would inform a recommendation that is made to the decision maker and stakeholders (Boardman et al. 2006).

Adoption of an innovation, such as PV, in the context of the production system of a firm, can be viewed as a decision concerning marginal adjustment in the firms' production systems. As such the analyst needs to account for the motivating drivers for adoption. Why adopt? What production problem does it solve? Does the innovation reduce cost of production, increase the quality of the product and hence its price, or does it increase yield or a combination of these three drivers? At the core of economic analysis is the notion of gross margin (GM) of an enterprise. On a vineyard, GM is a function of yield (Y) of the commodity being produced (i.e. grapes), price (P) of the commodity produced, and costs of production (C) of the commodity. Therefore, GM = Y*P - C.

It may be simply assumed that the grower, often the business manager, is wishing to maximise his or her profit margin in order to improve the welfare of his or her family (stakeholders/shareholders). In other words the production system as a whole (the vineyard) can be seen as a firm. If this is accepted, as commonly done so for farms and vineyards in developed nations, then it is possible to use the theory of the firm and its attendant methodologies of which marginal analysis is one (Kay et al 2012, Layton et al 2011).

The “with and without analysis” is different to an analysis of before and after the adoption of an innovation or the implementation of change on a business. In the without innovation scenario or the non-adoption scenario, things do not remain static at the firm level. Over time, the production system changes and the grower can adopt other things or find alternatives to their production problem. In addition the conditions of natural resources and capital assets such as building and machinery may deteriorate at various rates. The key is to understand and account for the “counterfactual” or the otherwise scenario of non-adoption.

This marginal analysis (i.e. analysis of a change in the production system) leads logically to the use of the partial budgeting technique. Since many innovations that require significant investment last longer than one season, this partial budgeting exercise then becomes a capital budgeting exercise. This type of analysis requires the use of discounted cashflow analysis technique. This is one component of the calculation of the net present value (NPV) of the “with and the without innovation scenario” and then look at return on investment (ROI) to the innovation.

Analysis of short term versus long term investments requires a different method because of the difference in the timing of the expenses and their attendant returns. Investing in innovations impacts the firm’s cash flows over several seasons. This is similar to capital assets with an extended life span of a few years to multiple decades which must be invested upfront requiring large initial expenses. The revenues generated by these initial investments are usually spread over several seasons in the future.

There are other reasons for careful analysis of capital investments because decisions about long-lasting assets are difficult to adjust on an annual basis. It is more difficult to change a capital investment decision once the asset is purchased or implemented. Therefore, more time and more accurate analytical techniques should be used when making these decisions.

Capital budgeting and partial budgeting can be used to analyse these investments by looking at changes in expenses and revenues over several seasons. These budgets must include discounted cashflows in order to account for the time value of money. To do so implies inclusion of an opportunity cost for the funds invested in inputs with short term outcomes as well as those with long term consequences for the production system.

While time may be of minor importance when analysing annual operating inputs, it becomes of major importance for assets such as land, buildings and technological innovations. They usually require a large one-off upfront investment, and the expenses and revenues generated from them will usually occur in different periods, often irregularly spread over many seasons. Analysis of these capital investments or the adoption of innovations requires careful consideration of the size and timing of the attendant cash flows (Kay et al 2012).

Key Elements of Investment Analysis

Investment analysis, or capital budgeting is used to assess the profitability and cash flow of an investment or innovations. Furthermore, this technique is used to compare the profitability and cash flow of two or more alternative investments or innovations. Such an analysis requires: the initial cost of the investment; the annual cash expenses and revenues associated with the investment; the terminal or salvage value of the investment; and the interest or discount rate used to account for time value of funds investment.

Time Value of Money

There are many reasons why money received today is worth more than a dollar at some future date. The first is that a dollar received today can be invested to earn interest and will therefore increase to a dollar plus interest by the future date. In other words, the interest represents the opportunity cost of receiving the dollar in the future rather than now. This is often termed the investment explanation of the time value of money. The second reason is that money can purchase goods and services for immediate consumption. People often prefer to have the funds for current consumption which results in reward or utility sooner rather than later. Risk is the third reason for preferring the dollar now rather than later. Some unforeseen circumstance could prevent a firm or an individual from collecting it in the future. Fourthly, inflation in the cost of goods and services may diminish what a dollar can buy in the future compared to today (Kay et al 2012).

Marginal Analysis of Innovations

Growers, as decision makers in a business context, often have to evaluate prospective innovations or proposed adjustments to the operations of their production system. These decisions often affect revenue and expenses of the whole property. The analysis of the profit potential of these partial changes in the overall whole-farm plan requires the use of partial budgeting technique. It enables assessment of the consequences of changes involving interactions between several aspects of a production system. In essence, partial budgeting, which usually incorporates discounted cashflow modelling, is a form of marginal analysis as far as the theory of the firm is concerned (Layton et al 2011).

If conducting partial budgeting as a marginal analysis exercise, it is necessary to identify all physical changes that are likely to occur as a consequence of the proposed changes to the farm operations which may include adoption of an innovation such as PV. These changes must be assigned a monetary value. A number of alternatives may be assessed with partial budgeting. The key data and information necessary are the costs and revenues arising from the changes associated if the proposed alternatives are put in place (if the innovation is adopted). These include: the new or additional costs that are likely to be incurred; the costs in the counter factual scenario or the business as usual scenario that may be reduced or eliminated if innovation is implemented; new or additional revenues that would be received as a consequence of change; and the revenue that may be lost or reduced (foregone) if adoption was to proceed (Kay et al 2012).

In conducting analysis of marginal impact of innovations such as PV it is important to consider changes to fixed costs that may occur as a consequence of adoption and implementation of the PV technologies and associated systems. Even though in farming systems in the short run fixed costs often do not change, they do change in long run when the production system is altered significantly. Through adoption of the innovation, it often becomes necessary to purchase or sell some capital assets which in the long-run change the fixed costs over the life of the project. Therefore, accounting for and estimating the fixed costs that are likely to occur because of adoption becomes an important component of analysis in partial budgeting.

Levelised Cost and the role of Precision Viticulture to enhance the decision making process

At this stage, it is important to step back and re-examine the role of PV technologies. Precision Viticulture is not a value adding input, but rather a decision enhancing tool with the potential to generate positive economic and environmental benefits. The question to ask is not how much economic benefit will PV technologies generate, but rather, what is the marginal cost of added information to the decision-making process, and at what point does a farmer achieve a relative maximum? At what point does one more unit of information not return a positive net benefit?

Instead of pursuing the typical methodologies of past research as outlined in this literature review, this thesis encourages the reader to step back and assess the current situation.

- The typical hedonic regressions used in wine economic analysis repeatedly generate contradictory results (Miller et al. 2007).
- The generation of a dollar value/ha net benefit of Precision Viticulture (Agriculture) has been shown to be infeasible due to the unique spatial variations inherent to every parcel of land (Cook and Bramley 2001, Lowell 2004, Zhang et al. 2002).
- The slow adoption rate of technology can be summarised simply as farmers wanting to see actual evidence of success before adoption (Adrian et al. 2005, Ancev et al. 2004, Baumgart-Getz et al. 2012, Lamb et al. 2008, Lowenberg-DeBoer 2003).

- And finally, there is no traceable view of quality (Fraser 2003, Jackson 2008). The lens, through which researchers have examined these issues in the past, does not appear to be yielding much overall benefit.

Instead of making assumptions about market dynamics, overall information, and extrinsic and intrinsic factors, this research takes a pragmatic approach and looks at quality as a differential of price through a levelised cost approach (Chapter 9). This technique, a tool commonly used in the economic analysis of renewable energies (Kasmioui and Ceulemans 2012), involves the creation of a total cost model - incorporating all costs including operating, overhead, and capital costs incurred throughout a project lifetime. This approach uses the pricing assumption common to agricultural commodities:

$$\text{Price} = \text{Cost} + \text{Profit Margin}$$

Any discrepancy between modelled price and actual price can be classified as a quality dividend. This research does not attempt to further segregate quality into intrinsic and extrinsic factors, but rather seeks to isolate a numerical value for quality. For the first time, quality can be explained as a dollar value and therefore be compared on a universally objective scale.

At this point, Precision Viticulture is introduced to the model as a step-wise adoption process. It breaks down cost of PV technologies into 3 steps: data acquisition, ground truthing, and implementation. Taking into account size and probability of received market price, optimal PV adoption for individual producers can be assessed through these “with and without scenarios” analyses.

This unique view of quality and cost offers the framework for future analysis to be conducted. It is grounded in data and driven by realistic commercial numbers and information; by nature it is traceable and transparent. Due to these fundamental elements, the applications of this model translate across the industry.

Chapter 3 The role of Precision Viticulture in distinguishing vigour zones in three Cabernet Sauvignon vineyards in Western Australia

Introduction

Variation in grapevine vigour, within a site, is an inherent and comparatively stable aspect of grape production. The spatial and temporal stability of vine vigour allows the manager to derive management zones with a high level of confidence (Arnó et al. 2005, Bramley 2007, Bramley 2001, Bramley and Hamilton 2004, Bramley and Hamilton 2007, Tisseyre et al. 2008). Bramley and Hamilton (2004) assessed spatial variability in 3 vineyards across three climatically-diverse wine regions (Coonawarra, Clare Valley, and Sunraysia). This study demonstrated that while high variability did occur, *k*-means clustering and probability analysis indicated "temporal stability in the patterns of yield variation…even though there were substantial year to year differences in mean annual yield" (Bramley and Hamilton 2004). The stability was also shown to extend to "quality indices," namely pH, titratable acidity (TA), total soluble solids (TSS), phenolics, colour, and berry weight. However, these findings were limited by the fact that pH, TA, and TSS were not significantly different across all 3 vintages involved in the study. Tisseyre et al. (2008) generally supported these findings. In a seven year trial on a dry-farmed Syrah vineyard in France, it was determined that yield, pruning weight, and canopy size exhibited greater temporal stability than did pH, TA, or TSS. However, this study utilised only 30 sampling points throughout the vineyard that were chosen based on soil type. Additionally, in a study conducted in Spain, relationships were found between within-field variability, topographical, soil characteristics, and yield (though variable) across vintages (Arnó et al. 2005). Bramley (2010) noted "the overwhelming evidence from contrasting vineyards from around the world is that, even though the range of within-vineyard variation is typically of the order of 10-fold (i.e. yield), within-vineyard patterns of spatial variability in grape yield and vine vigour are temporally stable."

Previous studies have shown that high vigour vines tend to yield fruit of a lesser quality compared to fruit derived from low vigour vines (Bramley et al. 2005, Johnson et al. 2001, Proffitt et al. 2010). Proffitt and Pearse (2004) found that (Cabernet Sauvignon) fruit sourced from low vigour vines received higher prices than did fruit from high vigour vines. In one of the most comprehensive studies, Bramley et al. (2011) found an overall relationship between vine vigour zones and fruit and wine quality, attempting to relate volatile compounds and sensory traits. A strong relationship has been derived between these volatile compounds and vigour (for example, Cortell et al. 2005 in Pinot Noir, Bramley et al. 2011 in Cabernet Sauvignon, and Wilkinson et al. 2006 in Cabernet Sauvignon). While vigour and the quality of fruit and wine derived from an individual block can change on an annual basis (Bramley and Proffitt 1999, Bramley 2005) the relative patterns of within-block variation are stable and can justify differential management (Proffitt et al. 2006).

Treating a vineyard block as a single management unit has been demonstrated to be a potentially inefficient approach to vineyard management and profitability (Bramley 2005, Bramley et al 2011, Cook and Bramley 1998). Evidence for this includes unnecessary input costs, and potential loss of revenue due to a lack of identification of a superior product (Proffitt and Bramley 2010). For example, varying vigour zones within a block can yield inconsistent quality throughout the vineyard (Bramley and Hamilton 2004, Bramley and Lamb 2003, Proffitt et al. 2006). When selectively harvested, the different quality fruit could potentially receive different prices with the potential for a higher net return (Bramley et al. 2011, Bramley et al. 2005, Scollary et al. 2008). As within block vigour variation is unique to every site, it is important for a grower/manager to understand the cost/benefit analysis of each technology as well as the total economic effects as they pertain to his/her site and requirements.

Precision Viticulture (as discussed in Bramley 2001), is a specific form of Precision Agriculture, that is a cyclical process of observation, interpretation, evaluation, and implementation (Cook and Bramley 1998). It involves an in-depth process of vineyard management that uses data derived from remotely sensed technologies (observation) which is often processed through Geographical Information Systems (GIS) into maps (interpretation). The maps so generated need to be ground-truthed. Ground-truthing (evaluation) is a form of data verification that can vary in the level of involvement from visual calibration to acquiring manual measurements (for example, trunk circumference); It is thus an important component of PV which contributes to effectively manage a unit of land

(Iland et al. 2011, Proffitt et al. 2006). Once the data have been collected, processed into a map, and evaluated for accuracy, then an informed management decision can be made (implementation) (Bramley et al. 2005, Bramley 2010). The process repeats itself, enacting a continuous cycle of information collection, interpretation, evaluation, and implementation (Cook and Bramley 1998).

Precision Viticulture (PV) enables a higher resolution of vineyard management than do standard practices (Arnó et al. 2005, Arnó et al. 2009, Johnson et al. 2001, Proffitt and Malcolm 2005). Through technologies like remote sensing, zones of comparable grapevine vigour within a vineyard can be identified. Once these zones are identified, further analysis is required to decide if the vigour differences are large enough to merit differential management. Precision Viticulture adoption and implementation is dependent on availability of a proven and cost effective technology (Bramley et al. 2005, Proffitt and Pearse 2004, Proffitt et al. 2006, Proffitt and Bramley 2010).

The use of PV in differential management strategies has the potential to change farming methodologies and viticultural practices (Bramley et al. 2005, Proffitt and Bramley 2010), hence the need for this study on costs and benefits. In the past, manually derived measurements of trunk circumference, canopy surface area, and pruning weights) have been used to delineate within block differences in a vineyard (Bramley et al. 2005). Generally, these techniques require more input time to acquire and process the data compared with acquiring and processing data by remote sensing. Therefore, remotely sensed data, such as PCD imagery, along with a host of other technologies, may offer a more cost effective and precise approach (Bramley et al. 2010, Bramley et al. 2011, Proffitt and Malcolm 2005). Plant cell density is a vegetation index derived from the ratio of reflected infrared to red light (near infrared red (NIR)/ red) (Dobrowski et al. 2003, Proffitt et al. 2006). The remotely sensed data allows more robust analysis of variables such as indices of vine vigour and aids in the subdivision of blocks into different zones based on similarity of viticulturally significant features (Lamb et al. 2001, Lamb et al. 2002, Lamb et al. 2004, Proffitt and Malcolm 2005, Proffitt and Bramley 2010). High density spatial information, such as PCD imagery, is being used in vineyards with greater frequency (Bramley 2005, Cortell et al. 2005, Proffitt et al. 2005). However, as noted previously, overall adoption is low, and therefore there is potential for an increase in use (Cook and Bramley 1998). Collectively, these studies demonstrate that an understanding of the inherent differences within a block is crucial to maximizing profit in a vineyard (Anselin et al. 2004, Bramley 2005, Bullock et al. 2000) and PV technologies offer a precise and potentially cost effective methodology of acquiring spatial information and using the data to make more informed, targeted management decisions (Proffitt et al. 2006).

One of the limitations of using GIS and spatial data is that while patterns are often visually apparent, many studies have failed to generate statistically significant relationships between parameters. Studies have looked at the relationship between PCD imagery and on the ground measures such as trunk circumference, canopy surface area and pruning weight (Bramley et al. 2010, Bramley et al. 2011, Proffitt and Malcolm 2005, Dobrowski et al. 2003). Hall et al. (2008) found that another vegetation index (Normalised Difference Vegetation Index, NDVI) and planimetric canopy area were significantly associated. Similarly, Johnson et al. (2003) found a correlation between NDVI and leaf area index. Proffitt and Malcolm (2005) also found a linear relationship between PCD and trunk circumference and canopy surface area variables; however sampling size was less than 50 vines. Also, as target vines used in this study were chosen based on PCD values, their methodology is likely to have included a sampling bias. It has been shown that the relationship between average bunch weight and PCD is inconsistent, though this is to be expected as vine training, pruning tactics, and weather have shown to be of greater influence (Proffitt and Malcolm 2005).

Previous research has attempted to quantify the relationship between PCD and berry chemistry values, most commonly pH, TS, and TSS. In a 4 year study, Bramley (2005) examined berry chemistry indices (pH, TA, TSS, colour, and phenolics) at two different Cabernet Sauvignon sites in Sunraysia and Coonawarra (respectively). Data were collected at the Sunraysia site over three vintages. Mean differences between berry chemistry indices of low and high vigour zone fruit at this site were minimal. Differences in pH values between the two zones ranged from 0.01 to 0.07, differences in TA ranged from 0.01 to 0.19 g/L, and differences in Baumé (a measure of specific gravity) ranged from 0 to 0.1 °Baumé. Data from the Coonawarra site was collected over four vintages and demonstrated marginally greater mean differences between the low and high vigour zone fruit.

Differences in pH values at this site ranged from 0.19 to 0.21, differences in TA ranged from 0.25 to 0.68 g/L, and differences in Baumé ranged from 0.1 to 0.6 °Baumé. Tisseyre et al. (2008) found that berry chemistry indices are less temporally stable than more robust vine measures like canopy surface area and pruning weight. This was further supported by McClymont et al. (2012), who found that Shiraz berry quality attributes (TSS, pH, TA, and anthocyanins) were seasonally different between management zones determined by Normalised Difference Vegetation Index (NDVI) - another vegetation index commonly used in PV technologies to distinguish between vigour zones in a vineyard.

This research examined the different methods of management unit demarcation within a Cabernet Sauvignon block and determined the economic effect and pertinence of remotely sensed data (PV technology, specifically PCD) vs manually sampled data collection methods in vineyards of varying sizes. It also investigated the relationship between PCD, berry chemistry indices (pH, titratable acidity, total soluble solids), and average bunch weight. It is hypothesized that PCD will share a positive linear relationship with trunk circumference and canopy surface area.

Methodology

This experiment was designed to compare three different methodologies of assessing variation in grapevine vigour, each of which differed in the level of complexity required for collection of the primary data. These methods were:

a) data acquisition via manual sampling of grapevine trunks and canopy surface area and
b) aerial assessment of plant cell density by the acquisition of reflectance data at 0.5 m resolution.

The experiment consisted of multiple measurements of vine vigour undertaken at a high sampling intensity across a spatially variable environment. These measurements were then compared with the remotely sensed data (PCD). The experiment was repeated across three vineyards of different sizes. Furthermore, the experiment sought to examine the relationships between vine vigour, grape bunch weight and grape chemistry, and examined costs of data acquisition of each treatment.

Sites

Three vineyards were identified from three climatically distinct wine regions (GI's) of Western Australia: Geographe, Margaret River and Great Southern. Each site was planted to Cabernet Sauvignon (Houghton clone) with vine spacing of 2.5 metres and row spacing of 3 metres. The sites ranged in size from 0.27 ha to 6.3 ha. PCD, trunk circumference, and canopy surface area data were collected from all three sites. At two of the sites, Geographe and Great Southern, further data collection was undertaken, which allowed the determination of some berry chemistry indices including pH, titratable acidity (TA), and total soluble solids (TSS) in addition to bunch weight. Vines at both the Margaret River and Geographe sites were spur pruned, and vines at the Great Southern site were cane pruned. Shoot thinning occurred at each site very early in the growing season (October 2012). Hedging at each site occurred at véraison; however, it was timed to be undertaken after canopy surface area and PCD measurements were collected (February 2013). Leaf plucking was undertaken at the Margaret River and Great Southern sites, and again, this occurred after PCD and canopy surface area measurements were collected (February 2013). No fruit thinning occurred at any of the sites.

Geographe:

This site is the smallest and northernmost vineyard, 0.27 ha, and is located at Latitude -33.413086, Longitude 115.825583. The average rainfall for the region is 730 mm, the mean daily maximum temperature from December to March ranges from 23 to 30°C, and the mean daily minimum temperature ranges from 13 to 16°C. The vines are spur pruned, the canopy is managed as a vertical shoot position (VSP) system, and the block is managed uniformly. Rows are predominantly oriented east to west; however, the block is situated on a hill so some consideration has been made to accommodate machinery. This site was manually harvested on 5 March 2013.

Margaret River:

This is the largest site used in this study, 6.3 ha, and is located at Latitude -34.0590227, Longitude 115.1399963. The average rainfall for the region is 1013 mm, the mean daily maximum temperature from December to March ranges from 25 to 28°C, and the mean daily minimum temperature ranges from 12 to 15°C. The vines are spur pruned and the canopy is managed as a VSP system. This site had been acquiring imagery for 6 years and had previously implemented a differential management strategy, where the low vigour zone (top of the slope) receives twice as many inputs (irrigation, fertiliser, compost) as the high vigour zone (bottom of the slope). Rows are oriented east to west. Vigour zones had previously been determined through PCD imagery and on-the-ground visual calibration by the site's viticulturist. This site was mechanically harvested over two days (3-4 April 2013). The reason for this extended harvest was due to mechanical issues with the harvester.

Great Southern:

This site is 1.66 ha, and is the southernmost site used in this study, located at Latitude -34.6354678, Longitude 117.407455. The average rainfall for the region is 726 mm, the mean daily maximum temperature from December to March ranges from 20 to 26°C, and the mean daily minimum temperature ranges from 9 to 13°C. The vines at this site are cane pruned and the canopy is managed as a VSP system. This site receives no irrigation and rows are orientated following the contour of the landscape. In the past, this block had received differential management treatment with regard to compost application with the low vigour zone receiving compost, but the high vigour zone receiving none. However, in the year of this study, no differential management occurred with regard to inputs. While no PCD imagery acquisition had been acquired prior to this study, low and high vigour zones had been determined by the site's viticulturist and winemaker based on visual assessment of vine canopy and vigour in addition to grape berry flavour profiles at harvest. Each year, the low and high vigour zones have been separated midway down the hill, dividing the block into 2 (almost) equal zones. This site was manually harvested on 9 April 2013.

Mapping each site

For each vineyard, a differential GPS (dGPS) was used to initially map the boundaries of the planted area and the ends of each row. A sample grid was created by selecting every fourth fruit-bearing vine (determined linearly along each row). These identified vines were labelled and georeferenced with the dGPS. These vines became target vines for direct measurements and for the remotely sensed PCD data.

Trunk circumference

Trunk circumference measurements were recorded (to the nearest mm) at 30 cm above ground using a flexible measuring tape. Due to the large size and intensive grid sampling strategy employed, measurements were recorded at the Margaret River site between 18 and 25 September 2012. The Great Southern measurements were taken on 17 September 2012. As it was the final site to agree to collaborate on this research, trunk circumference measurements were recorded at the Geographe site on 15 October 2012.

Canopy surface area

Canopy surface area measurements were carried out on all target vines at each site at véraison (January 2013), the stage of the growing season where the canopy of the vine is at its maximum size. Measurements at the Geographe site were recorded on 8 January 2013. Due to the large size and intensive grid sampling strategy, measurements at the Margaret River site were taken between 15 and 19 January 2013. Measurements at the Great Southern site were recorded 25 January 2013. It is noted that canopy surface area measurements, as opposed to canopy area measurements (only the top of the canopy), were undertaken for reasons explained in the following section (Plant Cell Density). Length, width, and height measurements of the vine’s canopy were taken from the crown of the vine and multiplied to obtain the canopy surface area. For vines of asymmetrical nature (with a high degree of variation from the crown to the outer extremities) multiple measurements were undertaken along the cordon and averaged. Each target vine (the same vines as the ones used for trunk circumference measurements) was measured throughout the entire block according to the sampling methodology.

Plant Cell Density

Remote sensing using light aircraft was arranged within a maximum of 2 weeks of the canopy surface area measurements being collected, before any hedging or leaf plucking was undertaken throughout the vineyard, and involved the acquisition of light reflectance data using a multispectral camera, commonly known as Digital Multi-Spectral Imagery (DMSI).

This equipment has a passive sensor (does not have its own light source), and is therefore influenced by external conditions at the time (sun angle, clouds, atmospheric conditions). For this reason, it is difficult to compare data captured at different times or between seasons, and it is imperative that PCD data be ground-truthed by visual means for calibration. It is possible to have different PCD values between years. For a given target the pixel values will differ depending on the amount of radiation returning to the sensor which is governed principally by target illumination conditions (cloud cover, sun angle, shadow, etc.). The only way to calibrate imagery is to position targets of known reflectance on the ground prior to the flight. So, for each of the three sites and for each season, the high vigour zones should have higher PCD values relative to the low vigour sites. And the zones at each site should be reasonably consistent between the 2 years. Light reflectance data is captured in 4 separate wavebands (blue, green, red, and near infrared) at 0.5 m resolution (industry standard). The data are processed to remove all non-vine data so only vine canopy reflectance data are included in the imagery. PCD values are determined as the ratio of near infrared to red wavelength values.

As noted previously, canopy management practices (hedging and leaf plucking) were undertaken after imagery was collected. Additionally, it should be noted that the reflectance signals from which the PCD index is derived do not come exclusively from a thin, flat section of the canopy. So, although most of the signal may come from the top of the canopy, other parts of the canopy contribute to the reflectance received by the sensors. For this reason, canopy surface area, as opposed to canopy area, measurements were undertaken. Bramley et al. (2011) demonstrated the utility of airborne imagery when vine canopies were under VSP system.

Data acquisition times were as follows: Geographe (17 January 2013), Margaret River (21 January 2013), and Great Southern (8 February 2013). Initial data were obtained in the form of raw meta data, maps and raster files of semi-processed data. PCD imagery was ground-truthed by visual calibration, in addition to comparison of on-the-ground measures of vigour. Subsequently, the data were analysed by calculating average PCD values per vine. This was calculated in ArcGIS by firstly creating a buffer with a 0.5 meter radius around the centre of every target vine. Then the Zonal Statistics tool was used to determine an average of all PCD values within the buffer zone of every target vine. This value was used in subsequent statistical analysis to examine what, if any, relationship exists between PCD and the other manually sampled variables (CSA and TC).

Berry chemistry

Berry chemistry of fruit on target vines was assessed 1 week prior to harvest. For each target vine, three bunches from different locations in the canopy were collected. The sample clusters from each vine were kept separate in a cool room (4°C) in labelled plastic bags, and then crushed (within 72 hours) inside the bag to obtain a representative juice sample. Each juice sample was assessed for pH, titratable acidity (TA), and total soluble solids (TSS) following the protocol of Iland et al. (2004).

Bunch weight

Target vines were harvested individually. The clusters from each vine were counted and weighed with a portable scale. Average bunch weight per vine was then calculated by dividing the total weight of the harvested fruit by the number of clusters.

Input costs

The input costs associated with collecting the trunk circumference and canopy surface area were recorded for both of the sampling techniques. Input costs include time and labour necessary to acquire data and process in GIS software. A simple cost analysis was performed to determine cost/ha of manually sampled data. This was compared with the costs of PCD data acquisition.

Data analysis

Data were entered into Microsoft Excel and then formatted in ArcGIS v 10.2. Maps for each parameter were generated following the protocol of Bramley and Williams (2001).

Statistical analysis of data were performed in SPSS v 22 (IBM Statistics). Linear regression analysis was performed to determine if a significant relationship existed between PCD and any of the other variables (trunk circumference, canopy surface area, pH, TA, TSS, and average bunch weight) to a significance level of $p<0.05$.

To determine the minimum number of manual sampling observations necessary to generate a map which is able to distinguish between two vigour zones (high and low), the full data set (25% population sampling) was reduced at random in an iterative process. Each iteration was then uploaded in ArcGIS and a map produced. The map was visually assessed for its potential usefulness for vineyard management decision-making. To meet the criteria, a map had to be able to clearly distinguish between the low and high vine vigour zones. This process was repeated until the map that was created no longer generated an output useful in distinguishing between vigour zones.

Results

The results from this experiment demonstrated a statistically significant yet relatively weak relationship between grapevine vigour measurements recorded via ground-based manual sampling and aerial remote sensing. Significant but weak relationships (R^2 varied from 0.16 to 0.31) were described between remotely sensed data (PCD), berry chemistry indices and average bunch weight. However, when the experiment was duplicated across different sites the relationships between parameters were not always repeatable and when significant relationships were described by linear regression, there were substantial differences in regression values among sites.

While statistically significant relationships were not consistent across all measurements, visual analysis of GIS maps for spatial vigour patterns demonstrated a relationship between some of the measured parameters. For the benefit of the reader, maps are included (Figure 3.4, Figure 3.5, Figure 3.6) as part of this section. Furthermore, cost analysis of aerial data acquisition (PCD) verses manual sampling techniques indicates the economic benefits of remote sensing.

Plant cell density, trunk circumference, and canopy surface area

Results from the Great Southern site demonstrated positive, linear relationships between PCD and trunk circumference and canopy surface area with coefficient of determination values (R^2) values of 0.21 and 0.17 respectively based on 640 measurements of each parameter (Figure 3.3). When the experiment was duplicated at the Margaret River site (n=1592), this finding was again supported (Figure 3.2). At that site the regression analysis described a similar statistically significant R^2 value for the relationship between PCD and canopy surface area (0.19), but a relatively weak (statistically significant) R^2 value for trunk circumference (0.06). The only site not to support these relationships was the Geographe site (n=150) (Figure 3.1). However, at this site the level of variance in the key parameters (PCD, trunk circumference, and canopy surface area) was similar.

Further investigation of the effects of size was conducted by comparing trunk circumference with canopy surface area. These are both manual sampling measurements collected on the ground which measure vigour between seasons (trunk circumference) and within-season (canopy surface area). At both the Margaret River and the Great Southern sites, a statistically significant, yet relatively weak, direct relationship between these variables was demonstrated (R^2= 0.03, 0.13 respectively). However, data at the Geographe site did not support this.

Plant cell density, berry chemistry, and average bunch weight

The most consistent relationships between PCD and berry chemistry (Figure 3.3) were observed at the Great Southern site. While the overall relationships were relatively weak (R^2 between 0.1 and 0.3), the regression equations for titratable acidity and average bunch weight describe a positive linear relationship with PCD, and a negative linear relationship with pH and TSS.

Results from the Geographe site showed similarly weak relationships (R^2 between 0.01 and 0.36), perhaps due to the small size of the block (0.27 ha) (Figure 3.1). TA and pH followed expected trends with the regression analysis describing an increase in TA with increases in PCD and a decrease in pH with an increase in PCD. However, TSS, average bunch weight, and yield were not related to PCD at this site. When trunk circumference and canopy surface area were compared with these measurements no significant relationship was found.

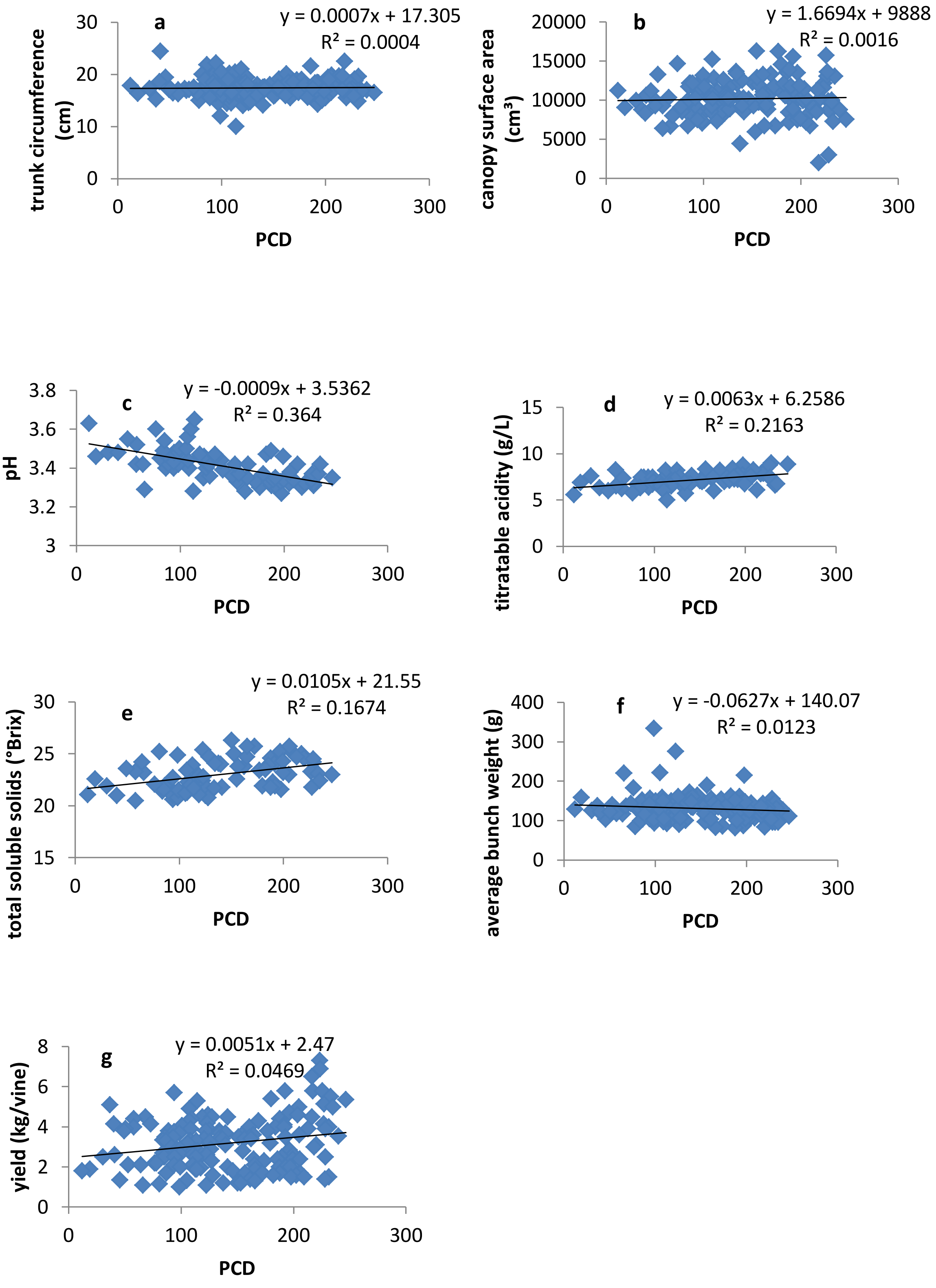


Figure 3.1 The relationships between plant cell density (PCD) and (a) trunk circumferences, (b) canopy surface area, (c) pH, (d) titratable acidity, (e) total soluble solids, (f) average bunch weight, and (g) yield at the Geographe site. Data are individual observations (n=150 for trunk circumference, canopy surface, average bunch weight; n=110

for berry chemistry indices) with fitted linear regressions, equations are fitted linear regressions and R^2 values are coefficients of determination.

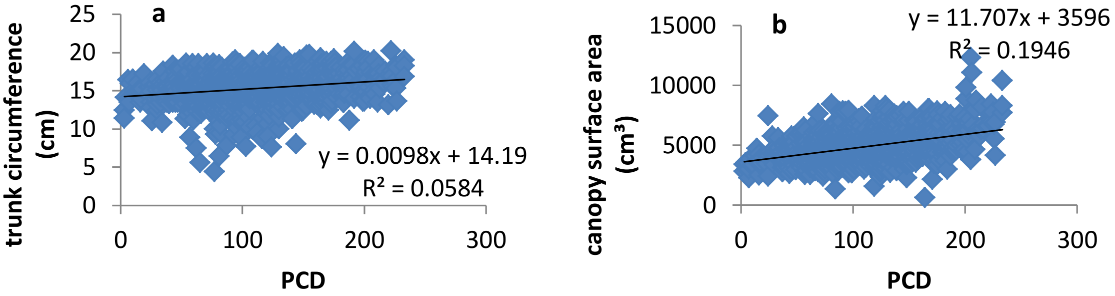


Figure 3.2 The relationships between plant cell density (PCD) and (a) trunk circumference and (b) canopy surface area at the Margaret River site. Data are individual observations (n=1592) with fitted linear regressions, equations are fitted linear regressions and R^2 values are coefficients of determination.

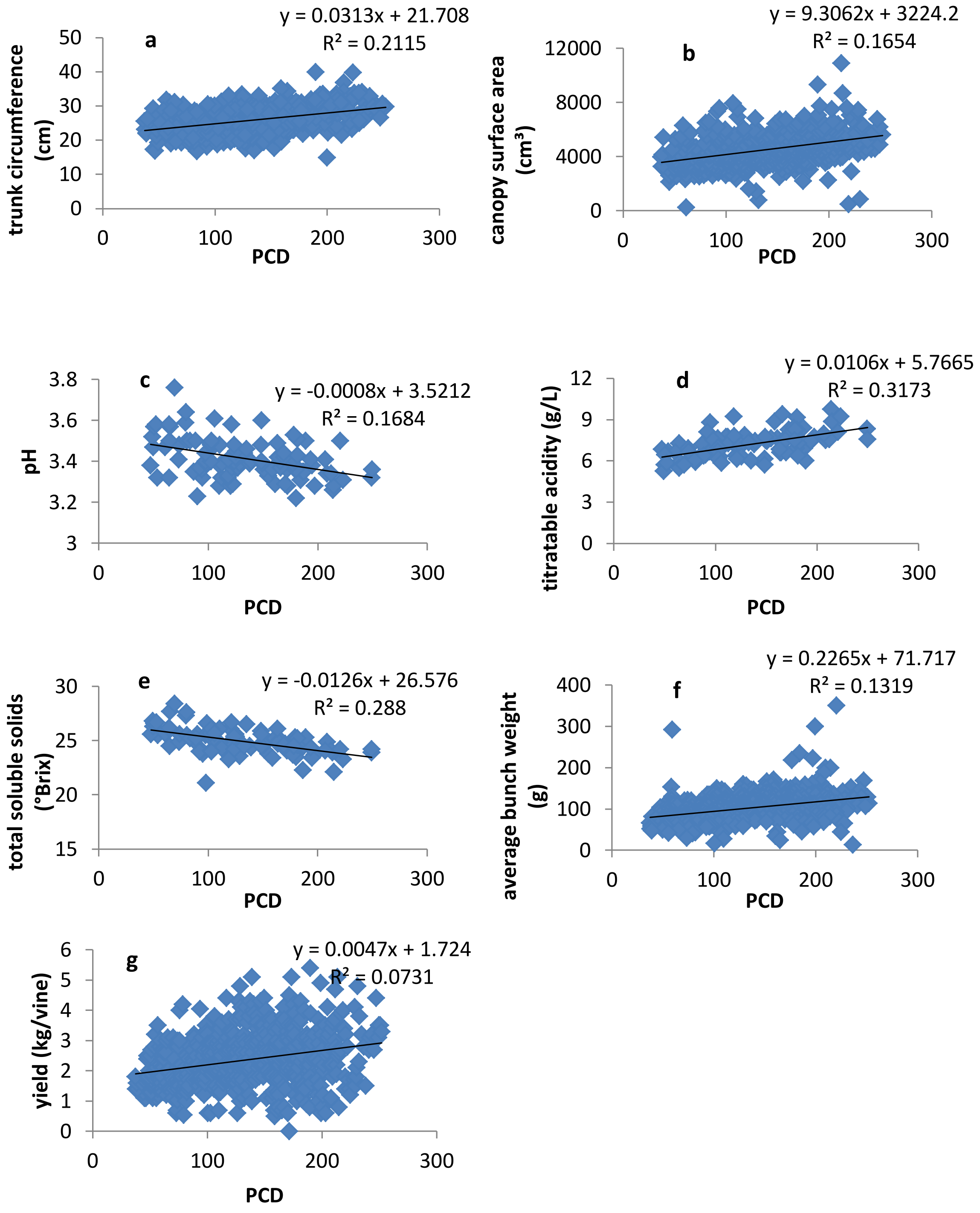


Figure 3.3 The relationship between plant cell density (PCD) and (a) pH, (b) titratable acidity, (c) total soluble solids, (d) average bunch weight, (e) trunk circumference, (f) canopy surface area, (g) yield at the Great Southern site. Data are individual observations (n=640 trunk circumference, canopy surface area, and average bunch weight; n=110 berry chemistry indices) with fitted linear regressions, equations are fitted linear regressions and R^2 values are coefficients of determination.

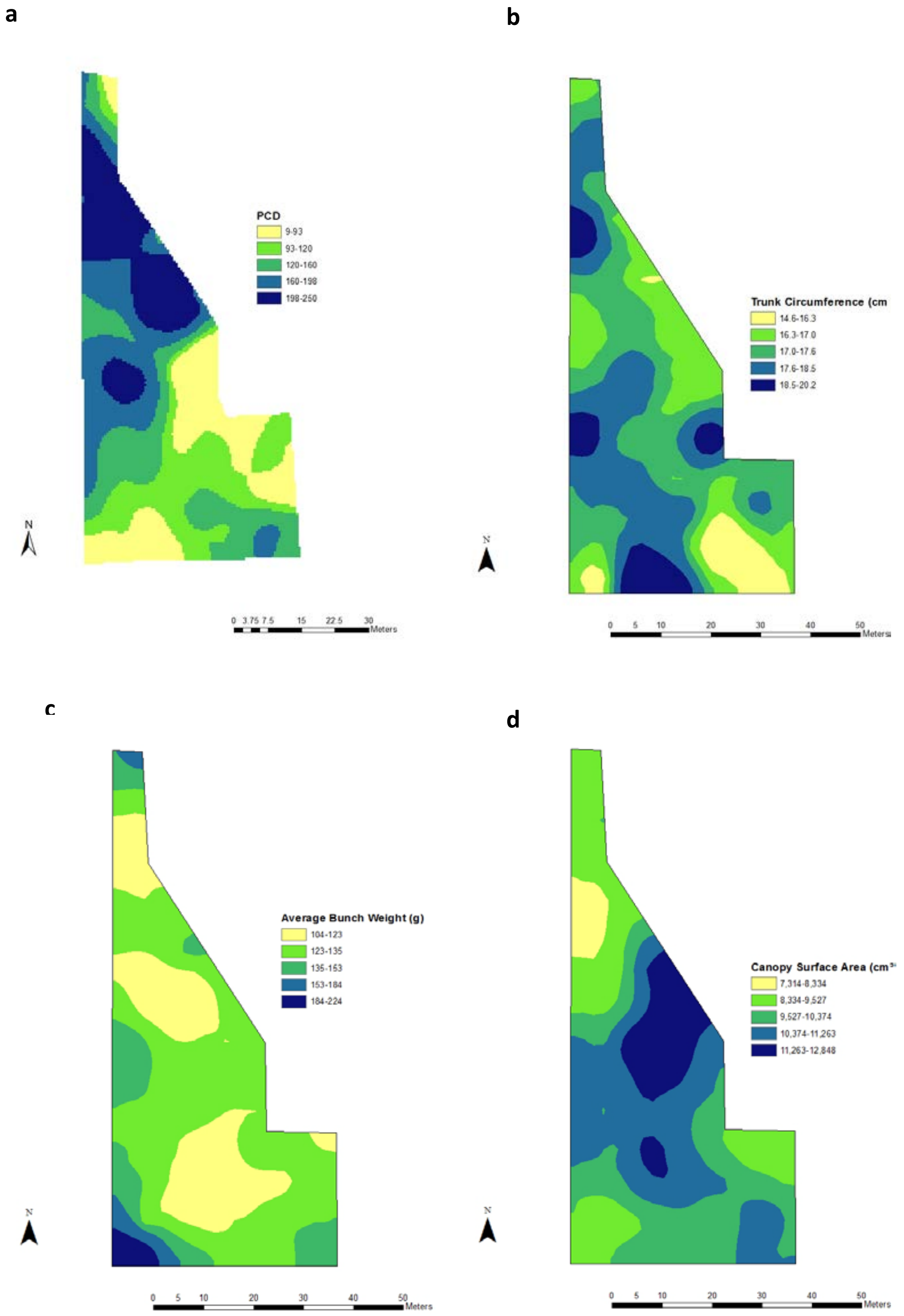
Visual pattern assessment of GIS maps

When assessed visually for patterns between the maps, it is apparent that the boundaries of zones delineated by PCD values are similar to the boundaries of zones delineated by other values (Figure 3.4–3.6). It should be noted that such an assessment is qualitative at best and hence the figures are provided for the reader's information.

Plant cell density and manual sampling cost analysis

It was found that a minimum population sampling of 7% is necessary to generate a map of sufficient accuracy to distinguish between vigour zones. This equates to roughly 150 samples per hectare sampled in a grid design. In order to complete this task on the ground it would take 6 hours per hectare to sample, plus a minimum of 3 hours data entry and analysis with GIS software. However, it is acknowledged this number may vary depending on how fast someone can transcribe the data and the level of GIS literacy of the operator. At $20/hour for labour, the cost of a manual sampling-derived map is about $180/ha (this does not include the cost of training staff to use the software or licensing fees applicable to the software suite). For light aircraft remote sensing to acquire reflectance data for determining PCD, a typical commercial service provider's pricing fees in 2013 were as follows: <10ha $350 fixed fee, 10 to 50ha $39/ha, 51 to 100ha $36/ha, 101 to 200ha $34/ha, 201 to 500ha $32/ha, >500ha $31/ha. These prices include data acquisition, processing, and delivery. It is, therefore, more economical (by about $140/ha) to acquire data using remote sensing technologies. It should be noted that, at the time of writing, other platforms exist for PCD imagery acquisition: i.e. unmanned aerial vehicles (UAV), and satellite. In a thorough technical cost analysis, Matese et al. (2015) found "an economic break-even between UAV and the other platforms (satellite and light aircraft) between 5 and 50 ha of area coverage, and also that aircraft remote sensing remains competitive with satellite above such threshold." All PCD imagery acquisition throughout this research was collected using light aircraft.

Geographe


a
PCD
9-93
93-120
120-160
160-198
198-250
N
0 3.75 7.5 15 22.5 30 Meters
b
Trunk Circumference (cm
14.6-16.3
16.3-17.0
17.0-17.6
17.6-18.5
18.5-20.2
N
0 5 10 20 30 40 50 Meters
c
Average Bunch Weight (g)
104-123
123-135
135-153
153-184
184-224
N
0 5 10 20 30 40 50 Meters
d
Canopy Surface Area (cm³
7,314-8,334
8,334-9,527
9,527-10,374
10,374-11,263
11,263-12,848
N
0 5 10 20 30 40 50 Meters

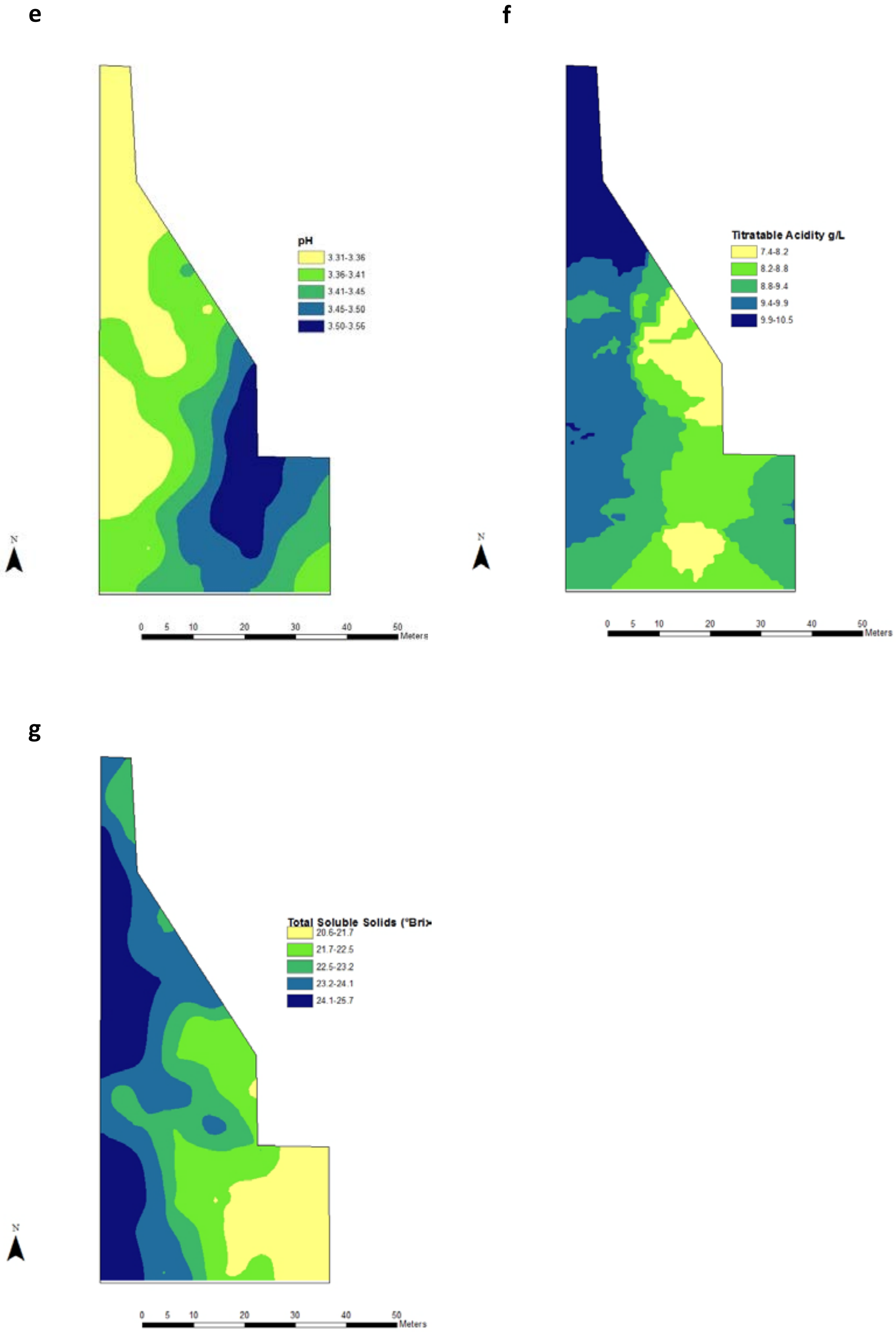


Figure 3.4 Geographe GIS maps of (a) plant cell density, (b) trunk circumference, (c) average bunch weight, (d) canopy surface area, (e) pH, (f) titratable acidity, and (g) total soluble solids.

Margaret River

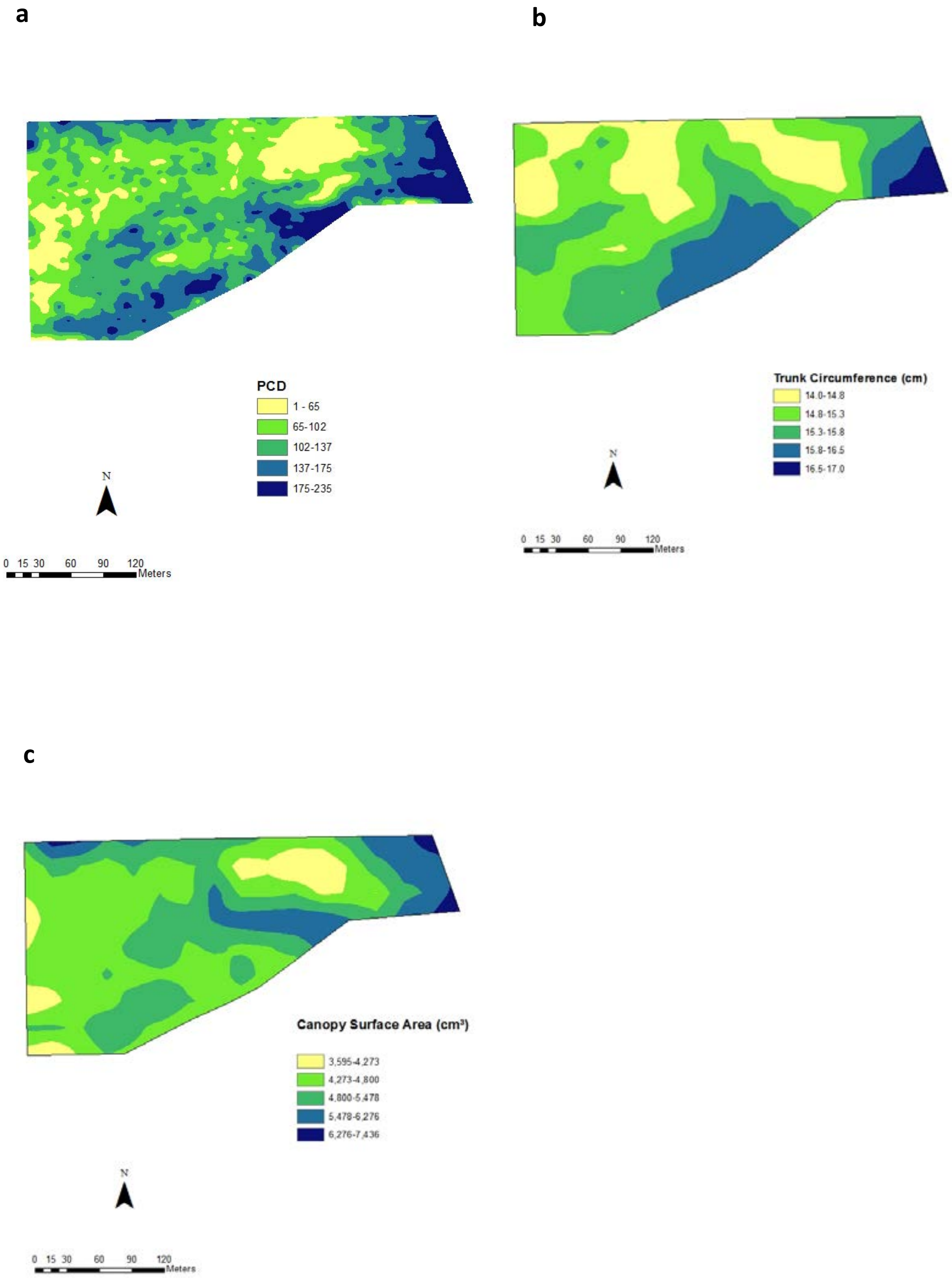
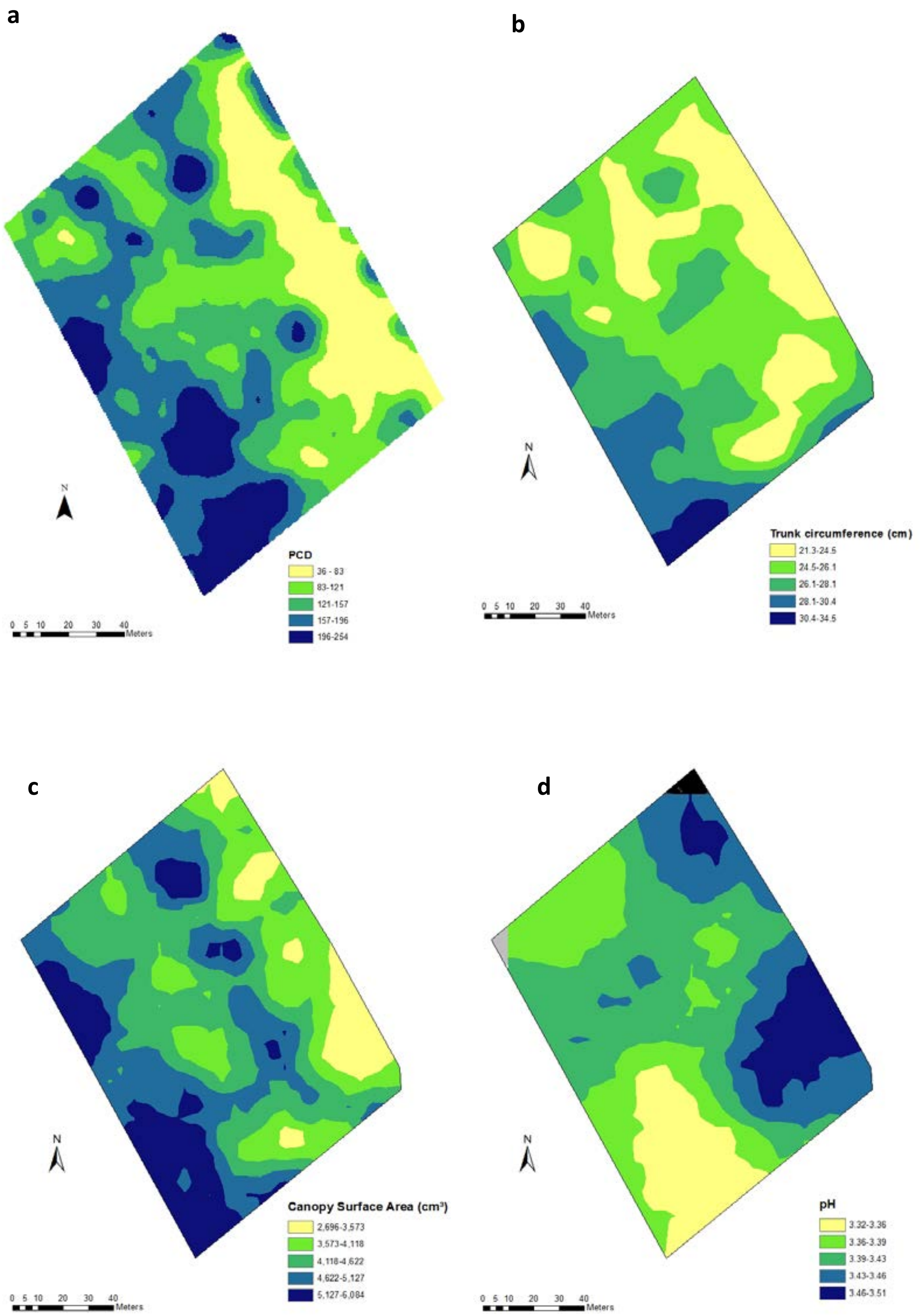


Figure 3.5 Margaret River GIS maps of (a) plant cell density, (b) trunk circumference, and (c) canopy surface area.

Great Southern


a
b
c
d
N
PCD
🟨 36 - 83
🟩 83-121
🟩 121-157
🟦 157-196
🟦 196-254
Trunk circumference (cm)
🟨 21.3-24.5
🟩 24.5-26.1
🟩 26.1-28.1
🟦 28.1-30.4
🟦 30.4-34.5
Canopy Surface Area (cm³)
🟨 2,696-3,573
🟩 3,573-4,118
🟩 4,118-4,622
🟦 4,622-5,127
🟦 5,127-6,084
pH
🟨 3.32-3.36
🟩 3.36-3.39
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0 5 10 20 30 40 Meters

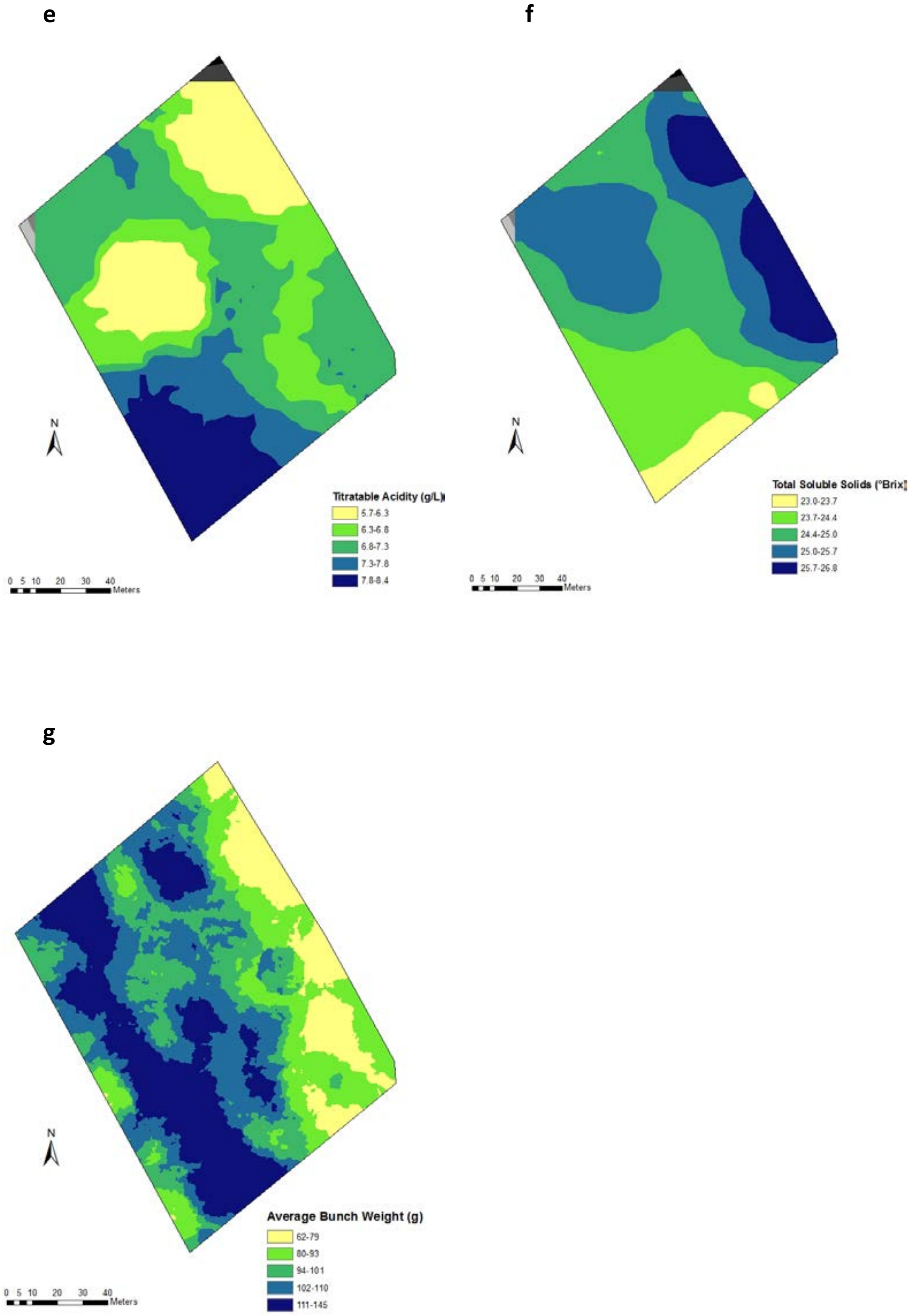

Figure 3.6 Great Southern GIS maps of (a) plant cell density, (b) trunk circumference, (c) canopy surface area, (d) pH, (e) titratable acidity, (f) total soluble solids, and (g) average bunch weight.

Discussion

This research examined the relationships between PCD and on-the-ground vine vigour measures (trunk circumference and canopy surface area) to establish the role of PCD imagery in distinguishing between vine vigour zones within a vineyard. The results indicate statistically significant, yet relatively weak, positive linear relationships at two of the three sites (MR and GS). This result demonstrates the validity of using PCD imagery to identify vigour zones; however suggests that the use of PCD imagery in more detailed analysis (i.e. developing direct relationships between PCD values and specific vine or berry measures) may be limited.

As noted previously, the utility of airborne imagery when vine canopies were managed as a VSP system has been shown by Bramley et al. (2011), and further supported by Scarlett et al. (2014). Both of these studies successfully used PCD imagery to define vigour zones within Sauvignon Blanc and Shiraz vineyards (respectively) under VSP systems. Therefore, the weakness of these relationships should not be attributed to an inability of PCD imagery to represent differences in canopy size and health using this canopy management system. Results from the Margaret River site demonstrated a stronger relationship between PCD and canopy surface area (R^2=0.19) than trunk circumference (R^2=0.06). As PCD and canopy surface area are measures of within-season variation in vigour and trunk circumference is a more temporally stable measure of vigour (across all seasons), this result is supported by previous studies, for example Bramley and Hamilton (2004, 2007) who also reported similar observations for Cabernet Sauvignon, Merlot, and Ruby Cabernet in the Coonawarra, Clare Valley, and Sunraysia regions. Results from the Great Southern site demonstrate a similarly weak relationship between PCD and trunk circumference (R^2=0.21) and PCD and canopy surface area (R^2=0.17). Interestingly, the relationships were not apparent at the third site, possibly due to the relatively small size of this site.

The overall weakness of the relationships between the vigour indices is in contrast to the findings of Proffitt and Malcolm (2005) who reported relatively strong relationships between PCD and trunk circumference and canopy surface area. Additionally, Tisseyre et al.

(2008) noted relationships between PCD and canopy size. However, both of these studies were limited by overall sample size. Proffitt and Malcolm (2005) and Tisseyre et al. (2008) each based analysis on only 30 measured vines.

Another potential reason for the strong relationships observed in previous studies between PCD, trunk circumference, and canopy surface area measurements could be the effects of targeted management. In a 2 year study (2003-2004), Proffitt and Malcolm (2005) identified 30 sample vines within an 8.8 ha block for trunk circumference and canopy surface area. A targeted sampling strategy was used, as opposed to grid sampling (the methodology for this study). No differential management had taken place before their trial began. In 2003, the R^2 value for the relationship between trunk circumference and PCD was quite strong, 0.83. The R^2 value for the relationship between canopy surface area and PCD was 0.78 for the same year. The following season targeted management of irrigation was implemented whereby varying vigour zones (high, medium, and low - as determined by PCD imagery and visual calibration) received differential water treatments during the latter part of the growing season. The low vigour zone received 64 litres/vine/week, whereas the high vigour zone received 32 litres/vine/week. In 2004, trunk circumference and canopy surface area measurements were again recorded and compared directly with PCD values. It is interesting to note that the strength of the relationships decreased. Linear regression analysis showed decreased R^2 values for trunk circumference and PCD (0.63 – a difference of 0.2) and canopy surface area and PCD (0.62 – a difference of 0.16). This suggests that targeted management throughout the growing season may decrease the strength of on-the-ground measures with remotely sensed PCD values. Additionally, due to the targeted nature of the sampling strategy, it is possible that a bias was introduced.

It is likely that sampling procedure could have created a bias in the previous experiments. To demonstrate the effect of this bias, a post hoc analysis of the data set was applied whereby a sub-set of target vines within the data set were chosen based on vigour zone (not on a grid). Vines were chosen based on location within high and low vigour zones in an effort to sample from the range of vigour types as determined by PCD imagery. The results indicated stronger relationships between PCD and manual sampling vigour measurements (canopy surface area and trunk circumference) than were found through grid sampling at a much higher intensity (Figure 3.7, Figure 3.8). The reason for the stronger relationship is likely due to the selection of target vines that have a range in their values in both variables (PCD values and manually sampled values). The R^2 values for PCD and canopy surface area increased from 0.20 to 0.60 at the Margaret River site and from 0.17 to 0.24 at the Great Southern site. Additionally, the R^2 values for PCD and trunk circumference improved from 0.06 to 0.16 at the Margaret River site and from 0.21 to 0.45 at the Great Southern site. The Geographe site, again perhaps due to small size, exhibited no statistically significant relationship. The targeted data sets of trunk circumference and canopy surface area were then compared with each other at both sites (MR and GS). Interestingly, a weak positive relationship between these variables exists at the Margaret River site (0.222), yet there is no relationship between variables at the Great Southern site (0.046) (Figure 3.9). As canopy surface area measures within season vigour and trunk circumference is a measure of temporal vigour (across seasons), it is possible that the targeted management strategies in place at the Margaret River site might have some effect on vine circumference. Also, as the Great Southern site is non-irrigated this might explain the strong correlation between trunk circumference and PCD. It is possible that PCD shows the strongest relationship with on-the-ground vigour measurements when canopies are at “extreme” levels, but perhaps the relationship is less clear when the canopy is of a relatively moderate size. Bramley et al. (2011) noted similar findings with trunk circumference measurements. When trunk circumference measurements from vines in the low vigour zone were compared with trunk circumference measurements from the high vigour zone, statistically significant differences were found. However, the mean trunk circumference in the middle vigour zone was not statistically different from that of either the high or low vigour zones.

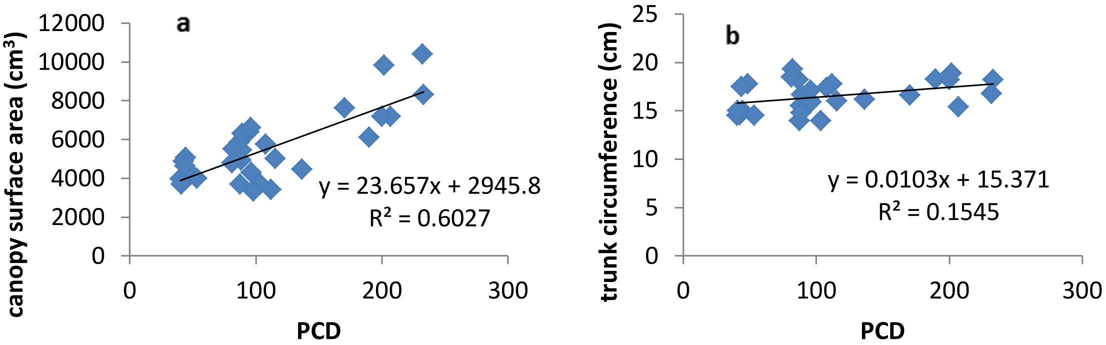

Figure 3.7 The relationships between plant cell density (PCD) and (a) canopy surface area and (b) trunk circumference at the Margaret River site. Data are individual observations (n=29 for trunk circumference and canopy surface area) with fitted linear regressions, equations are fitted linear regressions and $\boldsymbol{R^2}$ values are coefficients of determination.

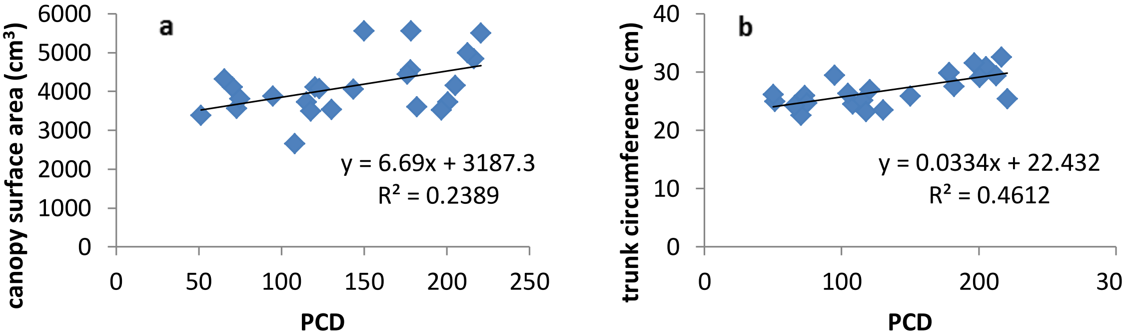

Figure 3.8 The relationship between plant cell density (PCD) and (a) canopy surface area and (b) trunk circumference at the Great Southern site. Data are individual observations (n=24 for trunk circumference and canopy surface area) with fitted linear regressions, equations are fitted linear regressions and $\boldsymbol{R^2}$ values are coefficients of determination.

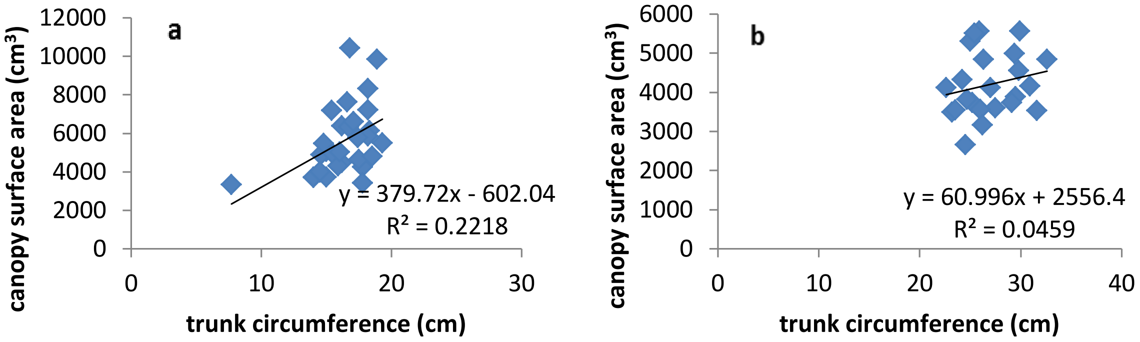

Figure 3.9 The relationship between canopy surface area and trunk circumference at the (a) Margaret River and (b) Great Southern site when vines were sampled based on vine vigour zone. Data are individual observations (n=31 and n=24, respectively) with fitted linear regressions, equations are fitted linear regressions and R^2 values are coefficients of determination.

A number of studies have emphasised the importance of using PV technologies, especially PCD imagery, as a tool to make more informed management decisions (Bramley et al. 2011, Cook and Bramley 1998, Dobrowski et al. 2003, Iland et al. 2011, Proffitt et al. 2006). As discussed in Chapter 2, Cook and Bramley (1998) emphasize the importance of PV technologies as a cycle of observation, interpretation, evaluation, and implementation. Proffitt et al. (2006) describe the importance of PV technologies as a tool to make more informed management decisions. This chapter supports these previous studies in encouraging the use of PCD imagery as a guide to identifying areas of divergent vigour and considering potential differential management techniques.

There are distinct limitations to the use of PCD values in statistical analysis. It is important to recall that airborne reflectance data is captured using a passive sensor, and therefore results are difficult to compare when gathered on different days or different times within a day (Bramley et al. 2011, Proffitt et al. 2006). The role of PCD imagery is to efficiently identify areas of divergent vine vigour within a block to enable more informed management decisions (Cook and Bramley 1998, Proffitt et al. 2006). Additionally, as Proffitt et al. (2006) noted and Bramley et al. (2011) emphasized, PCD imagery requires ground truthing to verify remotely sensed imagery with visual assessments. As shown throughout this chapter, the role of PCD values at the individual vine level in statistical analysis of on-the-ground measurements may be limited; yet there is merit in the analysis of maps and visual patterns between measured variables as was done in Bramley et al. (2011).

A further aim of the experiment was to examine the economic effect and pertinence of remotely sensed imagery (Precision Viticulture technology, specifically PCD) against manually sampled data collection. This research clearly demonstrates the positive economic advantage of PV technology vs manual sampling measurements. Economic analysis of data collection to create 'vigour' maps shows that manual sampling may cost around \$180/ha, whereas a map of greater accuracy, due to the higher density of measurement points, produced via remote sensing costs between \$35-\$45/ha. This saving of approximately \$140/ha demonstrates the economic viability of remote sensing by aircraft in the vineyard. To the best of the author's knowledge, no other research has determined minimum sampling size and related the cost of producing a vigour map based on manual sampling observations.

The final goal of this chapter was to examine the relationship between PCD, basic berry chemistry indices, and average bunch weight. The results indicate that a weak relationship exists between PCD and these variables. At the Great Southern site, statistically significant relationships were found between PCD and berry chemistry indices. There was a positive linear relationship between PCD, TA (0.32), and average bunch weight (0.14), and a negative linear relationship between PCD, TSS (0.29), and pH (0.17). The linear relationships described by this experiment are in line with *a priori* assumptions. This is supported by Zerihun et al. (2015) who noted significant relationships for these parameters in Shiraz across five sites over 3 years (except in 2008). The data were re-examined using only the targeted vines from high and low vigour zones (Figure 3.10), and no significant change was found between PCD and pH (R^2 decreased from 0.17 to 0.03), TA (R^2 decreased from 0.32 to 0.26), TSS (R^2 decreased from 0.29 to 0.23), or yield (R^2 increased slightly 0.07 to 0.09) (Figure 3.10). However, the relationship between PCD and average bunch weight increased significantly (R^2 increased 0.14 to 0.47). At the Geographe site only two variables were found to be consistently significant, pH (0.36) and TA (0.22), with PCD in positive and negative directions respectively. No significant relationship was found between TSS and average bunch weight with PCD. It is possible that there was a sink-source balance such that sugar concentrations were maintained as the average bunch size increased. This would mean that vines with higher PCD values had higher bunch numbers.

It is not unexpected that the correlation between vigour and crop yield is often poor. Dry and Loveys (1998) noted that “grapevines which exhibit excessive vegetative vigour are likely to produce less fruit of reduced quality, and vines with inadequate vigour may be compromised in terms of their yield potential.” Pruning technique has been shown to be a more important variable for yield determination than vigour indices (Dry and Loveys 1998, Proffitt et al. 2006). Shaded canopies can reduce the fruitfulness of vines (Smart 1985).

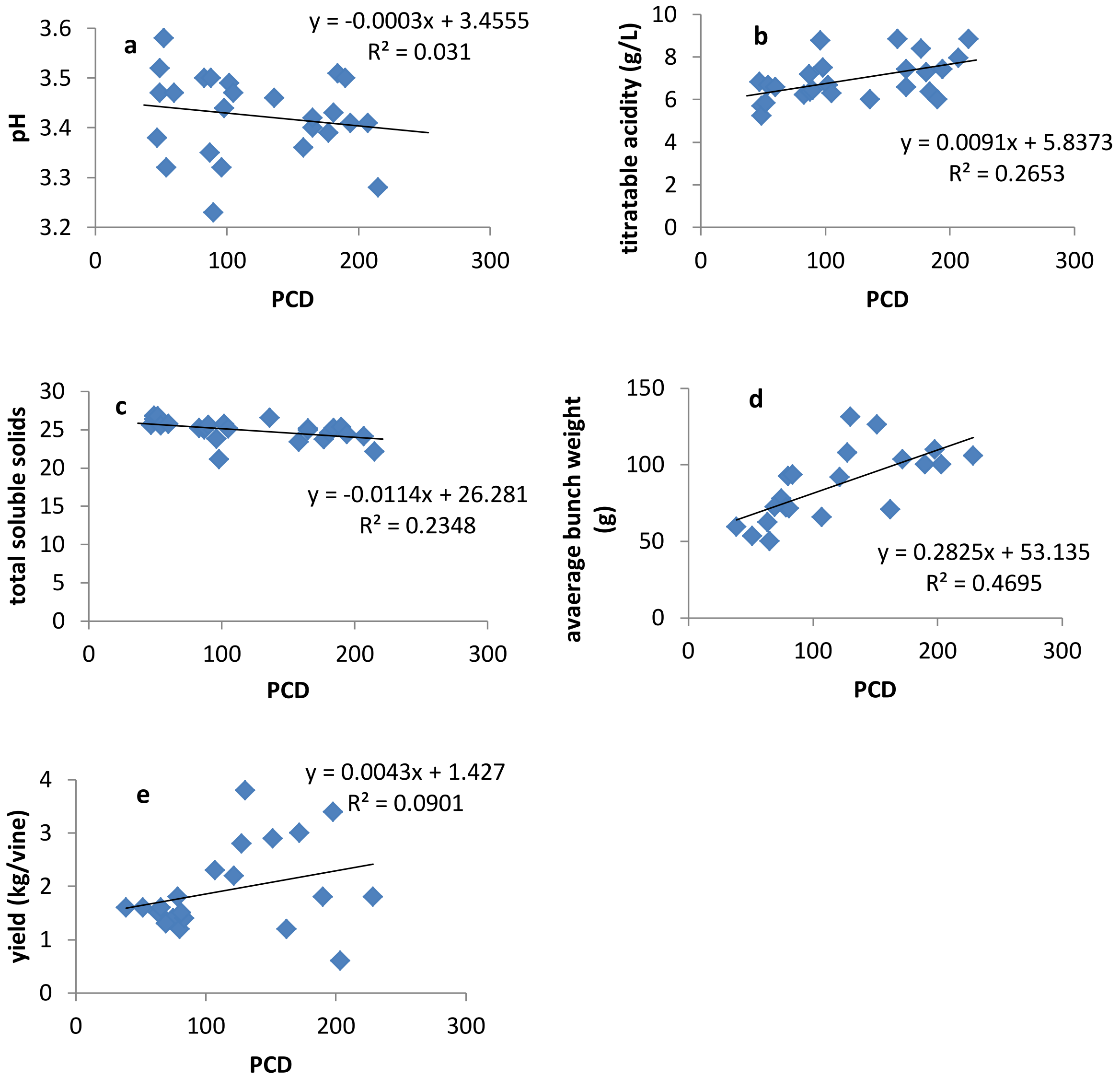

Figure 3.10 The relationships between plant cell density (PCD) and (a) pH, (b) titratable acidity, (c) total soluble solids, (d) average bunch weight, (e) yield at the Great Southern site. Data are individual observations (n=24) with fitted linear regressions, equations are fitted linear regressions and R^2 values are coefficients of determination.

The findings of this study support prior research in the field that indicate that relationships between PCD, berry chemistry, and average bunch weight may not be consistently strongly correlated across vintages. This is in line with Tisseyre et al. (2008), who noted that berry chemistry indices are less temporally stable than more robust measures such as canopy surface area. As noted in the introduction, depending on the site, mean differences between berry chemistry values of low and high vigour zone fruit were not significantly different or were only marginally different. This research is in line with results from Bramley et al. (2011). In a 3 year study of berry chemistry indices and average bunch weight between low and high vigour zones, this study found that none of these variables was consistently significant across all 3 vintages. Additionally, Bramley et al. (2011) noted "neither PCD nor trunk circumference were good predictors of grapevine yield" – which is consistent with results of this work. It should be noted that unless harvests are made at a predetermined Baume level, there can be year-to-year variations simply depending on when the samplings or harvests are made irrespective of vigour differences.

This study confirms findings from Monsó et al. (2013), who proposed an opportunity index (OI) for selective harvesting that was based on 3 parameters: spatial variability (PCD values or other measure of vine vigour), spatial structure (GIS mapping including infrastructure, soil and/or topography elements, etc.), and "a minimum surface, that guarantees that the benefits derived from the differentiation of the final product compensate for the expenses of the differential management." According to their OI, the Geographe site does not fall within these parameters, and therefore relative vigour differences may be too small to be noted.

Previous research indicated the relationship between PCD and berry chemistry through visual analysis of GIS maps. The visual patterns observed between PCD, berry chemistry, and average bunch weight in this work show similar results as the ones observed by Bramley (2005) and Bramley et al. (2011). However, while a visual relationship is perceptible, it is important to consider what correlations the data draws without GIS interpretation. Perhaps targeted sampling may have caused belief in a tighter relationship between variables. It is important to consider the difference between qualitative (visual) assessment and quantitative data/analysis. The results achieved through an objective form of quantitative analysis (i.e. linear regression or other statistical methods) are more robust and may be of greater assistance as a decision-making tool. It is acknowledged, though, that, at times, there can be discernible differences in “quality” without there being large differences in vigour.

As berry chemistry indices such as pH, TA, and TSS are only harvest indicators and are not the only determinates of fruit quality (Iland et al. 2011), future research should be targeted on a broader suite of key berry quality drivers in the berry and their relationship with vegetation indices such as PCD. It is noted that Scarlett et al. (2014) examined spatial variation of rotundone in Shiraz; and perhaps a similar experimental design should be used to explore compounds that are known to contribute to varietal traits in Cabernet Sauvignon (for example methoxypyrazines). In this regard, a further exploration of methoxypyrazines and vigour indices has been undertaken in Chapter 7.

Conclusion

This chapter examined the viability of PCD imagery as a decision-making tool both economically and as a direct comparison to manual sampling. While linear regression analyses based on grid sampling yielded statistically significant, but contrary to expectations relatively weak, relationships between PCD and on-the-ground measures of vigour, further analyses of a targeted data set indicated stronger relationships. Additionally, ground truthing by visual calibration (industry standard protocol) verified PCD imagery and was found to be an accurate portrayal of the vine vigour status as assessed on the ground. These results indicate the utility of PCD in distinguishing between high and low vigour zones; however the role of PCD values (at the individual vine level) in direct statistical analysis of manually sampled vigour measures is not advised. Relatively weak relationships were found between PCD and pH, TA, TSS, average bunch weight, and yield. Additionally, it was determined that a minimum population sampling of 7% is necessary to generate a map of sufficient accuracy to distinguish between vigour zones. The findings of this research indicate that PCD imagery is an economically viable decision-making tool to efficiently identify vigour zones within a vineyard.

Chapter 4 Partial gross margin analysis of different management techniques in the vineyard

Introduction

Increased farming efficiency may come from the adoption of differential management strategies aided by the use of Precision Viticulture (PV) technologies. The rising cost of labour, the availability of technology, and affordable rates for data acquisition and processing make adoption of new technologies not just wise but due to their potential to allow farmers to pursue finer scale management and hence improved profitability they be potentially mandatory for future success (Bramley 2001, Bramley et al. 2011). However, the technologies have been available to growers for some time and adoption rates have been slow (Arnó et al. 2009, Cook and Bramley 1998). Much of the past work has focussed on the biophysical aspects of the technologies and there are limited published reports which have examined the farm-scale economic drivers for adoption.

Precision Viticulture is not a panacea for the financial woes of wine grape growers. It is a tool that can be used to make better decisions in the vineyard (Cook and Bramley 1998, Proffitt et al. 2006). However, the potential merits of PV, especially Plant Cell Density imagery, are widespread. As demonstrated in the previous chapter, it allows the user to identify areas of divergent vine vigour quickly, efficiently, and economically (Hall et al. 2002, Johnson et al. 2003). This aids in the transfer of knowledge and reduces communication errors (Proffitt et al. 2006). Detailed knowledge of vineyard properties can be siloed to the vineyard manager or viticulturist. However, through PV's "continuous cyclical process of observation, evaluation and interpretation" (Iland et al. 2011, Proffitt et al. 2006), information is readily accessible, easily understood, and shared to make more informed management decisions (Cook and Bramley 1998, Proffitt et al. 2006). While this process does not add direct dollar value, these indirect benefits are positive remunerations that should provide sufficient incentive to a farmer (Robertson et al. 2007). Additionally, the knowledge PCD imagery provides offers the potential to receive direct economic benefits through differential management. This may be achieved by reducing cost through more efficient farming - adding inputs only where they are required - and increasing revenue -

either by selectively harvesting fruit and selling fruit at different price points or homogenizing the block and reducing variability (Bramley et al. 2003, Bramley et al. 2005, Bramley 2010, Proffitt et al. 2006, Scollary et al. 2008). For example, it may be determined that vines in the high vigour zone require less irrigation, less compost, and less fertiliser than do vines in the low vigour zone leading to reduced input costs and potentially improved gross margins.

Existing research in PV (Bramley 2005, Bramley et al. 2005, Cortell et al. 2005, Lamb and Bramley 2001, Lamb and Bramley 2002, Proffitt et al. 2004, Proffitt and Bramley 2010, Scollary et al. 2008, Trought and Bramley 2011) has attempted to gauge differences between selective and conventional harvesting practices. The shortcomings of the past studies lie in the lack of an adequate control. While the past projects selectively harvested fruit from different management units, only one utilised a representative control (Scollary et al. 2008).

Previous studies have examined the profitability of PV using only data acquisition costs in the partial gross margin analysis (not including extra costs attributable to ground truthing or implementation). Bramley (2010) recorded input cost savings of $290/ha through the use of PV technologies in differential management. Proffitt and Malcolm (2005) estimated input cost savings to be between $140 and $300/ha. Scollary et al. (2008) noted price differences between fruit sourced from the low and high vigour zones to be $200/tonne. These studies were limited by the size of vineyard sites the smallest vineyard block in any study was 3.6 ha (Bramley and Hamilton 2004) while the largest site was 8.8 ha (Proffitt and Malcolm 2005). This research investigated the economic efficiency of PV technologies across a range of vineyard sizes, from 0.27 to 6.3 ha.

The aim of this chapter was to analyse the economic effects generated from differential management (specifically the use of remotely sensed imagery) with regard to fruit price and input costs as compared with uniform management. By tracing costs over the growing season and examining final fruit chemistry, quality, and price from different vigour zones, partial gross margin analysis (annual dollars/ha profit) was performed to determine the economic effect of differential management in the vineyard. It was hypothesized that differential management will increase gross margin as compared with uniform management.

This chapter applied a detailed approach to the analysis of price point values for both fruit at the farm gate and wine produced. The analysis included information from growers and producers, in addition to sensory and chemical analysis to determine price points for each of the high vigour/yield, low vigour/yield, and control fruit and wines, with an emphasis on internal accounting's price point assignment. It incorporated the use of realistic scenarios, including two vineyards that implemented zonal management and one that operated uniformly.

The study included three different sites from three different wine regions whose climatic and environmental conditions. Using multiple sites from warm to cool climates and incorporating inland and coastal aspects, allows for generalizations to be made of the project outcomes.

Methodology

This experiment was designed to analyse the effects (biophysical and economic) of adoption of PV in the vineyard. The experiment employed four steps: zonal identification, basic juice chemistry analysis, cost tracing and partial gross margin analysis. It sought to compare fruit chemistry and fruit price from areas of contrasting vigour (low and high). Furthermore, the experiment was undertaken to examine the economic benefits or otherwise of PV implementation at the fruit level. This experiment was duplicated at three different sites.

Site selection

The same three sites from the previous chapter were utilised (Chapter 1).

Vigour Zone Identification

Plant cell density (PCD) imagery was collected in January and February 2013 (Chapter 1). The findings of the fly-over were verified by manual sampling measurements of trunk circumference and canopy surface area, which enabled visual calibration of the reflectance data (Chapter 1). Each of the blocks was divided into management units based on vine vigour assessments (Chapter 1), viticulturist and winemaker input, and visual assessment. The initial PCD maps were then used to identify areas of divergent vigour by ground truthing and boundaries were created around each area for the purpose of delineating the management units. These were designated as ‘low’ or ‘high’ vigour. Within the high and low vigour management units, 3 harvest zones were chosen that comprehensively represented each management unit. Fruit from the harvest zones was processed separately to maintain vineyard differences. Additionally, 3 control blends were made from each of the low and high vigour harvest zones (i.e. low vigour harvest zone 1 + high vigour harvest zone 1, low vigour harvest zone 2 + high vigour harvest zone 2, etc.) based on proportionate yield (Table 4.1). In total 9 parcels of fruit were obtained: 3 from the low vigour zone, 3 from the high vigour zone, and 3 proportionate control blends. This experiment was replicated at two other sites.

Table 4.1 Control Wine Blending Proportions. Number of vines, yield (tonnes/ha), and total % contribution per vigour zone wine (based on yield) to overall control blend.

2013 Vintage	Geographe	Margaret River	Great Southern
Number of vines in low vigour zone	280	6480	1216
Number of vines in high vigour zone	320	6264	1344
Yield (tonnes/ha) low vigour zone	4.3	2.3	2.2
Yield (tonnes/ha) high vigour zone	4.3	2.3	3
% contribution of low vigour wine to control blend	50%	50%	40%
% contribution of high vigour wine to control blend	50%	50%	60%

Plant Cell Density data processing

Initial PCD data were obtained in the form of raw meta data, maps and raster files of semi-processed data. ArcGIS 10.2 software (ESRI, Redlands, CA, USA) was used to process the PCD metadata and generate a map of vigour following the protocol described in Bramley and Williams (2001). Average PCD values were generated for each of the harvest zones using the Zonal Statistics as a Table tool, following the industry standard protocol. As the control fruit samples were blended according to yield information, an average PCD value for the control fruit was generated using proportionate PCD values per zonal yield.

Berry chemistry analysis at harvest

Fruit was harvested from each of the harvest zones and processed separately via small scale crusher-destemmer into individually labelled 20L demijohns. Juice samples were taken from each of the low and high vigour zones and uniform control replicates, and analysed following industry standard protocol (Iland et al. 2004) for pH, titratable acidity (TA), and total soluble solids (TSS). Analysis of variance (ANOVA) was used to compare the treatment effects to a significance level of $p<0.05$.

Partial gross margin analysis

Operating costs were traced throughout the growing season for the 2012-2013 vintage following activity based costing methodology (Innes et al. 2000). When the price of a task was not attributable at the individual vine level, tasks were timed and the price of a task was determined on an hourly basis. In some instances operations were not performed consistently across the vineyard. When this occurred the costs were traced back to the zones, low and high, and a "uniform" cost measure was created. Uniform cost represents the costs/ha that would have been incurred had the block been managed homogenously. Yield was attributed to both the low and high vigour zones based on yield data collected in Chapter 1. Uniform (whole-of-block) yield was calculated as a weighted yield/area percentage blend of low and high vigour zone yields. Revenue was calculated by multiplying yield by fruit price received. Partial gross margin analysis followed the equation below:

$$Partial\ Gross\ Margin = Revenue(Yield\ X\ Price) - \ Operating\ Costs$$

Results

The results of this experiment demonstrate the economic viability of using PCD and PV as a management tool to target vine vigour variations within a paddock. Berry chemistry at harvest suggests vine vigour may drive berry ripening, however berry chemistry may be altered through targeted management. Furthermore, these results demonstrate positive benefits (between $37 and $3,134/ha in gross margin return) achieved through differential management at all but the smallest site, suggesting the existence of a minimum size threshold to achieve a pay-off through PV implementation (differential management using PV technology).

Juice chemistry at harvest

When the experiment was undertaken at the Geographe site (Table 4.2) the treatments generated statistically significant differences in pH across the low, high, and control wines. For example, for the low vigour zone pH was 0.13 units higher than the high vigour zone.

The control sample recorded a pH value in between the 2 zones. Additional (small) differences were demonstrated between TA of the low and high vigour zones with a total difference of 0.8 mg/L. The winemaker decided the flavour profiles of the two batches were too similar to be differentially allocated.

At the Margaret River site (Table 4.2), no significant differences were found between berry chemistry values (at harvest) from the different vigour zones, even though distinct vigour differences were apparent at véraison as shown by PCD imagery. The winemaker decided the fruit from each zone was similar enough to bulk together.

Results from the Great Southern site (Table 4.2) described statistically significant differences between pH across the low, high, and control samples with values ranging from 3.44 to 3.56. Significant differences between TSS across only the low and high vigour zones were also demonstrated, with the low zone recording a TSS value of 1.4 higher than the high vigour zone. No significant differences were found between TA values across the low, high, and control samples. The operators at this site selectively harvested the vigour zones and the fruit qualities were deemed to be different enough to merit separate price tiers.

Table 4.2 Juice chemistry values pH, titratable acidity (TA), and total soluble solids (TSS) at harvest and plant cell density values (PCD) at véraison for 3 sites for 2013 vintage. Means followed by a different letter are significantly different at $p<0.05$.

Geographe

	pH	TA (g/L)	TSS	PCD (ratio)
Low	3.62a	6.1a	24.5	97a
High	3.49b	6.9b	24.9	191b
Control	3.55c	6.5a,b	24.7	144c

Margaret River

	pH	TA (g/L)	TSS	PCD (ratio)
Low	3.57	4.9	25.7	64a
High	3.58	5.6	25.3	155b
Control	3.58	5.3	25.5	110c

Great Southern

	pH	TA (g/L)	TSS	PCD (ratio)
Low	3.56a	6.1	25.4a	108a
High	3.44b	6.2	24.0b	167b
Control	3.50c	6.1	24.7a,b	137c

Partial gross margin analysis

The extra cost of acquiring PCD data is small (only about 1 to 3% of operating costs – Table 4.3). As such a grower would be required to achieve either a $40/ha increase in revenue, $40/ha savings in input costs, or the same value in informational assets (i.e. the visualisation of vineyard variation in a format readily understood and transferred) or environmental benefits to break even. Also, total operating cost per vineyard did not vary much among the vineyards. However, fruit price does vary dramatically among regions, and the effect of vineyard age and reputation seem to play a paramount role. Additionally, these results further support the assertion that ripeness indicators (pH, TA, TSS) are not viable surrogate measures for quality and subsequent price point analysis.

Table 4.3 Partial gross margin analysis (revenue less operating costs) at 3 sites 2012-2013. Data are values derived for each property activity based costing and revenue/ha, operating cost/ha, and net profit/ha for the 2012-2013 growing season.

Operating Costs for 3 Vineyards 2012-2013 Growing Season	**Geographe**			**Margaret River**			**Great Southern**		
	Low	High	Uniform	Low	High	Uniform	Low	High	Uniform
Tonnes/ha	4.3	4.3	4.3	2.3	2.3	2.3	2.2	3.0	2.6
Price/ton	1,400	1,400	1,400	2,700	2,700	2,600	10,000	8,000	8,000
Revenue/ha	6,020	6,020	6,020	6,210	6,210	5,980	21,687	24,096	20,720
Major variable cost categories ($/ha)									
Precision Viticulture									
PCD imagery acquisition	40	40	-	36	36	-	39	39	-
Maintenance									
Netting on/off	480	480	480	450	450	450	470	470	470
Wire Lifting	240	240	240	100	100	100	100	100	100
Canopy Management	140	140	140						
Fertiliser and mulch									
Chemical	400	400	400	294	294	294	325	325	325
Fertilizer	-	-	-	366	300	366	296	296	296
Irrigation	30	30	30	27	20	27	-	-	-
Casual labour									
Pruning	800	800	800	1,509	1,509	1,509	1,781	1,781	1,781
Shoot thinning	480	480	480	685	685	685	728	728	728
Fruit thinning	-	-	-	-	-	-	166	166	166
Harvest	1,600	1,600	1,600	130	130	130	1,030	1,430	1,230
Other	680	680	680	1,353	1,353	1,353	-	-	-
Total Operating Cost	**4,890**	**4,890**	**4,850**	**4,950**	**4,877**	**4,914**	**4,935**	**5,335**	**5,096**
Revenue Less Operating Cost	**1,130**	**1,130**	**1,170**	**1,260**	**1,333**	**1,066**	**16,752**	**18,761**	**15,624**

No difference in partial gross margin through PV implementation was observed when the analysis was applied to the Geographe site (Figure 4.1, Table 4.3). The overall small size of the block, 0.27 ha, was deemed too small to be economically viable to instigate differential management. The fruit was kept separate after harvest until the winemaker decided there were not large enough differences between fruit parcels to differentiate fruit price. This may suggest that both size and quality thresholds exist to gaining PV benefits. As no differential management or product differentiation was undertaken at this site, the only difference in partial gross margin between differential and uniform management was the cost of PCD data acquisition, $40/ha.

At the Margaret River site (Table 4.3, Table 4.4, Figure 4.1,) the analysis demonstrated that differential management would increase the partial gross margin by a maximum of $267/ha. This was largely due to the differential management of inputs (irrigation and fertilizer) throughout the growing season. This had been done in an attempt to homogenize the block and reduce differences between vigour zones. The fruit from both zones was separately harvested on the same day and determined by the winemaker and viticulturist to be of uniform quality. Cost analysis of the high vigour zone against uniform management showed PV yielded a decrease in operating expenses of $37/ha (including PCD data acquisition costs of $36/ha). As this site differentially managed, uniform costs were estimated based on anticipated operations without zonal delineation. The uniform management fruit price was determined to be $100 less than the price received through differential management as unnecessary inputs to the high vigour zone would have decreased the final fruit quality and it is unlikely the fruit from the entire block would have been of consistent, homogenous quality without targeted management. However, it is readily acknowledged that this fruit price is circumstantial and the reader should be aware that as the vineyard zones received differential input treatments, a final uniform product (unaffected by targeted management) was unavailable. This price point assignment methodology follows similar methods used in previous research (i.e. Bramley et al. 2005, Bramley et al. 2011, Proffitt et al. 2006). As differential management prohibited the acquisition of a control (uniform) parcel of fruit, partial gross margin analysis using an assumed price for the latent variable (uniformly managed fruit-control) demonstrated increases of $194 and $267/ha for the low vigour and high vigour zones, respectively.

Results from the Great Southern site (Figure 4.1,Table 4.3) demonstrated a dramatic benefit to implementing PV, a total gross margin difference of $3,134/ha. This was achieved through product differentiation and input cost savings at harvest as the low vigour zone had less fruit and less canopy structure to navigate, therefore the labourers were able to harvest this section faster. Fruit from the low vigour zone was given a price of $10,000/tonne while fruit from the high vigour zone was allocated $8,000/tonne. The viticulturist indicated that these prices were not generated only from internal accounting and that third party buyers have purchased fruit from this vineyard at these prices. This site has consistently produced top tier fruit and is planted to the oldest vines in the region which are cuttings from the oldest vines in the state. The fruit price for uniform management was determined to be the same as the high vigour zone.

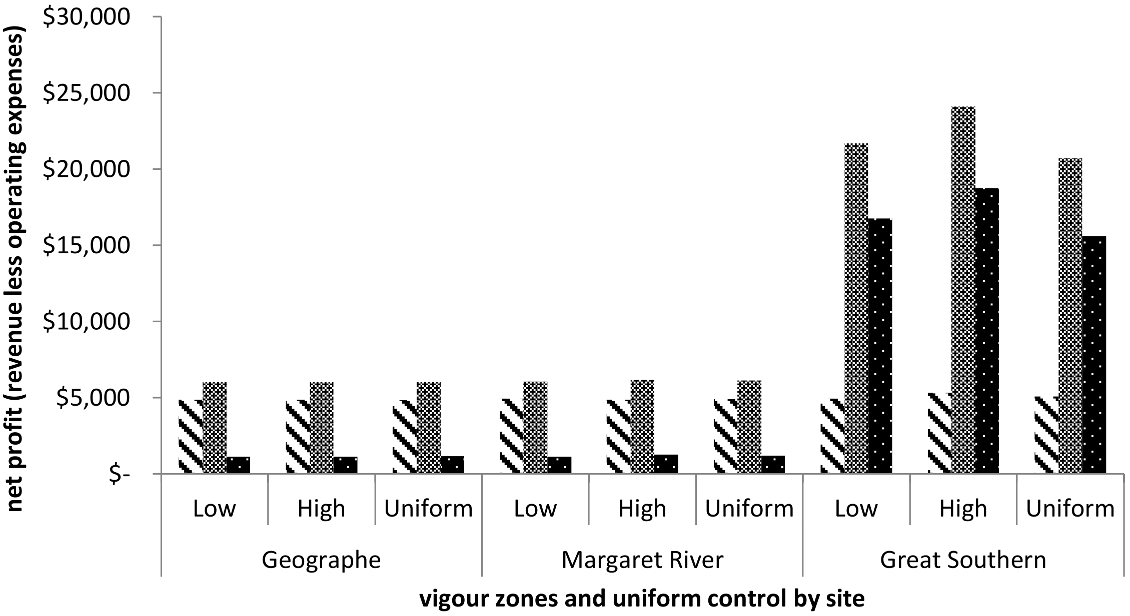

Figure 4.1 Operating expenses, revenue, and partial gross margin/ha for three sites for growing season 2012-2013. At two of the three sites PV enabled lower costs and/or increased fruit price resulting in an increase in revenue/ha. Operating expenses are in detailed with black and white diagonal lines, Revenue is coloured grey, and partial gross margin (net profit) is black with white dots.

Discussion

The aim of this research was to analyse the economic effects generated from differential management (specifically the identification and targeted management of divergent vigour zones) with regard to fruit price and input costs; and the results found that sites of a minimum of 1.5 ha block size received a benefit from the use of PV either in input cost savings or fruit price increase. Partial gross margin analysis at the Geographe site (Table 4.4), at 0.27 ha, did not demonstrate a difference in operating expenses or total fruit price. However, based on the PCD imagery coupled with on-the-ground calibration of remote sensing data, benefits may be derived at this site through regulation of inputs such as water, compost, and fertilizer according to the identified vigour zones. Results from the Margaret River and Great Southern sites demonstrated between $37 and $3,134/ha gross margin benefits (from input cost savings and/or fruit price increase) through the use of PV (Table 4.4). As the Great Southern site is planted to some of the oldest vines in the state, these results indicate the benefits of PV can be gained not only in young vineyards, but also in very old, well established vineyards.

Previous research has demonstrated similar outcomes through partial gross margin analysis, examining fruit price increases and cost savings through PV. Bramley et al. (2003) and Bramley (2005) used partial gross margin analysis at the fruit and wine levels finding overall price increases from 20% to 80%. Bramley and Hamilton (2005) found a maximum fruit price increase of 36%. Most studies gave the high vigour zone the same price as the whole of block (uniform management) scenario (Bramley et al. 2011, Scollary et al. 2008). Proffitt and Malcolm (2005), Proffitt et al. (2006), and Bramley (2010) all found input cost savings from 2%-12% through PV. This research applied the same methodology and found similar results. Additionally, this research demonstrated the benefits of PV technologies (specifically remotely sensed imagery) as a tool to enable more efficient differential management strategies across multiple climatically distinct wine regions in the same growing season.

However, this research has also identified a size distribution effect that was noted in Monsó et al. (2013), but not specifically addressed by any economic analysis either theoretically or in case studies. This chapter demonstrated that in the case of the small Geographe site (0.27 ha) no difference was found between fruit from the two vigour zones. Additionally, due to the small size, differential application of inputs was not viable; therefore this site did not receive PV benefits through cost savings. Previous studies noticed economic benefits received from differential management utilising PV technologies either through cost savings, product differentiation, or increased price through more uniform product. Yet, the smallest site used was a 3.6 block of Merlot (Bramley and Hamilton 2004) and the smallest block size for Cabernet Sauvignon in the reported studies was 7.3 ha (Bramley and Hamilton 2004). Bramley et al. (2011) used an 8.2 ha block of Cabernet Sauvignon and Proffitt and Malcolm (2005) used an 8.8 ha block of Cabernet Sauvignon.

A further aim of this chapter was to examine differences in berry maturity indices (pH, TA, TSS) between the high and low vigour zones and the uniform control. Perhaps due to the overall small size of the Geographe site (Table 4.4), only small differences in pH and TA (not TSS) were demonstrated. No significant differences were described between zones at the Margaret River site (Table 4.4), though this is not surprising as this site differentially managed the block to homogenize the fruit from the two zones. Results from the Great Southern site demonstrated statistically significant differences between pH and TSS (not TA) and were determined to be different enough to be allocated to different product streams. These results support prior findings in the field, especially by Bramley et al. (2011) who recorded inconsistencies in significance levels of these parameters when analysed at harvest from low and high vigour zones over a 3 year study. This is further supported by Bramley (2005) who noted that neither pH, TA, nor Baumé, was consistently significantly different between high and low vigour zone fruit across multiple vintages.

Future research should examine total costs (variable and fixed) in addition to extra costs associated with PV. This is accomplished later in Chapter 9. This chapter, like previous research in the field, has considered only the cost of PCD data acquisition. It should be noted that the use of PV generates three costs: a) data acquisition, b) ground truthing, and c) implementation. A more inclusive cost analysis incorporating capital and overhead costs may yield more insightful results. Additionally, as pH, TA, and TSS have been shown to be not directly correlated with quality, further exploration is warranted into flavour profiles and quality drivers in fruit.

Table 4.4 Overview of sites including size, management strategy, historical fruit price, wine RRP (recommended retail price). Sites are ordered with respect to geographic location moving north to south.

Site	Size	Management Strategy/ unique site attributes	Historical fruit price ($/tonne)	Wine RRP ($/750mL)
Geographe	0.27 Ha	Uniformly managed	$1,300-$1,600	$25
Margaret River	6.3 Ha	Differential management of inputs to homogenise the fruit from entire block (high and low vigour zones)	$1,500-$2,700	Normally used for midrange wine RRP $15-25, though has been used in wines above and below this range
Great Southern	1.66 Ha	Selective harvesting of the low and high vigour zone fruit, however, no differential allocation of inputs; dry farmed	Low vigour: $10,000 High vigour: $8,000	Low zone always used for top tier wine RRP $65; high zone sometimes allocated to top tier, sometimes allocated to lower tier RRP $35

Conclusion

This chapter examined the operating costs/ha of various sized vineyards from three GIs representative of Western Australia, and it found that blocks of a minimum of 1.5 ha received a benefit to differential management and the use of PCD imagery. It showed that acquiring PCD imagery only accounts for 1 to 3% of total operating costs, which translates to roughly $6/tonne of fruit. While results showed that one site demonstrated a significant difference in price received for differentially harvested fruit ($2,000/tonne), the benefits of collecting PCD imagery are not limited to higher price point received at the farm gate. The information generated from PCD imagery provides the grower with information about vigour differences within a block and offers the potential for differential management which could enable cost savings through reduced inputs. Results from two sites demonstrated input cost savings between $37 and $161/ha.

It found no consistently significant relationship between Cabernet Sauvignon berry chemistry harvest indicators (pH, TA, and TSS), vigour zone, and PCD values at all three sites. However, this could be attributed to management practices of the Margaret River site (delaying harvest times, variation of inputs, etc.) aimed at homogenizing fruit. Additionally, the relatively small size of the uniformly managed Geographe block contributed to a lack of difference. However, as the Great Southern site was managed differentially for different vigour and quality variations, results from this site described a difference between berry chemistry and overall price point for the low and high vigour zones.

This chapter identified a potential size threshold (minimum vineyard block size of 1.5 ha) to achieving economic benefits through adoption of PV technologies. Additionally, it highlighted the need for more in depth analysis of costs incurred through adoption of PV. Only data acquisition costs have been included in this and previous PV economic analysis studies. It can be argued that PV incurs not only data acquisition costs, but also costs associated with ground truthing and implementation (Chapter 9). As one of the main reasons for a slow adoption rate of PA technologies is a lack of corresponding agronomic analysis (Adrian et al. 2005, Ancev et al. 2004, Baumgart-Getz et al. 2012, Lamb et al. 2008, Lowenberg-DeBoer 2003), the importance of a more in-depth analysis is paramount.

Chapter 5 Industry assessment of Cabernet Sauvignon wines from different vigour zones using winemakers from the region

Introduction

Previous studies have demonstrated the potential of Precision Viticulture technologies, especially PCD imagery, to identify areas of contrasting vigour within a paddock (Bramley and Hamilton 2004, Bramley 2005, Bramley 2010, Proffitt et al. 2006, among others). The benefits of targeted management strategies lie not only with environmental benefits and cost savings, but also the potential to increase revenue through improved fruit prices for higher and/or more consistent quality fruit (Bramley 2005, Bramley and Lamb 2003, Bramley 2008, Proffitt et al. 2006). As it has been shown that different vigour zones have significantly different sensory attributes (Bramley and Hamilton 2007, Bramley et al. 2011), the need to either separate or homogenize the differences are clear.

Past research has attempted to look at the relationships between vine vigour, fruit quality, and price. For example, researchers have used PCD imagery acquired at véraison to divide vineyard blocks into distinct high and low vigour zones (Bramley 2003 and 2005, Bramley and Hamilton 2004, Bramley and Hamilton 2007, Proffitt and Pearse 2004, Scollary et al. 2008). The subsequent wines made from fruit harvested from these zones were allocated price points either arbitrarily or based on input from a sensory panel comprised of winemaking staff from the participating winery (Bramley et al. 2011, Scollary et al. 2008). Scollary et al. (2008) used a panel of company winemakers (from the experimental site) to assess the differences between wines made from different vigour zones and control blend. Bramley and Lamb (2003) used the input and sensory analysis of the participating winery's winemaker to decide price point analysis. Holt et al. (2008) also used the participating company's personnel (mainly winemakers) as the sensory analysis panel. It can be argued that this link between quality and price is not comprehensive.

To determine if a relationship exists between wine quality and price, it is necessary to evaluate wines objectively. Some studies bulked fruit together from vigour zones, therefore blending unique nuances of the vineyard and defeating statistical purposes of triplicate production (Bramley et al. 2011). One study attempted to classify a “juice index” for quality using basic measurements of pH, titratable acidity, and total soluble solids (Trought and Bramley 2011). This index was then used to allocate price. These measures are only basic harvest indicators, and no proven relationship exists between these variables and price or quality (Iland et al. 2011). Additionally, two of these projects used only one site or one region throughout a growing season, therefore not accounting for regional variation (Scollary et al. 2008, Trought and Bramley 2011).

Multiple problems are associated with using only the input from the experimental site’s winemaking staff for price point assignment. While the wines may be unlabelled and coded, the winemakers know from which block the fruit was sourced. It can be argued that this introduces an information bias and may not yield accurate results repeatable across other platforms (using completely uninformed winemakers). This weakens the utility of the results obtained from the studies which may in turn limit adoption of the technologies by others. Additionally, it has been shown that winemaker and consumer preferences are not always in alignment (Blackman et al. 2010, Dodd et al. 2010, Lattey et al. 2010, Lesschaeve 2007). There are a multitude of wine styles that are considered desirable, and these appeal more or less to different individuals (Jackson 2008, Iland et al. 2011). Unless a panel is fully or partially trained, winemakers may have different perceptions of overall quality depending on style preference (Stone and Sidel 2004). Using multiple winemakers from an array of institutions across multiple regions may potentially eliminate any style bias associated with a particular winery. Furthermore, this may assist industry to adopt the research findings with a higher level of confidence.

This chapter addresses the shortcomings of past projects including:

- lack of an adequate control
- limited experimental design and imprecise triplicate wine production
- use of theoretical (arbitrary) price points rather than actual data
- limited scope of study (no account for regional variation)
- sensory panels with information bias

The goal of this chapter was to examine the relationship between perceived quality and price of wines from different vigour zones and regions using qualified, objective participants with no information bias. It involved the use of accurate triplicate wines and controls sourced from three geographic indications (GIs) of Western Australia. It was hypothesized that wines from the low vigour zone will be scored higher for quality and price than the high vigour and control wines.

Methodology

This experiment was designed to examine the differences in quality and price between wines made from contrasting vigour zones (low and high). It involved vigour zone identification, small batch winemaking, and descriptive sensory analysis. Furthermore, the experiment was undertaken to examine what, if any, relationship exists between perceived quality and price point allocation. This experiment was repeated at three climatically distinct sites in September 2013.

Site selection

The same three sites described in the previous chapter were used.

Vigour Zone Identification

The same vigour zones and harvest zones from the previous chapter were used.

Small lot winemaking

Fruit was harvested from each of the 6 harvest sections (3 from the low zone and 3 from the high zone). Fruit was kept separate to maintain specific vineyard traits. The winemaking protocol followed industry standard small batch winemaking techniques (Iland et al. 2004). Twenty kilogram batches of fruit were separately processed via small-scale crusher-destemmer into labelled demijohns. Based on yield ratios (Table 4.1), control wines were blended from one of each of the high and low vigour harvest zone replicates (i.e. Low Vigour Harvest Zone 1 blended with High Vigour Harvest Zone 1, Low Vigour Harvest Zone 2 blended with High Vigour Harvest Zone 2, etc.). After a 24 hour cold soak, wines were inoculated with yeast (Lallemand EC1118). Punch down of the cap occurred twice daily in the morning and evening. Specific gravity (Baume levels) was individually assessed with a hydrometer each morning, and temperature was maintained below 25°C. Lactic acid bacteria (Lallemand VP41) was added after 48 hours in accordance with industry recommended co-fermentation procedures. Ferments were pressed at a specific gravity of -1 Baume into 15L glass demijohns and fitted with airlocks to finish malolactic fermentation (MLF). Upon completion of MLF, sulphur was added to each wine until a desired level of 25 mg/L free sulphur was obtained. The wines were subsequently bottled (May 2013), labelled, and stored in a climate controlled cellar at 16°C. This experiment was replicated at three sites.

Sensory Analysis

After bottling, the wines were subjected to descriptive sensory analysis following the protocol outlined in Stone and Sidel (2004, p. 201-244). A panel of 27 winemakers or similarly qualified industry personnel with extensive experience tasting pre-release wines was aggregated based on interest and availability. The wines were grouped into 3 flights based on site; however, within each of the 3 flights the order of the 9 wines was randomised. Each participant was asked to score each of the wines for both quality, on a 70 to 100 point scale (Table 5.1) as used by wine professionals (Halliday 1999), and price, using the price point tier structure (

Table 5.2) as denoted by Ernst and Young Entrepreneurs (1999) as a guideline. The study was conducted in a light and temperature controlled room and following the guidelines of ISO 8589:2007.

Table 5.1 Quality score guide for descriptive sensory analysis.

95-100	Superior: a great wine
90-94	Outstanding: a wine of superior character and style
85-89	Very good: a wine with special qualities
80-84	Good: a solid, well-made wine
75-79	Mediocre: a drinkable wine that may have minor flaws
70-74	Not recommended

Table 5.2 Price point tiers for descriptive sensory analysis derived from the protocol outlined in Ernst and Young Entrepreneurs (1999).

$0-15	1
$15-25	2
$25-35	3
$35-45	4
$45-60	5

Statistical analysis

All statistical analysis was conducted using IBM® SPSS® Statistics (Release 22.0, IBM Corp. Armonk, NY, USA) to a significance level of $p<0.05$.

Results

As the experiment was repeated across three sites, the data were aggregated and MANOVA was used to analyse the relationship between the wines and their respective quality (n=702) and price (n=702) scores to determine if there were significant differences among sites or site*vigour interactions. Small differences were found between sites, however, no statistically significant differences were found across vigour or site*vigour effects.

For both price and quality, significant differences existed between the Margaret River wines, which were preferred to the Great Southern wines; however, these differences were small. No significant differences were found between price or quality scores from the Geographe wines as compared with either Margaret River or Great Southern wines. For price (Table 5.3), wines from the Margaret River site were ranked highest with an average price score of $20, followed by wines from Geographe with an average price score of $19, and then wines from the Great Southern with an average price score of $17. For quality (Table 5.3), again the wines from Margaret River were ranked highest with an average quality score of 86, then wines from Geographe with an average quality score of 85, followed by the Great Southern wines with an average quality score of 85. As each of these sites is commercially harvested, the actual retail price for the commercial wine is included next to the region.

Linear regression analysis showed a positive linear relationship (y=0.7253x + 1.41) between price and quality (R=0.721, R Square= 0.520, Adjusted R Square=0.519, Std. Error of the Estimate= 0.721).

Table 5.3 Commercial recommended retail price (RRP), and mean price and quality scores for each site's control, high, and low vigour wines. Data are means (n=77).

Site	Vigour	Commercial RRP	Mean Price Score	Mean Quality Score
Geographe	Control	$25	$19	85
	Low		$19	86
	High		$18	85
Margaret River	Control	$20	$20	86
	Low		$21	88
	High		$18	85
Great Southern	Control	$65	$17	85
	Low		$18	85
	High		$15	85

Discussion

The goal of this study was to analyse the overall quality and relative price points of wines made from high and low vigour zones from 3 climatically distinct vineyard sites as determined by uninformed, non-biased winemakers (or similarly qualified industry personnel). From these results it is clear that even qualified industry personnel were unable to accurately distinguish between wines of different price points without relevant information as to site and region. It is interesting to note that the panel determined that there was very little variation in quality or price scores with a total range of only $6/bottle total difference between the lowest and highest ranked wines and only 3 points on the quality scale. The commercial scale counterparts of these wines retail between $20 and $65 a bottle (750 mL). Perhaps there is a bias toward ranking a wine as "average" when little to no information is available about the wine. All wines were put into the same general quality classification, "very good," and the second price tier of $15 to $25.

This research does not formally support or reject the findings of previous PV research, however it calls into question the price point methodologies historically used. Most prior research has relied on the input and price point allocations of (informed) company winemakers and staff (Bramley and Lamb 2003, Holt et al. 2008, Scollary et al. 2008). The results from this chapter suggest that the role of information may lead to bias scoring. As a panel of uninformed winemakers could not accurately distinguish between the wines, the need to understand and quantify the constituent features of quality and how these parameters drive price becomes clear. Trought and Bramley (2011) created a “juice index” for quality and subsequent price point allocation based on winemaker recommendations of pH, TA, and TSS indices, however, the parameters used to define this index have been shown to be no more than basic harvest indicators and therefore are not useful in determining a direct quality relationship (Iland et al. 2011). The results from this chapter suggest that quality is a multidimensional facet that is contingent upon multiple parameters: wine chemistry, but also perhaps colour, phenolics, or flavour profile.

Previous research has shown that winemakers and consumers tend to differ in their respective wine preferences with regard to sensory properties and glucose additions. Blackman et al. (2010) found that consumers with different wine drinking experience levels preferred varying levels of glucose additions. Novice consumers preferred wines with more glucose additions than did experienced wine drinkers. Winemakers preferred wines with less glucose additions than experienced wine consumers. This is supported by Dodd et al. (2010), who noted a similar trend in sweetness preference among inexperienced wine consumers while more experienced drinkers preferred less sweet wines. Lattey et al. (2010) found that “a relatively small set of sensory attributes were of greatest importance to consumer liking, and these generally dominate varietal differences.” Additionally, it was noted that consumers and winemakers maintain different definitions of wine quality. In a review of wine sensory evaluation practices, Lesschaeve (2007) noted the differences in sensory perceptions and descriptions of winemakers and consumers. This chapter only explored the ability of winemakers to distinguish and accurately rank wines from different vigour zones and wine regions. Consumer preferences were not measured in this chapter; however, this is accomplished in Chapter 8. These results indicate that without any prior information or panel training, the ability of winemakers to accurately assign a price point and quality score to pre-release Cabernet Sauvignon wines is limited. This is in line with results from Hughson and Boakes (2002) who noted the positive effect that extra information yielded in the ability of an expert wine critic to accurately describe a wine. As noted before, the wines used in this study retail at prices between $20 and $65, yet the winemakers' price point assignments ranged from only $15 to $21. The importance of panel training and consumer sensory analysis is highlighted.

This chapter found that price and quality share a positive relationship as determined by winemakers; however, do price and quality share a positive relationship when analysed by consumers? As consumers and winemakers tend to differ in their respective wine quality definitions (Blackman et al. 2010, Dodd et al. 2010, Lattey et al. 2010, Lesschaeve 2007), further research into the sensory perceptions of consumers is warranted (this is achieved in Chapter 8).

Additionally, it leads to the question of "cellar palate". Without panel training and calibration, it may be possible that winemakers will revert to personal preference when analysing a wine for price point and quality, as opposed to maintaining an objective position. The results of this chapter support Lesschaeve (2007) who recommends commercial wineries use external personnel for sensory evaluation of wines.

Future research is suggested into the role of small batch wines as surrogates for commercial scale wines in experimental settings (this is accomplished in Chapter 6). As experimental wines are potentially different to commercial scale wines because they are fermented in small quantity and receive no oak, perhaps they are not comprehensive enough to use as a surrogate for economic analysis experiments. All economic analysis of past projects has relied on small scale wines. It is suggested that a direct comparison be made between commercial and small scale wines to determine their applicability in further studies. If it is found that they are comprehensive, it is suggested that a more in-depth sensory analysis be performed, involving panel training and multiple trials.

Conclusions

This chapter examined the relationship between price and quality of different wines made from varying vigour zones of three vineyard sites from across Western Australia. A semi-trained panel of experienced winemakers was able to discern a slight difference between wines from different sites (total difference of $6/bottle between highest and lowest scoring wines). However, no relationship was found between wines of different vigour zones and price or quality. Additionally, it found a positive relationship between price and quality, indicating that price is not just an arbitrary allocation but rather based on quality. However, it is possible that in the absence of training or any relative information, a bias in scoring a wine for quality and price may exist. It is recommended that specific quality and price attributes be explored further through sensory and chemistry analysis.

Chapter 6 Commercial vs small batch wines: Are experimental Cabernet Sauvignon wines representative of their commercial scale counterparts?

Introduction

In the wine industry, it is common practice to use small batch experimental wines during the research, development and extension phases of innovation to trial different management practices in the vineyard or various winemaking techniques in the cellar to decide if they play a role in final wine quality (Ewart and Sitters 1991, Iland et al. 2011). The low risk and low cost implementations of small batch winemaking the most cost effective approach for innovation as opposed to trialling differences at the commercial level. Small batch winemaking has been used to test different treatment effects in the vineyard (Chapman et al. 2004, Kennedy et al. 2002, Kotsederis et al. 1999, Morrison and Noble 1990, Robinson et al. 2011, to name just a few), which are not possible under commercial conditions. Without small batch winemaking these experiments would have had limited utility for industry as while differences in fruit quality are important and measurable industry adoption is more readily driven by the demonstration of a win quality outcome. For example, Chapman et al. (2004) examined sensory attributes of small batch wines made from vines with different crop yields, while Chapman et al. (2005) analysed sensory attributes of small batch wines made from vines with varying irrigation treatments. Kotsederis et al. (1999) used experimental wines to test the “effects of selected viticultural and oenological factors on levels of 2-methoxy-3-isobutylpyrazine in wines.” Experimental wines have been used to trial winemaking techniques and oenological properties (Belancic and Agosin 2007, Gelpiacute 2011, Sala et al. 2004, among many others). Belanacic and Agosin (2007) and Sala et al. 2004 used small batch wines to examine methoxypyrazine concentrations in fruit, musts, and wines. Robinson et al. (2011), Gelpiacute (2011) and many other studies (enumerated in Robinson et al. 2014a, 2014b) analysed the relationship between chemistry and sensory properties of small batch wines. To have performed these analyses at a commercial level, without first conducting a small scale trial, would have been costly and risky and hence it can be concluded that small batch wine making has played an important role in innovation in the industry to date.

Precision Viticulture research, development and extension has relied upon small batch wine making to examine the effects of different treatments on both the chemistry and sensory aspects of resultant wines. It is a credit to past researchers that small lot winemaking has been employed to demonstrate the effects of PV techniques on fruit quality (Bramley 2001, Bramley and Hamilton 2004, Bramley et al. 2005, Bramley and Hamilton 2007, Bramley et al. 2011a, Bramley et al. 2011b, Proffitt 2002, Proffitt et al. 2006, Trought and Bramley 2011, among many others). Experimental wines have been used in final economic analysis of vineyard management practices, with final wine prices (and profits therein) decided based on the overall "quality" of small batch wines (Bramley et al. 2011, Scollary et al. 2008). However, while small lot winemaking is important and a pragmatic step towards increasing the utility of research outcomes the author is only aware of one published paper that compares the small batch wines directly to their commercial scale counterparts. The step is important to verify that experimental wines are representative of the commercial wines and the significance of this step increases as studies seek to examine the limitations to adoption and cost and benefits of doing so. Bramley et al. (2011) used an untrained panel to compare small lot vs commercial wines via duo-trio testing. However, small lot wine samples were well mixed (not maintaining potential differences). Bramley and Hamilton (2004) indicated that comparisons between small scale and commercial wines were conducted; however specific experimental methodology and results were not included.

Before relying heavily on analysis derived from experimental wines, it is important to determine their representation of commercial scale wines and therefore their applicability in past and future analyses. As sensory analysis is crucial to understanding overall wine quality, it is important to undertake a direct product analysis (small batch against commercial scale wines) to assess the utility of small batch wines as commercial scale representatives (Lesschaeve 2007, Noble 2001).

This chapter aims to fill a research gap in the industry by directly analysing the relationship between small batch wines and their commercial scale counterparts. It will provide an overall quality link between the two wines and examine the applicability of experimental wines as a surrogate for potential commercial wines. As sensory analysis is an industry standard application for examining overall wine quality (Jackson 2008), this study will implore the use of repeated product comparison sensory analysis (Stone and Sidel 2004).

It was hypothesized that the small batch wines will be of equal overall quality as the commercial scale wines.

Methodology

This experiment was designed to compare the relationship between small batch wines and their commercial scale counterparts. It employed two wine treatments: one made in small batch and one at commercial scale, and involved sensory analysis of perceived quality. It sought to examine the potential of small batch wines to act as representative commercial wine samples and determine their role in trials and analysis. A diverse array of wines were drawn from across the vigour zones from the Margaret River and Geographe sites used in Chapters 4 and 5 plus an additional site in Margaret River.

Site selection

The Geographe and Margaret River sites from the previous chapter were used for this experiment. A second site in Margaret River was also used. This site is planted to Houghton Cabernet Sauvignon clonal selection and is cane pruned. It undergoes similar vineyard management practices as the other two sites (the site undergoes each activity once): shoot thinning, hedging at véraison, and leaf plucking. This site is uniformly managed (no differential management of vigour zones).

Harvesting

This experiment was conducted in 2014. For the 2 sites used in Chapters 4 and 5, the same harvest zones were used to acquire fruit samples for the small batch wines and employing the same proportionate yield/area-blending strategy. For the third site, triplicate samples were acquired after the fruit had been processed in the winery. This site was mechanically harvested and processed in the winery before being deposited into a stainless steel fermenter. Three 20 L demijohns were filled with (processed) fruit from the fermenter, thus ensuring an adequate sampling from the entire block.

Small batch winemaking

The same small batch winemaking methods were used as in Chapter 5. For the third site, fruit samples were collected at the winery post-processing. Fruit taken from the cellar floor (post-processing by the winery and therefore a thoroughly mixed sample from the whole block) was placed into 3 separate labelled 20 L demijohns as well. The winemaking protocol was the same as the other small batch ferments.

The partner wineries agreed to separately ferment the fruit harvested from the vineyard block through secondary fermentation. Separate winemaking protocol was followed at the winery subject to the winemaker’s discretion. Different yeast and lactic acid bacteria (LAB) were used at each winery; specific details of yeast and LAB were not disclosed. However, each site (Geographe and Margaret River) fermented the fruit in stainless steel fermenters and ensured a moist cap through either punch downs or pump overs twice a day at the beginning of the ferment and then once a day at the end of fermentation. The Geographe site co-inoculated LAB 48 hours after inoculating the yeast. The two Margaret River sites inoculated LAB after completing primary fermentation. Samples were collected after the wines had been inoculated with lactic acid bacteria and pressed. No oak treatment was received prior to sample collection. Upon completion of secondary fermentation, they were also bottled, labelled, and stored in the same climate controlled cellar. All sample wines (experimental and commercial) were given sulphur additions to a target of 25 mg/L free sulphur. This was repeated at 3 different sites.

Sensory analysis

Approval for this sensory analysis was given by the Curtin University Research Ethics Committee (RD-11-14). Twelve senior students at Curtin University of Technology were selected as panellists based on interest and availability. Sensory analysis involved the use of a semi-trained panel to analyse each of the triplicate and commercial wines in a paired-comparison discrimination test (Stone and Sidel 2004). Each judge was presented with two wines labelled with a unique three digit code. On a separate sheet the respondent was asked to circle the code of the wine that he/she found to be of a greater overall quality or the equal sign if he/she found the wines to be of equal overall quality. Panellists were instructed to score taste and aroma attributes equally. Each triplicate was analysed directly against the commercial wine, and, as a quality control measure, each commercial wine was analysed against itself. In total, 12 pairs of wines were assessed on one occasion. Wines were evaluated as 50 mL samples in clear tulip shaped glasses following industry standard guidelines (ISO 8589:2007). An example of the score sheet is included in Figure 6.1.

Score Sheet

In front of you are 2 samples. Starting with the sample on the left, please evaluate both wines and circle the code of the wine you find to be of a higher overall quality. If you find them to be of equal quality levels, please circle the equal sign "=". For the purposes of this test please score taste and aroma attributes equally. Please allow a 30 second rest in between samples, during which time you can rinse your mouth with water.

645 = 794
243 = 832

Figure 6.1 Example of panellist Score Sheet from the paired-comparison discrimination sensory evaluation. Panellists were asked to circle the code of the wine he or she perceived to be of the greater quality. If the wines were of equal quality then they were instructed to circle the equal sign.

Data analysis

All statistical analysis was conducted using IBM® SPSS® Statistics (Release 22.0, IBM Corp. Armonk, NY, USA) to a significance level of $p<0.05$.

Results

Paired samples t-test (n=108) results indicate that no significant difference exists between the commercial and experimental wines ($p=0.417$). However, when analysed based solely on mean score preferences, the experimental wines (mean=0.48) were slightly preferred to the commercial wines (mean=0.41). This indicates that experimental wines are indeed comprehensive substitutes for commercial wines and their use as a proxy in both research and industry trials is therefore representative.

Discussion

The aim of this study was to investigate the overall quality differences between small batch and commercial scale wines; and the results indicate that small batch wines are a sufficient representation of their commercial scale counterparts and support their use in experimental designs. A semi-trained panel determined through paired comparison sensory analysis that small batch wines are of equal or greater overall quality when compared directly to the commercial scale counterparts.

This chapter supports the decision by past researchers to rely on small-scale wines for experimentation (Belancic and Agosin 2007, Bramley et al. 2005, Bramley et al. 2011, Chapman et al. 2004, Cortell et al. 2005, Cortell et al. 2007, Kennedy et al. 2002, Kotsederis et al. 1999, Morrison and Noble 1990, Robinson et al. 2011, Sala et al. 2004, among many others) and others, especially Bramley and Hamilton (2004) who mentioned a similar analysis (comparison of small batch to commercial wines) but did not provide specific methodology or analysis of results.

For the purpose of this thesis the utilisation of small batch wines to derive parameters for economic analysis is validated. Furthermore, for the purpose of facilitating industry adoption researchers and staff involved in development and extension should extend research results with confidence. If there is a gap in utility in research outcomes associated with vineyard experiment carried through to small scale wines and commercial wines it is small.

Future research is encouraged into the specific differences in sensory and volatile properties of small batch and commercial wines to investigate the effect of fermentation size and winemaker influence on resulting wines.

Conclusions

This study is the first to publish methodology and results of a direct comparison between experimental and commercial wines. It showed that no significant difference existed between the overall perceived quality of experimental wines and commercial scale wines. This research provides a foundation of support for their use as proxy or surrogate samples for analysing potential effects of different treatments both in the vineyard and the winery.

The economic benefits of using small scale winemaking, as opposed to implementing untested management or production changes, are clear. This research shows that a minimum quality level has been fulfilled and that these experimental wines are representative of their commercial scale counterparts.

Chapter 7 The relationship between vine vigour and wine methoxypyrazine concentration for Cabernet Sauvignon grown at three sites across Western Australia

Introduction

Vegetative notes and green characters in Cabernet Sauvignon are varietal traits that can influence sensory perceptions in fruit and wine. Methoxypyrazines (MP) are the main contributors to the vegetative notes indicative of the Cabernet Sauvignon variety of *Vitis vinifera* (Boison and Tomlinson 1990). Methoxypyrazines are nitrogen-containing compounds commonly found in Cabernet Sauvignon, Sauvignon Blanc, Semillon, Cabernet Franc, Merlot, and Carmenere grape cultivars (Jackson 2008). There are three main types of methoxypyrazines: isobutyl-methoxypyrazine (IBMP), isopropyl-methoxypyrazine (IPMP), and secbutyl-methoxypyrazine (SBMP) (Allen 2007). Methoxypyrazines are known to contribute to the sensory properties of Cabernet Sauvignon grapes and subsequent wines and are often associated with “green” vegetative characteristics (Chapman et al. 2004, Noble et al. 1995, Allen 1991, Boison and Tomlinson 1990). While IBMP has been described as contributing a “bell pepper” aroma and is clearly distinguishable at 15 ng/L (Roujou de Boubée et al. 2000, Roujou de Boubée 2002, Wilkinson et al. 2006), IPMP is more often characterized by asparagus or earthy notes and has been shown to have a sensory threshold of 2 ng/L (Allen et al. 1995, Allen 2008, Chapman et al. 2004). Methoxypyrazines are mostly found in the stems, seeds, and skin of the fruit (Roujou de Boubée et al. 2002). As methoxypyrazines contribute sensory properties to wine, it is necessary to explore the exogenous factors driving their concentrations in wines.

Environmental and management conditions influence the concentration of methoxypyrazines in Cabernet Sauvignon. Methoxypyrazine concentration increases throughout the growing season, culminating at véraison when it begins to decrease as the berry ripens (Allen and Lacey 1999, Allen 2007, Boss et al. 2008, Reynolds 2010, Sala et al. 2004). It has been shown that cool climate regions tend to produce fruit with higher concentrations of methoxypyrazines than do warmer climates (Boss et al. 2008, Lacey et al. 1991). Several studies have examined relationships between vine characteristics and methoxypyrazine concentration in the fruit, concluding that concentrations are correlated with climate, sun exposure, canopy, and yield (Belancic and Agosin 2007, Chapman et al. 2004, Chapman et al. 2005, Dunlevy et al. 2009, Falcão et al. 2007, Hashizume and Samuta 1999, Heymann and Noble 1987, Noble et al. 1995, Reynolds 2010, Robinson et al. 2012, Robinson et al. 2011, Sala et al. 2004). Chapman et al. (2004) found a general negative (inverse) relationship between vegetative characteristics and yield, indicating that pruning to a higher number of buds decreased vegetable characteristics, however, cluster thinning have little effect on sensory perception of vegetative characteristics. Furthermore, Chapman et al. (2005) found a positive linear relationship between irrigation and vegetative notes, noting that increased irrigation also increased MP concentrations in the fruit. Hashizume and Samuta (1999) found that direct sunlight exposure to a ripening berry decreased methoxypyrazine concentration, while some studies found that final concentrations of pyrazines (concentration at harvest) were negatively correlated with direct sunlight exposure to the fruit (Allen and Lacey 1999, Hashizume and Samuta 1999, Roujou de Boubée et al. 2000, Sala et al. 2004). Overall, it has been shown that vine training and canopy style have a material effect on methoxypyrazine concentration in grapes, especially in terms of canopy structure (sunlight exposure to the fruit) and irrigation. However, none of these studies have quantified vigour using either canopy surface area measurements or remote sensing (PCD) techniques.

While the relationship between methoxypyrazine, vigour, and vegetative characteristics in the berry has been described in a general sense, further research is required to assess the correlation between canopy size, region, and methoxypyrazine concentration in wine. Heymann and Noble (1987) noted that wine from cooler regions contained higher concentrations of IBMP than wines from warmer regions. In the recent work from Robinson et al. (2012), a general relationship was found between climate and IBMP concentration, with cooler climate wines tending to contain higher concentrations of IBMP than wines produced from warmer regions. However, this relationship seemed to be superseded by growing season conditions, suggesting that weather during ripening has a stronger effect on IBMP concentration than region alone. Similarly, Howell et al. (2006) noted overall low levels of IBMP (2.31-5.48 ng/L) in the study's wines, even though the grapes were grown in a cool-climate and were harvested at a relatively low TSS level (20.0-22.0).

This chapter aimed to address shortcomings of previous studies that were limited by:

- lack of an adequate control,
- no accurate scale/definition of vigour,
- blending of fruit from vigour zones (therefore not accurately reflecting unique nuances throughout outlined vigour zones), and
- lack of analysis at wine level.

Prior studies generally used a single site or block to conduct their research over the course of one growing season. This chapter uses three different sites from three different climatically distinct wine regions of Western Australian. Using multiple sites from warm to cool climates and incorporating inland and coastal aspects, allows for generalizations to be made of the research outcomes. Collecting data from multiple sites over two growing seasons is also useful in analysing growing season effects on vigour differences in the three different regions. The inclusion of a robust control allows for direct comparisons to be made between wines of varying vigour zones. Analysis of methoxypyrazine concentrations in resultant wines is of vital importance, as wine grapes are a value-adding commodity.

The goal of this chapter was to analyse the relationship between vigour and associated methoxypyrazine concentrations of wine made from Cabernet Sauvignon fruit harvested from different vigour zones within a block. Furthermore, it sought to examine the relationship between methoxypyrazines and climate. It is hypothesized that vigour, estimated here as PCD, will have a positive linear relationship with wine methoxypyrazines concentrations. Additionally, it is hypothesized that methoxypyrazine concentrations will increase with cooler climates.

Methodology

This experiment was designed to analyse the relationship between vine vigour and methoxypyrazine concentration. It accomplished this through: vigour zones delimited from

PCD imagery analysis, small lot winemaking, and targeted analysis of methoxypyrazine concentrations via gas chromatography mass spectrometry (GC-MS) analysis. This experiment was carried out at three climatically distinct sites. For two of the sites, the experiment was repeated for a second year.

Site selection

The same sites from Chapter 4 were used in this experiment.

Vigour Zone Identification

The same vigour zones and harvest zones from Chapter 4 were used in this experiment.

PCD data processing

PCD data were processed as described in Chapter 4.

Small lot winemaking

The same small lot winemaking procedures used in Chapters 5 and 6 were used in this experiment. Analysed wines were made from 2 vintages 2013 and 2014 (Figure 7.2, Figure 7.3, and Figure 7.4).

Volatile analysis

After bottling, the wines were analysed for methoxypyrazines via headspace-solid phase micro-extraction and gas chromatography (HS-SPME-GCMS) by Metabolomics Australia at Australian Wine Research Institute. Full details of the methodology for this analysis are included in Bizaj et al. (2012). The following text is the published methodology (as per Bizaj et al. 2012) used by Dr. Natoiya Lloyd and her team at Metabolomics Australia.

“The analysis was performed on an Agilent 7890A gas chromatograph equipped with a Gerstel MPS2 multi-purpose sampler and coupled to an Agilent 5975C VL mass selective detector. Instrument control was performed with Agilent ChemStation E.02.00. The gas chromatograph is fitted with a 30m x 0.18mm Restek Stabilwax – DA (crossbond carbowax polyethylene glycol) column with 0.18um film thickness connected to a 5m retention gap. Helium (Ultra High Purity) is used as the carrier gas in constant flow mode. The oven temperature is started at 35°C, held at this temperature for 4 min then increased to 60°C at

4°C/min, then heated to 230°C at 8°C/min and held at this temperature for 5 min, the total run time is 36.5 min.

The conditions of large volume headspace sampling used were as follows:

The vial and its contents are heated to 40°C for 10 minutes with agitation. A heated (55°C) syringe penetrates the septum and removes 2.0 mL of headspace. The contents of the syringe are then injected into a Gerstel PVT (CIS 4) inlet fitted with a Tenax TA inlet liner (0.75 mm I.D., pre-conditioned in the GC inlet at 200°C for 1 hour and then ramped to 350°C to remove all contaminants before first injection).

The inlet conditions used were as follows:

Prior to injection the inlet is cooled to 0°C with liquid nitrogen. While maintaining 0 °C, the sample is introduced to the inlet using split mode. Multiple headspace sample enrichment (pressurised) is also applied. Following capture of analytes on the Tenax liner, the injector is heated to 330°C at 12°C/min.

The mass spectrometer conditions used were as follows:

The mass spectrometer quadrupole temperature was set at 150°C, the source was set at 230°C and the transfer line was held at 250°C. Positive ion electron impact (EI) spectra at 70eV were recorded in SIM and SCAN mode with no solvent delay (Bizaj et al. 2012)."

Statistical analysis

All statistical analysis was conducted using IBM® SPSS® Statistics (Release 22.0, IBM Corp. Armonk, NY, USA) to a significance level of $p<0.05$. Linear regression analysis was used to determine the relationship between zonal mean PCD values and methoxypyrazine concentrations (IBMP, IPMP, SBMP). ANOVA was undertaken to examine the effects of PCD, vintage, site, and vigour on methoxypyrazines.

Results

Only IBMP was detected in this analysis, IPMP and SBMP were not detected and are therefore not considered further. The results of this experiment demonstrate that there are trends of IBMP concentration dependent on vigour as measured by PCD (Figure 7.1). Significant differences exist between the IBMP concentrations recorded in wines from the

Great Southern and the IBMP concentrations found in the wines from the more northern Margaret River and Geographe sites.

Main effects of vintage, site, and vigour on methoxypyrazine

ANOVA was undertaken to test effects of vintage, site, and vigour zone on methoxypyrazine concentrations of wines. Results from this analysis indicated only IBMP concentrations were significantly different between the southern (Great Southern) and more northern sites (Geographe and Margaret River). Wines from the Great Southern did not contain detectable concentrations of IBMP; therefore when the results from this site are excluded, there is no region (GI) effect on IBMP for the samples under consideration (Margaret River and Geographe).

A significant treatment effect was found at the vine vigour level (Figure 7.5), and at the GI x vigour level interaction (Figure 7.2, Figure 7.3, and Figure 7.4). In 2013 wines derived from vines grown within the low vigour zone had, on average, 0.4 ng/L more IBMP than wines derived from vines grown within the high vigour zone. The following year a similar treatment effect was apparent: wines derived from the low vigour zone had 0.3 ng/L more IBMP than wines from the high vigour zone.

Additionally, there was a significant effect of vintage for the Geographe and Margaret River wines (Figure 7.8). The marginal mean of IBMP concentration for Geographe wines show an increase of 0.2 ng/L from 2013 to 2014, while IBMP concentrations of Margaret River wines decreased by 1.1 ng/L from 2013 to 2014.

Relationship between vigour and methoxypyrazine concentration

A linear regression analysis of methoxypyrazine concentration on zonal mean PCD values was carried out by region and vintage. The results for the Margaret River GI showed wine IBMP concentrations declined with increasing vigour (Figure 7.1) For the Geographe site (Figure 7.1), the results indicated a negative relationship between IBMP and vigour in both years. However, as shown in Appendix 1, the high and low vigour zones were not stable across vintages for this site. As the same harvest zones were used in consecutive vintages, it is interesting that 2 of the 3 low vigour harvest zones had PCD values greater than the values of the high vigour harvest zones. Wines from the Great Southern site did not contain detectable levels of IBMP.

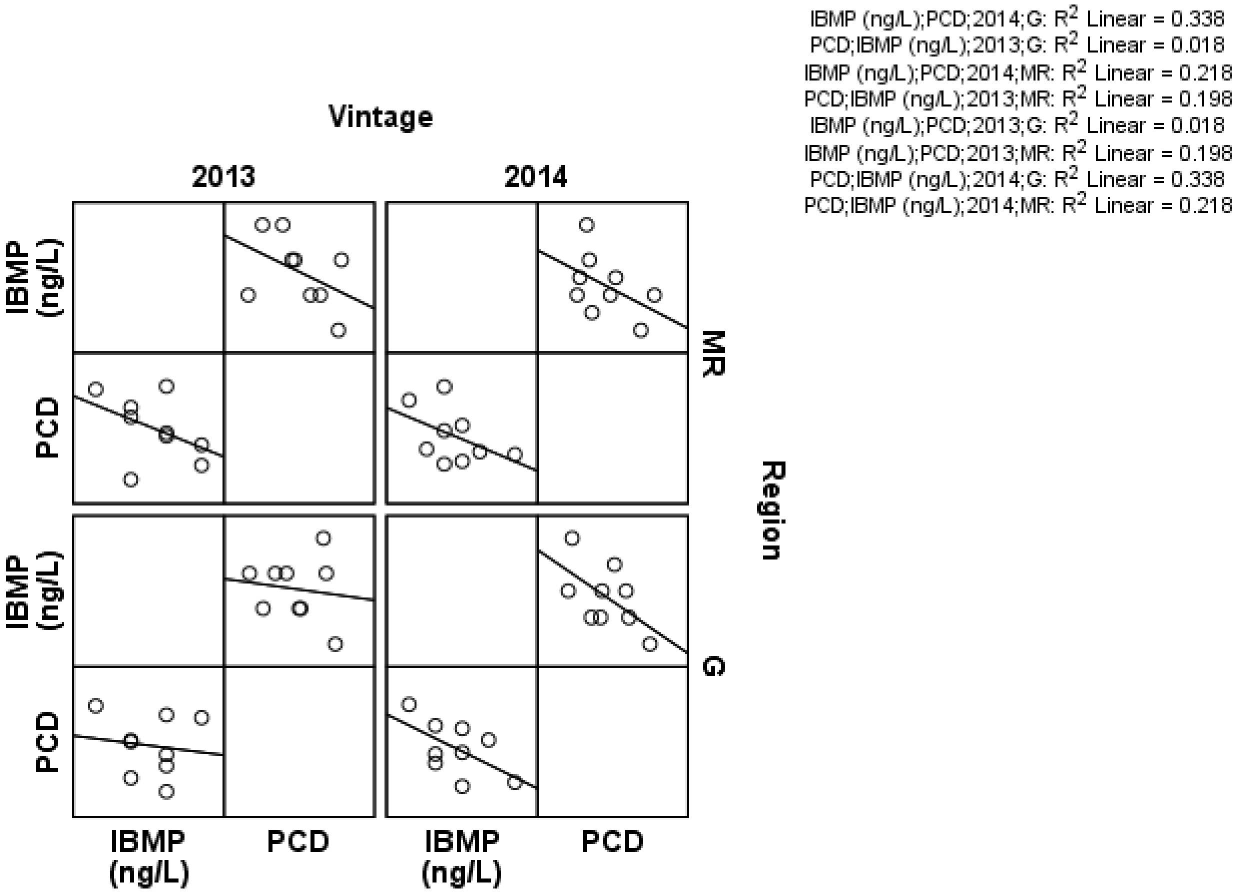

Figure 7.1 Relationship between isobutyl-methoxypyrazine (IBMP) and plant cell density (PCD). Matrix plot shows results of IBMP against PCD by region (Margaret River and Geographe; no IBMP was detected in Great Southern wines) and vintage. MR is Margaret River and G is Geographe. Linear regression R^2 values are located at top right.

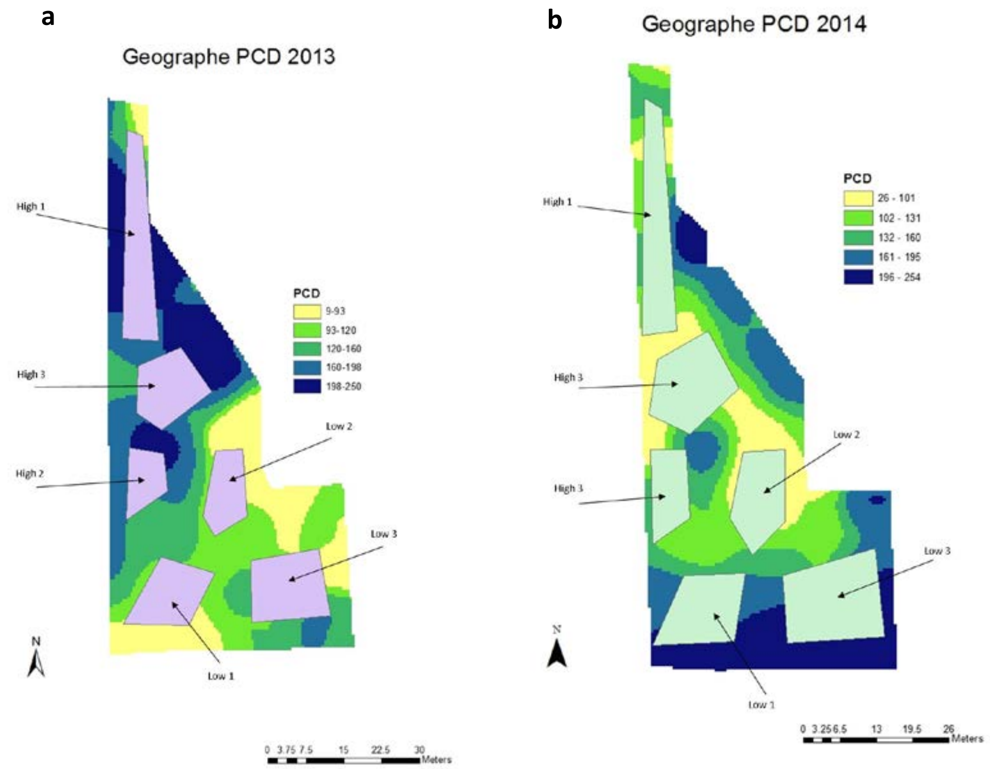

Figure 7.2 Plant cell density (PCD) imagery for the Geographe site for 2013 (a) and 2014 (b) vintages overlayed by harvest zones. Harvest zones are shaded polygons and labelled by vigour zone (high or low) and harvest zone number (1, 2, or 3).

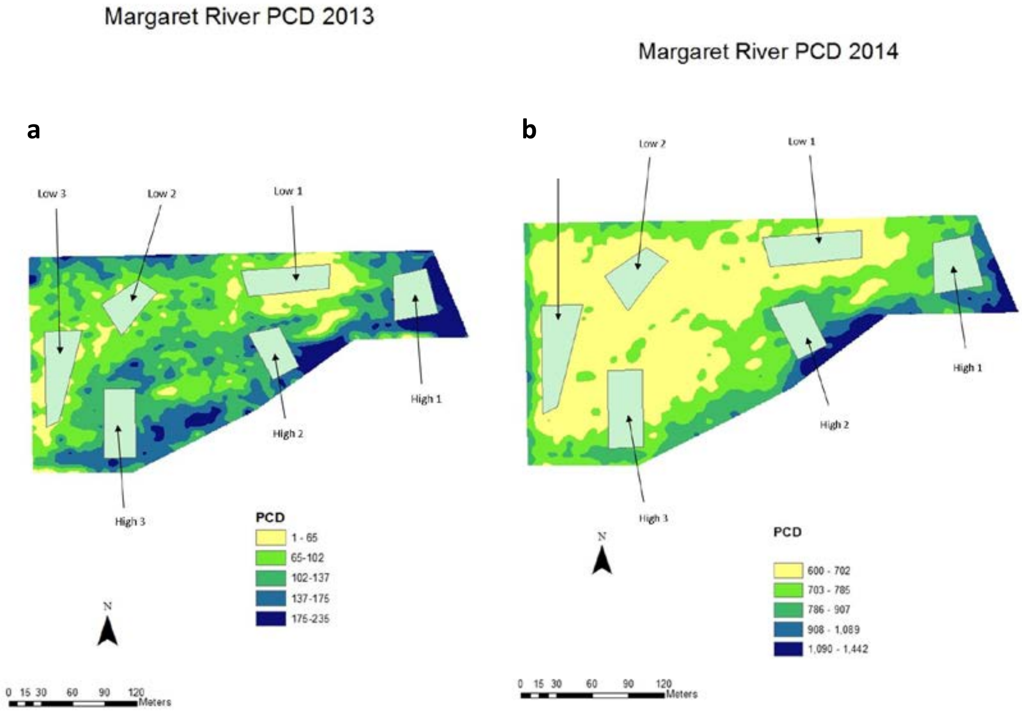

Figure 7.3 Plant cell density (PCD) imagery for the Margaret River site for 2013 (a) and 2014 (b) vintages, overlayed by harvest zones. Harvest zones are shaded polygons and labelled by vigour zone (high or low) and harvest zone number (1, 2, or 3).

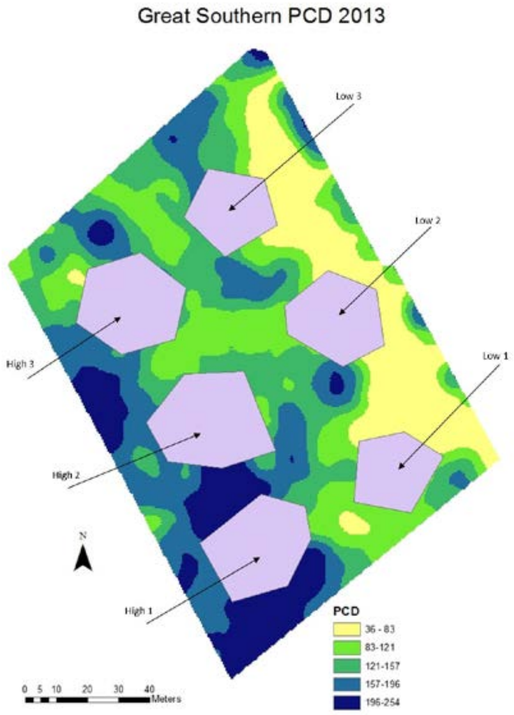

Figure 7.4 Plant cell density (PCD) imagery for the Great Southern site for the 2013 vintage overlayed by harvest zones. Harvest zones are shaded polygons and labelled by vigour zone (high or low) and harvest zone number (1, 2, or 3).

None of the wines from any of the sites recorded an IBMP concentration above 15 ng/L (Figure 7.6, Figure 7.7, Figure 7.8), which Roujou de Boubée (2000, 2002) demonstrated to be a clearly distinguishable threshold. Also of note is the average IBMP concentration by site: wines from the cool climate region, Great Southern (Figure 7.4), recorded no IBMP concentration, whereas wines from the warmer regions, Geographe (Figure 7.2) and Margaret River (Figure 7.3), recorded between 7 and 12 ng/L (Figure 7.6, Figure 7.7, Figure 7.8).

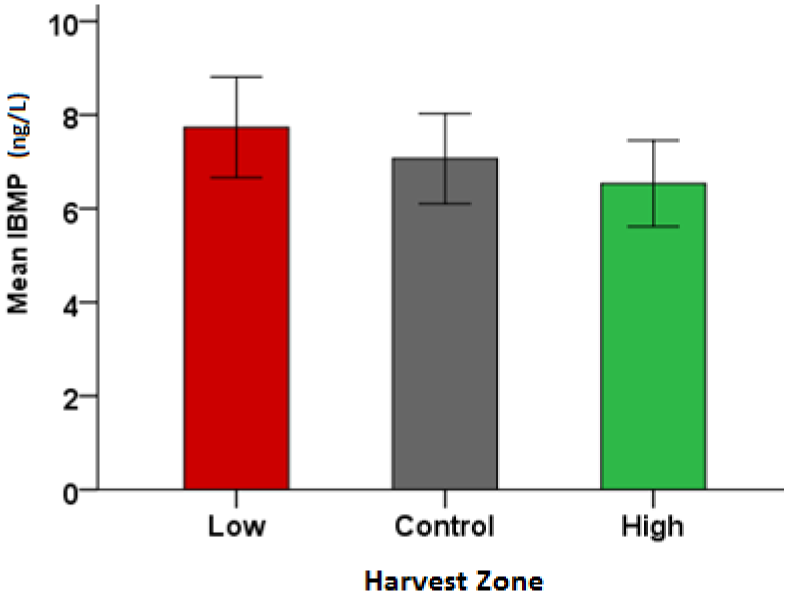

Figure 7.5 Mean isobutyl-methoxypyrazine (IBMP) concentrations across the low and high vigour zones and the control blend (n=18). Mean values were calculated from 2 vintages of wines (2013 and 2014) for the Geographe and Margaret River regions and 1 vintage of wines for the Great Southern (2013). Error bars indicate +/- 1 standard error of the mean.

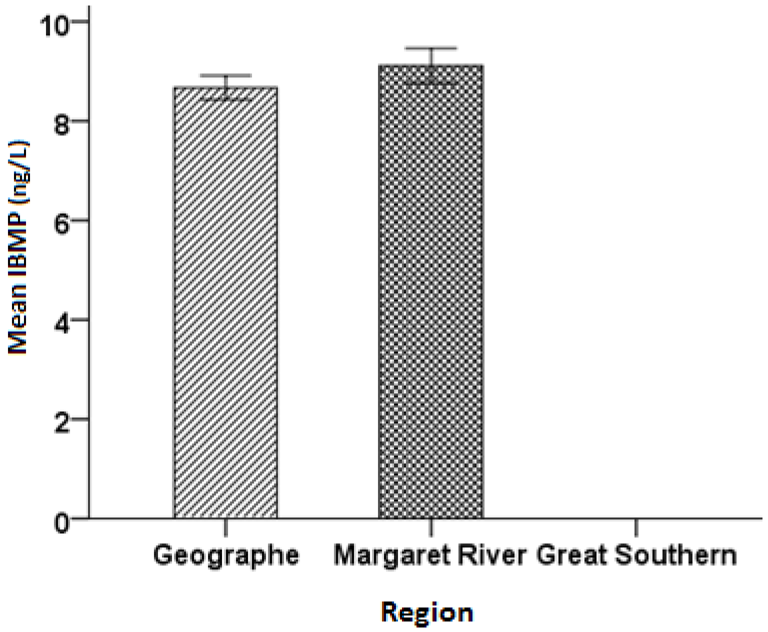

Figure 7.6 Mean isobutyl-methoxypyrazine (IBMP) concentrations (n=18) across the 3 sites: Geographe, Margaret River, and Great Southern. Mean values were calculated from 2 vintages of wines (2013 and 2014) for the Geographe and Margaret River regions and 1 vintage of wines for the Great Southern (2013). No IBMP was detected in wines from the Great Southern site. Error bars indicate +/- 1 standard error of the mean.

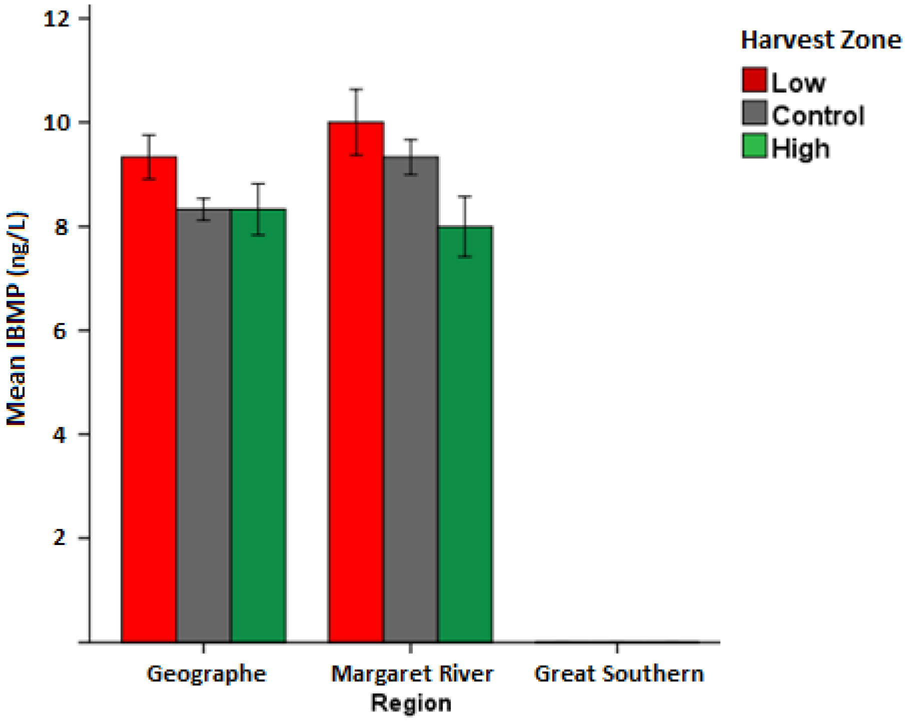

Figure 7.7 Mean isobutyl-methoxypyrazine (IBMP) concentrations of each vigour zone and control blend (n=6) for the two vintages. Mean values were calculated from 2 vintages of wines (2013 and 2014) for the Geographe and Margaret River regions and 1 vintage of wines for the Great Southern (2013). No IBMP was detected in the wines from the Great Southern site. Error bars indicate +/- 1 standard error of the mean.

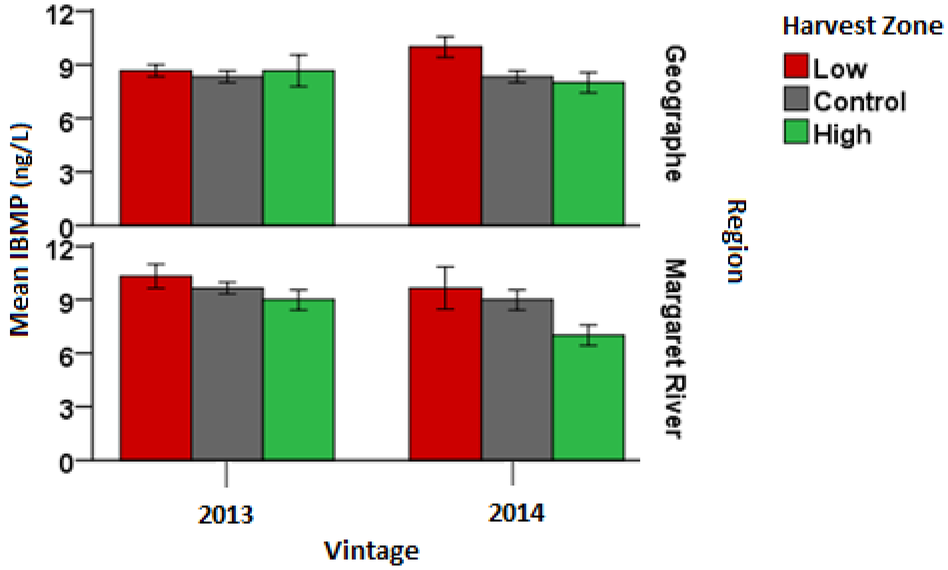

Figure 7.8 Mean isobutyl-methoxypyrazine (IBMP) concentrations by vigour zone and control blend from the 3 sites and across the 2 vintages. Mean values were calculated from 2 vintages of wines (2013 and 2014) for the Geographe and Margaret River regions and 1 vintage of wines for the Great Southern (2013). No IBMP was detected in wines from the Great Southern site. Error bars indicate +/- 1 standard error of the mean.

Isobutyl-methoxypyrazine (IBMP) and total soluble solids (TSS)

It is possible that factors other than vigour influenced the concentration of IBMP or that harvest management (delayed harvest) eliminated the potential effect of vigour. Information on the specific dates that "sugar maturity" was reached for each site is unavailable; however, TSS measurements of final juice chemistry for each of the zones were collected at harvest. Regression analysis of IBMP and TSS (not including Great Southern data) indicates a statistically significant yet relatively weak relationship between these variables (R^2=0.10). When the analysis is performed separately for each site and both vintages, the relationship is increasingly weak (R^2 values between 0.003 and 0.08), with the exception of analysis from the Margaret River site in 2014 ($R^2 = 0.66$).

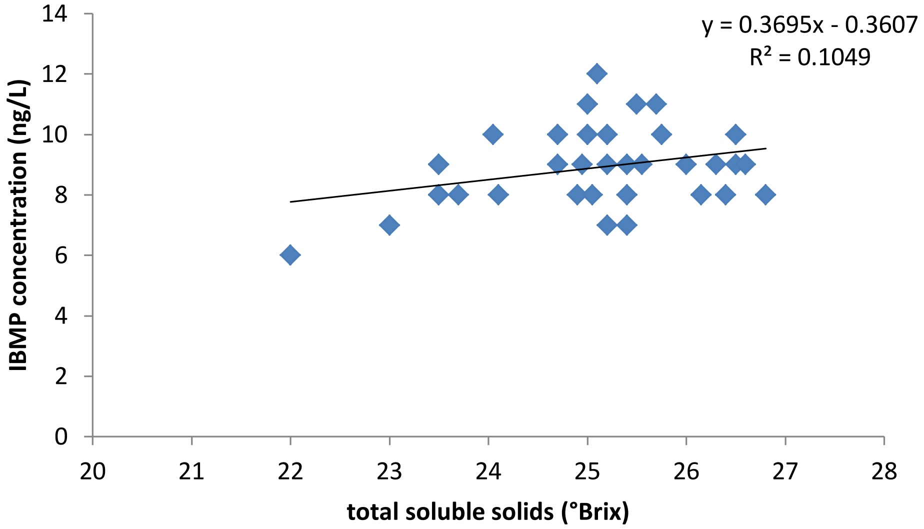

Figure 7.9 The relationships between isobutyl-methoxypyrazine (IBMP) and total soluble solids (TSS). Data are individual observations (n=36) with a fitted linear regression, equations are fitted linear regressions, and R^2 values are coefficients of determination. As no IBMP was detected in the wines from the Great Southern, data has not been included in this analysis.

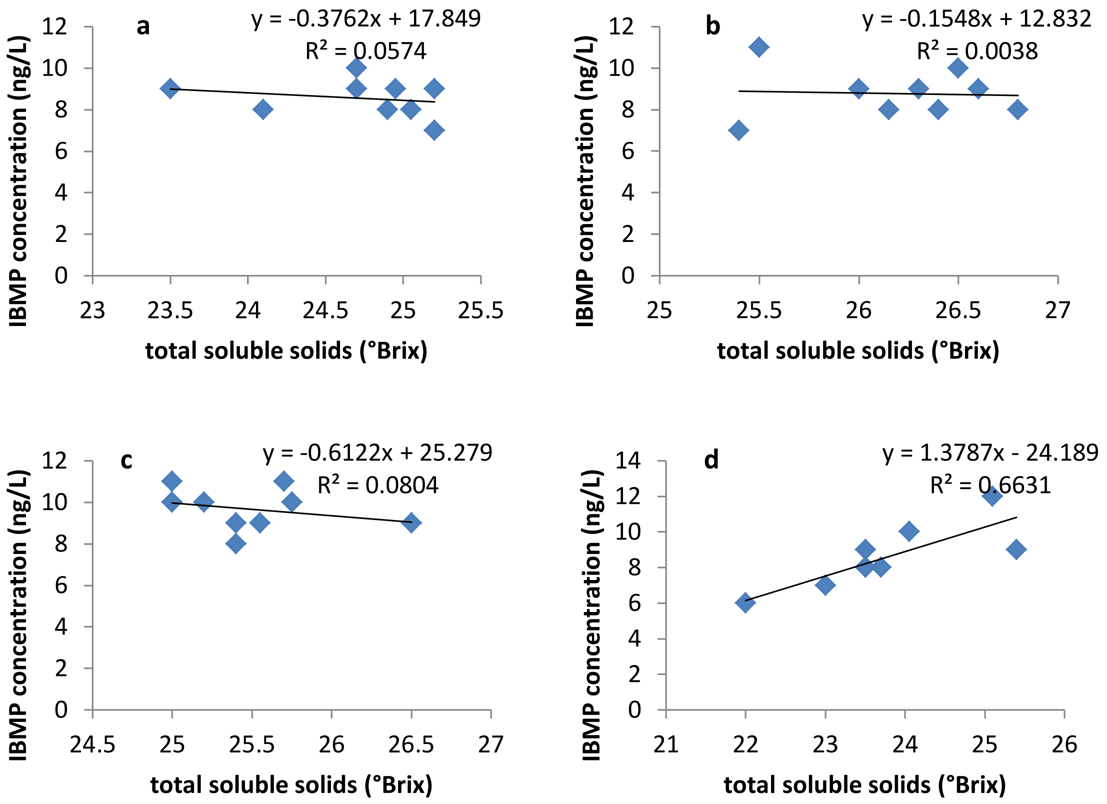

Figure 7.10 The relationships between isobutyl-methoxypyrazine (IBMP) and total soluble solids (TSS). Data are individual observations (n=9) with a fitted linear regression, equations are fitted linear regressions, and R^2 values are coefficients of determination. The analysis is shown for both the Geographe and Margaret River sites separately for each vintage: (a) is

analysis of the Geographe site's data in 2013, (b) is analysis of the Geographe site's data in 2014, (c) is analysis of the Margaret River site's data in 2013, and (d) is analysis of the Margaret River site's data in 2014.

Discussion

This chapter examined the relationship between PCD and methoxypyrazine (MP) concentrations from different vigour zones across three climatically distinct sites, and found a negative linear relationship between MP (specifically IBMP) concentration and PCD value. Additionally, the results suggest that a relationship between IBMP and climate may exist as results from the Great Southern site, a cool climate region, had no measurable IBMP while results from the two more northern sites, Margaret River and Geographe, had IBMP concentrations ranging from 7 to 12 ng/L. However, it is possible that canopy management (i.e. leaf plucking or other canopy management strategy to maximise sunlight exposure to the fruit) may have been responsible for the lack of IBMP detection in Great Southern wines. Also, it should be reiterated that the level of detection of IBMP in this study was 5 ng/L, therefore it is possible that wines from this site may have contained IBMP concentrations below this detectable limit.

It has been shown that high vigour vines tend to yield fruit with higher concentrations of IBMP than do low vigour vines (Wilkinson et al. 2006). Sala et al. (2004) noted that IBMP concentration in Cabernet Sauvignon decreases as the fruit ripens. As this study found no consistently strong correlation between IBMP and TSS, it is possible that a harvest management strategy may have neutralised the effect of vigour. For example, if the fruit did not struggle to ripen and were left on the vine to develop flavour compounds, IBMP concentrations would have decreased throughout this time. Sidhu et al. (2015) noted that "delaying the harvest can lower IBMP levels in the fruit, thus it is important for wine regions that exhibit higher herbaceous or green odour characteristics in wines to select appropriate harvest dates in an attempt to minimize MP levels prior to vinification, if the weather permits." This is in line with findings from Allen et al. (1991, 1994) that demonstrated the importance of temperature during ripening as a more important factor than TSS. Unfortunately, specific data as to maturity (TSS measurements) dates for each of the 3 sites in this chapter were unavailable. It is possible that the relatively late harvest of the Great

Southern (9 April 2013) fruit may have contributed to a lack of IBMP detection. As the relationship between IBMP and TSS at the Geographe and Margaret River sites was relatively weak (R^2=0.1), perhaps harvest management strategy (i.e. delayed harvest) eliminated the effect of vigour.

Previous research indicated a potential relationship between MP (specifically IBMP) concentration and climate (Allen et al. 1991, Boss et al. 2008, Heymann and Noble 1987, Lacey et al. 1999, Noble et al. 1995). Sidhu et al. (2015) noted that "vines in cooler regions experience greater water availability and soil fertility, which leads to increased vigour and shading, which both have influences on IBMP concentration." However, there is a degree of conjecture to this claim, as Robinson et al. (2012) noted that this relationship is often superseded by growing season conditions. Additionally, not all cooler regions have greater water availability and soil fertility. These properties are site specific; therefore, vines from a site from a cool region may or may not be more vigorous than vines from a warmer region. This is further supported by Howell et al. (2006) who noticed relatively low IBMP concentrations (<5 ng/L, which is the detectable limit of this experiment) from cool climate wines harvested at relatively low TSS levels. Again, this research did not detect IBMP in wines from the cool climate Great Southern region, but this could be due to harvest timing, canopy management, or overall vine vigour.

Past work has also found that vine training and canopy style have a profound effect on MP concentrations in grapes, however, specific vigour quantification has been lacking. Overall, it is known that MP concentrations tend to increase with less direct sunlight exposure to the fruit (Allen 1993, Allen and Lacy 1999, Hashizume and Samuta 1999, Heymann et al. 1986, Roujou de Boubée et al. 2000, Sala et al. 2004); however, it could be that canopy structure as opposed to canopy surface area (vigour) is of greater importance. Heymann et al. (1986) found that direct sunlight exposure to the fruit decreased methoxypyrazine concentrations. Allen et al. (1988) found similar results, noting that leaf plucking early in the growing season (pre-véraison) decreased methoxypyrazine concentrations in Sauvignon Blanc. This was further supported by Allen (1993), who demonstrated the effect of canopy architecture (leaf plucking to expose fruit to sunlight) on reduced concentrations of methoxypyrazines in Sauvignon Blanc. Ryona et al. (2008) noted the effect of sunlight exposure on IBMP concentration, finding that fruit exposed to sunlight pre-véraison demonstrated a significant decrease in IBMP concentration, yet sunlight exposure post-véraison exhibited no significant effect. Wilkinson et al. (2006) found that high vigour vines "allowed between 59% and 87% less light to infiltrate the canopy than low vigour vines." Additionally, Wilkinson et al. (2006) noted that fruit from high vigour vines also yielded wines with higher IBMP concentrations than did fruit from low vigour vines. It is possible that the reduced light infiltration to the canopy, as opposed to overall vine vigour, caused the increased IBMP concentrations. As the results from this chapter found that IBMP tended to decrease with an increase in PCD, perhaps it is canopy structure that is the stronger driver of IBMP concentration in wine rather than vine vigour. So, if for low vigour vines leaf plucking was limited or avoided altogether while for high vigour vines the fruiting zone was more exposed by leaf removal, then the observed relationships between PCD and IBMP is not an oddity. Additionally, due to the early timing of the leaf plucking (pre-véraison) at the Great Southern site, it is possible that canopy management played a large role in the lack of detectable IBMP in the wines.

It is known that IBMP contributes to the vegetative and bell pepper characteristics in Cabernet Sauvignon (Chapman et al. 2004, Noble et al. 1995, Robinson et al. 2011, Robinson et al. 2012, Roujou de Boubeé et al. 2000). By more closely understanding the relationships between IBMP concentrations and vine vigour as measured by PCD values, PV technologies (like PCD imagery) could potentially be used to identify zones of higher IBMP concentration in a vineyard. This chapter found a negative linear relationship between IBMP concentrations and PCD values, indicating that low vigour vines tended to contain higher concentrations of IBMP than did high vigour vines. Through a greater understanding of the volatile drivers of sensory characteristics and the specific vine attributes driving the production of these volatiles, PV technologies could potentially be used to map these traits and create a targeted zonal management strategy specific to the desired wine style.

Additionally, the small size of the Geographe site has had conflicting results not in line with *a priori* assumptions. As stated in the methods, the same harvest zones were used in consecutive vintages. The high and low vigour zones were temporally stable at the Margaret River and Great Southern sites, yet the Geographe site exhibited mixed results. Two of the harvest zones in the low vigour section should have been classified as high vigour, whereas 1 of the harvest zones from the high vigour section should have been classified as low vigour. Again, perhaps due to the very small size of the block, 0.27 ha, vigour zone effects are not as anticipated.

It is suggested that future research should more closely examine the effects of canopy size, canopy structure, and vigour on methoxypyrazine concentrations in fruit as well as wine.

Conclusion

This research was undertaken to examine the relationship between vigour in the vineyard and methoxypyrazine concentration in resultant wines from three climatically distinct regions of WA. A negative linear relationship was found between vigour and IBMP concentration. However, whereas previous research reported that wines from cooler climates as well as from high vigour zones tended to be higher in IBMP: this research found the opposite trend: wines from the cool climate region, Great Southern, recorded no IBMP while wines from the warmer Margaret River and Geographe sites recorded IBMP concentrations between 7-12 ng/L, also wines from high vigour zones fruit tended to have lower concentrations of IBMP than wines from low vigour zone fruit. This may be due to the particular vineyard management style of the Great Southern site.

Chapter 8 Gas Chromatography Mass Spectrometry (GC-MS) and descriptive sensory analysis of Cabernet Sauvignon wines from varying vigour zones from three different sites in Western Australia

Introduction

What sets the price point of fruit and wine? A large spectrum of price points exists in the wine industry (Costanigro et al. 2007, Davis and Ahmadi-Esfahani 2006, Ernst and Young Entrepreneurs 1999). Price point assignment of wines is an interesting and perplexing problem economists have endeavoured to model and understand (Jones and Storchmann 2001, Lecocq and Visser 2006, Ling and Lockshin 2003). Econometric analysis, primarily hedonic regression has been used to try and identify main drivers of price (Angulo et al. 2000, Oczkowski 2001, Oczkowski 2006, Schamel and Anderson 2003, Unwin 1999, among others). This approach has had contradictory results, with some researchers arguing that intrinsic properties have no significant relationship to price (Landon and Smith 1998, Oczkowski 2001, Lecocq and Visser 2006), others arguing that intrinsic characteristics are significant drivers of price (Cardebat and Figuet 2006, Nerlove 1995, Schamel and Anderson 2003), and still others arguing that the methodology used in most analyses is fundamentally flawed (Miller et al. 2007, Unwin 1999).

Notwithstanding these incongruous results, most of the research has tended to focus on extrinsic characteristics (region of origin, alcohol content, etc.). It has been difficult to separate intrinsic and extrinsic characteristics of quality (Cardello 1995, Jackson 2008, Lawless 1995, Steenkamp 1989, Verdú 2004), especially since sensory analysis is essential to acquiring meaningful data on intrinsic aspects of wine quality (Noble 2001, Stone and Sidel 2004). Unfortunately, sensory analysis can be challenging to conduct and interpret results due to inherent human variability (Stone and Sidel 2004). However, as Jackson (2008) notes "although sensory evaluations are to a large degree subjective, and therefore largely unquantifiable, they have greater significance than objective chemical analyses."

Recent developments in the analysis of wine chemistry, specifically in the form of gas chromatography mass spectrometry, have enabled scientists to take a closer look at specific wine compounds and attempt to trace their connection with sensory properties. For example, several studies have found a relationship between methoxypyrazines and vegetal aromas (Robinson et al. 2011, Robinson et al. 2012). However, Preston et al. (2008) noted that

> “methoxypyrazines, typically associated with vegetal aromas, were also measured for these wines and were not correlated with any of the descriptive terms, suggesting that other classes of aroma compounds contribute to the vegetal aromas in wines. The results indicate a more complex interrelationship between chemical composition and sensory perception of vegetal aromas in Cabernet Sauvignon wines than had previously been hypothesized.”

This finding was supported by Ebeler (2001) who noted the importance of analysing the interactions of volatiles and non-volatile compounds in addition to just volatiles with each other. Furthermore, Robinson et al. (2014) noted that “it is still not possible to fully predict aroma quality based on chemical composition alone” due to the inherent complexities of wine volatile and non-volatile properties in addition to sensory perceptions.

Relatively limited research has been undertaken to compare vine attributes such as yield, irrigation techniques, canopy, and region to wine chemistry and sensory properties (Chapman et al. 2005, Holt et al. 2008). It is crucial to observe effects through the full production cycle, as some aspects that are strongly perceptible at the berry level, may be minimally or not at all perceptible at the wine level (Holt et al. 2008). One uniquely comprehensive study was that from Bramley et al. (2011) which investigated potential relationships between vine vigour, vineyard attributes, and organoleptic and chemical characteristics of subsequent wines. Through descriptive sensory analysis they found that low vigour wines tended to be more fruit driven, while high vigour wines were dominated by more vegetative, green characters.

Overall, the interrelationships between vine attributes, vineyard characteristics and resultant wine chemistry and organoleptic properties have proven complex. Holt et al. (2008) found that wine composition was not always “directly influenced by berry composition,” and that the interrelationships between berries, wine sensory, and wine quality can vary dramatically within a block. Chapman et al. (2004) found that Cabernet

Sauvignon sensory properties are significantly affected by yield only when manipulated early in fruit development. The following year, Chapman et al. (2005) found that irrigation has an inverse relationship with fruity characteristics and a direct relationship with vegetative characteristics.

Previous research has also shown a relationship between region, site, and within vineyard traits. Robinson et al. (2012) explored the concept of regionality in Cabernet Sauvignon and how it is manifested in both sensory perception and chemical composition. Robinson's study found correlations between sensory attributes and chemical profiles of wines. Additionally, it found differences between the commercial wines from each of the GIs included in the study. The findings indicate that sensory and chemistry aspects of Cabernet Sauvignon are related to region of origin. Robinson et al. (2011) found that site, followed by canopy management had the strongest relationship with sensory and chemistry characteristics. No significant relationship was found between yeast strain and sensory perceptions, even though the wine chemistry profile indicated significant differences in composition.

This chapter provides a comprehensive look at what many researchers have selectively analysed by looking at site, vigour (canopy characteristics), yield, vintage, sensory, chemistry, and price. It incorporates two new sensory measures: balance and complexity. The introduction of these parameters was facilitated by the descriptive sensory analysis panellists, who felt that the analysis of aroma and taste receptors did not provide adequate means for analysis of wine quality. To the best of the researcher's knowledge, these parameters have never before been reported in descriptive sensory analysis scoring.

This research examines the intrinsic characteristics of wine (both sensory and chemistry), vine vigour (as measured by PCD), and any potential relationship with price. It analyses the role of intrinsic quality factors in price point assignment, and evaluates the relationship between wine chemistry profile and organoleptic perceptions. It is the first study of this kind to test the relationships between vineyard traits (region, vigour zone, and PCD value), detailed sensory analysis by a trained panel, volatile profiling via GCMS technology, and price point assignment. It attempted to assess if certain price points have similar viticultural, chemical, or sensory characteristics. It was hypothesized that wines from the low vigour zones will be more strongly correlated with "positive" sensory traits and higher price points than the wines from the high vigour zones.

Methodology

This experiment was designed to compare the organoleptic and volatile properties of wines made from different vigour zones and any relationship these characteristics may share with price. It accomplished this through vigour zone identification through PCD imagery analysis and manual sampling methods, small lot winemaking, targeted and untargeted volatile analysis via gas chromatography mass spectrometry, and quantitative descriptive sensory analysis. Furthermore, it sought to examine the relationships between vintage, region, and vigour.

Site selection

The same sites from Chapter 7 were used in this experiment.

Vigour Zone Identification

The same vigour zones and harvest zones from Chapter 7 were used in this experiment.

Small lot winemaking

The same wines from Chapter 7 were used in this experiment.

Sensory Analysis

Approval for this sensory analysis was given by the Curtin University Research Ethics Committee (RD-11-14). Eight oenology students at Curtin University of Technology were selected as panellists based on interest and availability. Six training sessions and four formal evaluations were conducted in August and September of 2014. At the start of each training session, each panellist was asked to evaluate 11 reference standards (seven aroma and four taste) and identify the corresponding aroma or taste. Reference standards were prepared according to the guidelines in Table 8.1. The scores of these individual assessments were recorded to monitor panellist ability and serve as objective criteria in panellist performance. Through panellist discussion, it was determined that an additional two characteristics should be included in the study: balance and complexity. No reference standards were made for these.

At every training session, the panellists were presented with three flights of nine wines, segregated based on site. Wines (20 mL samples) were provided in clear coded tulip shaped glasses. Within flights the wines were presented randomly. Panellists were informed that all the wines were Cabernet Sauvignon and a price point was given for the middle wine. Other than this, no information about the wines was supplied. They were asked to assess the wines for each of the 11 reference standards, balance, complexity, and price. Using a 15 cm unstructured line scale anchored with the terms “low” and “high,” they were asked to score each wine individually for each of the 13 characteristics and assign a price point. They were asked to use the given price point as an anchor to score the other two wines in the flight. After each flight, the panellists spoke about their scores and collectively developed an index to intensity scoring. Through discussion and repeated trials, panellists were able to calibrate their descriptions, scores, and price points with one another.

The same wines were assessed formally over the course of four evaluation sessions. Reference standards were available for panellist reference during the formal evaluations. Twelve wines (20 mL samples) were presented per session in a random order. Panellists were asked to score each wine separately for each of the 13 characteristics and assign a price point. All sensory analysis was conducted in a sensory specific laboratory with controlled lighting and in accordance with ISO 8589:2007.

Table 8.1 Composition of aroma and taste reference standards

Descriptor	**Standard (375 mL wine)***
Red berry	2 strawberries, 10 raspberries
Dark fruit	5 blackberries, 10 blueberries, 10 mL cassis
Jam	1 tsp each of strawberry, blackberry, and blueberry jams
Capsicum	2.5 g capsicum (chopped)
Eucalyptus	1 drop eucalyptus extract
Canned Vegetable	10 mL green bean brine, 2 segments each of green bean and asparagus
Fault	1 drop 4 ethyl phenol
Sweet	80 g sugar in 500 mL water
Sour	200 mg citric acid in 500 mL water
Bitter	800 mg caffeine in 500 mL water
Astringent	800 mg tannin in 500 mL water

*All standards were prepared in 50 mL Hardy's Regional Range Cabernet Sauvignon

Volatile Analysis

Wines were analysed via targeted and untargeted analysis by Metabolomics Australia at the Australian Wine Research Institute, following the methodology of Bizaj et al. (2012) outlined in Chapter 7. Targeted analysis involves the measurement of specified volatile compounds, whereas untargeted analysis is a comprehensive analysis of "all the measurable analytes in a sample including chemical unknowns" (Roberts et al. 2012).

Statistical Analysis

All statistical analysis was conducted using IBM® SPSS® Statistics (Release 22.0, IBM Corp. Armonk, NY, USA) to a significance level of $p<0.05$. Automated linear modelling was performed on the individual data sets (sensory and volatile) and on the combined data set (sensory + volatile) to determine primary drivers of price. Model outcomes were used to perform more in-depth linear regression and determine the most significant attributes influencing price. Optimal scaling (quantitative principal component analysis) was used to determine correlation and grouping among variables. Partial least squares (PLS) regression was used to compare the standardized responses (i.e. centred and scaled) for significant volatile compounds and sensory characteristics.

Results

The results of this experiment determined a number of sensory (Table 8.2, Table 8.3) and volatile (Table 8.4, Table 8.5) drivers of price; these included: balance, complexity, astringency, ethyl 2-methylpropanoate, and ethyl acetate. Additionally, it examined associations between sensory characteristics, volatile properties, and price, determining that fruity characteristics, (i.e. red berry, dark fruit, and jam) tended to be grouped with balance, complexity, price, and ethyl propanoate. Vegetative characteristics, bitterness, astringency, and a number of volatile compounds were negatively associated with price. Furthermore, it analysed the main effects of vintage, site, and vigour and their interactions on sensory and volatile properties of the wines, which dominated in that order.

Sensory drivers of price

Multiple regression analysis of price against sensory attributes yielded two candidate models with Akaike's information criterion values within 5 points of each other. Akaike's information criterion value is a measure of the quality fit of potential models to a data set (Hu 2007). Stepwise multiple linear regression of price on sensory attributes identified three potential models ($p<0.05$) (Table 8.6).

Table 8.2 Mean sensory scores by vigour zone for each site (2013 vintage). Data are mean scores (n=9) is followed by standard errors.

	2013								
	Geographe			**Margaret River**			**Great Southern**		
	Low	**Control**	**High**	**Low**	**Control**	**High**	**Low**	**Control**	**High**
Astringent	4.18 ± 0.24	3.73 ± 0.29	3.45 ± 0.13	4.72 ± 0.4	4.73 ± 0.31	3.87 ± 0.2	3.95 ± 0.19	4.55 ± 0.24	3.44 ± 0.1
Balance	5.41 ± 0.18	6.77 ± 0.2	5.95 ± 0.51	4.9 ± 0.25	5.26 ± 0.32	5.54 ± 0.12	5.21 ± 0.05	6.45 ± 0.23	6.8 ± 0.22
Bitter	3.34 ± 0.17	3.33 ± 0.08	2.48 ± 0.07	3.95 ± 0.09	3.34 ± 0.23	2.98 ± 0.21	3.17 ± 0.16	3.04 ± 0.03	3.24 ± 0.17
Canned vegetable	2.88 ± 0.08	2.28 ± 0.11	2.26 ± 0.19	3.21 ± 0.4	2.17 ± 0.26	2.33 ± 0.2	2.4 ± 0.29	1.64 ± 0.03	2.49 ± 0.27
Capsicum	1.88 ± 0.2	2.15 ± 0.18	1.74 ± 0.27	2.4 ± 0.15	1.41 ± 0.12	1.38 ± 0.34	1.19 ± 0.11	1.41 ± 0.25	1.42 ± 0.14
Complexity	5.47 ± 0.35	5.38 ± 0.41	4.93 ± 0.26	4.34 ± 0.18	3.94 ± 0.25	5.7 ± 0.02	5.47 ± 0.11	6.3 ± 0.13	5.33 ± 0.12
Dark fruit	5.16 ± 0.15	6.28 ± 0.59	5.29 ± 0.1	4.94 ± 0.1	5.35 ± 0.27	6.45 ± 0.23	5.95 ± 0.25	7.04 ± 0.11	5.66 ± 0.51
Eucalyptus	1.86 ± 0.22	1.82 ± 0.11	2.68 ± 0.49	1.17 ± 0.15	1.47 ± 0.07	1.87 ± 0.28	2.4 ± 0.45	2 ± 0.14	1.23 ± 0.27
Fault	0.04 ± 0.02	0.01 ± 0	0.14 ± 0.08	0.01 ± 0.01	0.01 ± 0	0 ± 0	0.13 ± 0.07	0 ± 0	0.02 ± 0.01
Jam	4.58 ± 0.28	4.41 ± 0.22	4.68 ± 0.23	4.08 ± 0.15	4.55 ± 0.3	4.71 ± 0.19	4.67 ± 0.28	5.51 ± 0.29	4.71 ± 0.45
Red berry	5.36 ± 0.19	5.33 ± 0.5	3.94 ± 0.41	3.59 ± 0.19	3.82 ± 0.2	4.4 ± 0.05	4.67 ± 0.07	5.2 ± 0.33	5.55 ± 0.37
Sour	3.09 ± 0.05	2.97 ± 0.17	2.95 ± 0.19	2.33 ± 0.22	3.23 ± 0.06	2.59 ± 0.2	2.83 ± 0.18	2.46 ± 0.22	3.27 ± 0.2
Sweet	0.8 ± 0.05	0.81 ± 0.12	0.82 ± 0.11	0.92 ± 0.18	0.75 ± 0.11	0.67 ± 0.1	0.8 ± 0.15	0.62 ± 0.08	1.22 ± 0.1

Table 8.3 Mean sensory scores by vigour zone for each site (2014 vintage). Mean score is followed by standard error.

	2014					
	Geographe			**Margaret River**		
	Low	**Control**	**High**	**Low**	**Control**	**High**
Astringent	4.65 ± 0.44	4 ± 0.29	4.65 ± 0.4	5.33 ± 0.41	5.03 ± 0.22	4.79 ± 0.15
Balance	6.12 ± 0.49	5.75 ± 0.22	5.83 ± 0.18	5.5 ± 0.12	5.32 ± 0.16	5.9 ± 0.33
Bitter	4.08 ± 0.23	3.41 ± 0.13	3.72 ± 0.04	3.37 ± 0.12	3.44 ± 0.28	3.47 ± 0.2
Canned vegetable	2.7 ± 0.23	3.4 ± 0.21	3.28 ± 0.35	2.63 ± 0.14	2.69 ± 0.21	3.46 ± 0.31
Capsicum	1.79 ± 0.16	1.7 ± 0.11	1.66 ± 0.17	1.99 ± 0.03	1.34 ± 0.22	2.11 ± 0.24
Complexity	5.69 ± 0.45	5.15 ± 0.31	5.25 ± 0.24	4.66 ± 0.26	4.55 ± 0.22	5.18 ± 0.1
Dark fruit	6.56 ± 0.22	6.48 ± 0.34	5.63 ± 0.17	6.39 ± 0.18	5.76 ± 0.14	5.78 ± 0.32
Eucalyptus	2.08 ± 0.17	2.45 ± 0.45	1.72 ± 0.26	1.59 ± 0.08	2.52 ± 0.04	1.83 ± 0.34
Fault	0 ± 0	0.02 ± 0.01	0.05 ± 0.02	0.01 ± 0	0.02 ± 0.01	0.58 ± 0.32
Jam	5.15 ± 0.14	4.97 ± 0.17	4.74 ± 0.14	4.67 ± 0.02	4.1 ± 0.14	4.48 ± 0.32
Red berry	5.19 ± 0.31	4.81 ± 0.11	4.99 ± 0.13	4.73 ± 0.25	4.64 ± 0.51	4.92 ± 0.17
Sour	2.8 ± 0.29	3.18 ± 0.27	2.61 ± 0.14	2.8 ± 0.06	2.51 ± 0.03	3.17 ± 0.06
Sweet	1.24 ± 0.03	1.12 ± 0.19	1.27 ± 0.09	0.87 ± 0.17	0.81 ± 0.03	0.65 ± 0.16

Table 8.4 Mean volatile concentrations (ng/L) by vigour zone for each site (2013 vintage). Mean concentration is followed by standard error.

	2013								
	Geographe			Margaret River			Great Southern		
	Low	Control	High	Low	Control	High	Low	Control	High
ethyl acetate	52524 ± 1664	48611 ± 609	53211 ± 2084	56675 ± 646	55506 ± 517	61439 ± 2760	52112 ± 2135	52491 ± 386	49887 ± 1481
ethyl propanoate	370 ± 5	414 ± 4	359 ± 11	289 ± 9	297 ± 2	290 ± 4	426 ± 11	420 ± 4	417 ± 4
ethyl 2-methylpropanoate	141 ± 6	146 ± 2	118 ± 5	87 ± 5	85 ± 0	82 ± 2	121 ± 5	118 ± 2	110 ± 4
2-methylpropyl acetate	22 ± 1	19 ± 0	20 ± 1	25 ± 0	25 ± 0	29 ± 2	21 ± 1	22 ± 0	22 ± 0
ethyl butanoate	247 ± 6	212 ± 6	213 ± 3	236 ± 3	196 ± 6	151 ± 4	182 ± 2	188 ± 3	196 ± 5
ethyl 2-methylbutanoate	38 ± 2	41 ± 0	32 ± 1	34 ± 1	34 ± 0	31 ± 0	41 ± 1	39 ± 0	37 ± 1
ethyl 3-methylbutanoate	48 ± 2	46 ± 0	39 ± 1	37 ± 1	36 ± 1	33 ± 0	44 ± 1	42 ± 0	41 ± 1
2-methylpropanol	28726 ± 618	26770 ± 565	26835 ± 984	31881 ± 437	31873 ± 265	34976 ± 1498	34505 ± 909	32567 ± 836	32826 ± 998
2&3-methylbutyl acetate	492 ± 15	282 ± 14	263 ± 16	348 ± 7	288 ± 17	323 ± 15	183 ± 2	179 ± 6	183 ± 5
butanol	1874 ± 46	2212 ± 70	1947 ± 43	2770 ± 75	2606 ± 29	2495 ± 20	2500 ± 89	2190 ± 19	1857 ± 61
2&3-methylbutanol	230969 ± 6302	229258 ± 2339	233930 ± 3583	249909 ± 2964	249561 ± 1151	255372 ± 2469	232462 ± 2161	235816 ± 1901	225086 ± 2698
ethyl hexanoate	492 ± 15	484 ± 12	474 ± 8	418 ± 5	361 ± 9	304 ± 11	293 ± 3	323 ± 8	320 ± 12
hexyl acetate	3 ± 0	2 ± 0	2 ± 0	3 ± 0	2 ± 0	2 ± 0	1 ± 0	1 ± 0	1 ± 0
hexanol	1525 ± 164	2396 ± 76	2382 ± 187	1286 ± 14	1362 ± 55	1438 ± 96	1314 ± 98	1458 ± 60	1220 ± 97
ethyl octanoate	501 ± 5	370 ± 11	398 ± 1	443 ± 8	375 ± 18	293 ± 9	284 ± 5	318 ± 15	318 ± 17
ethyl decanoate	125 ± 3	131 ± 8	143 ± 13	116 ± 8	111 ± 5	95 ± 4	101 ± 3	104 ± 8	109 ± 9
isobutyl-methoxypyrazine	9 ± 0	8 ± 0	9 ± 1	10 ± 0	10 ± 0	9 ± 0	0 ± 0	0 ± 0	0 ± 0

Table 8.5 Mean volatile concentrations (ng/L) by vigour zone for each site for the 2014 vintage. Mean concentration is followed by standard error.

	2014					
	Geographe			Margaret River		
	Low	Control	High	Low	Control	High
ethyl acetate	53500 ± 148	54202 ± 454	55248 ± 417	39297 ± 912	42971 ± 1821	34955 ± 610
ethyl propanoate	343 ± 12	359 ± 4	358 ± 3	295 ± 8	351 ± 13	315 ± 3
ethyl 2-methylpropanoate	28 ± 1	28 ± 0	27 ± 1	18 ± 0	20 ± 1	18 ± 0
2-methylpropyl acetate	30 ± 0	28 ± 0	28 ± 0	28 ± 1	27 ± 0	24 ± 1
ethyl butanoate	206 ± 2	216 ± 2	207 ± 5	178 ± 5	160 ± 2	144 ± 2
ethyl 2-methylbutanoate	7 ± 0	9 ± 0	9 ± 0	8 ± 0	8 ± 0	8 ± 0
ethyl 3-methylbutanoate	9 ± 0	9 ± 0	9 ± 0	7 ± 0	7 ± 0	7 ± 0
2-methylpropanol	24801 ± 287	24538 ± 205	25912 ± 441	26453 ± 266	27353 ± 280	26654 ± 501
2&3-methylbutyl acetate	842 ± 17	664 ± 7	566 ± 24	613 ± 35	433 ± 28	480 ± 22
butanol	1895 ± 43	1927 ± 35	1985 ± 27	1725 ± 95	1585 ± 16	1363 ± 28
2&3-methylbutanol	249666 ± 5267	243785 ± 2409	247351 ± 1457	256140 ± 397	246773 ± 3092	252428 ± 3992
ethyl hexanoate	333 ± 11	293 ± 2	295 ± 2	376 ± 10	336 ± 3	385 ± 3
hexyl acetate	4 ± 0	3 ± 0	2 ± 0	4 ± 0	3 ± 0	3 ± 0
hexanol	942 ± 66	1013 ± 36	920 ± 63	1375 ± 75	1532 ± 55	1235 ± 62
ethyl octanoate	411 ± 14	383 ± 6	365 ± 2	483 ± 15	401 ± 16	443 ± 5
ethyl decanoate	165 ± 5	170 ± 7	181 ± 3	214 ± 6	224 ± 12	226 ± 26
isobutyl-methoxypyrazine	8 ± 0	8 ± 0	10 ± 0	10 ± 1	9 ± 0	7 ± 0

Analysis of the models showed model #3 is the best predictor of price. This model included three variables (balance, astringent, and complexity) to be significant drivers of the dependent variable, price (Table 8.7). The model results suggest that while both balance and complexity have a positive influence on price, the effect of astringency is negative: price point of the wines drops by about $1.30 for a unit increase in astringency score.

Table 8.6 Summary of stepwise multiple-linear regression analyses of price on sensory attributes (balance, astringent, and complexity).

Model	R	R Square	Adj. R Square	Std. Error Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	0.584	0.341	0.326	2.729	0.341	22.279	1	43	0.000
2	0.636	0.405	0.376	2.626	0.063	4.462	1	42	0.041
3	0.682	0.465	0.426	2.519	0.061	4.64	1	41	0.037

Table 8.7 Summary of model coefficients for best fit linear regression analysis of price on sensory attributes. The unstandardized coefficients (B) are the regression coefficients with the corresponding standard error. Standardized coefficients are the regression coefficients when the data has been standardized. The collinearity statistics, tolerance and variance inflation factor (VIF) describe the degree of correlation between predictor variables.

	Unstandardized Coefficients		Standardized Coefficients			Collinearity Statistics	
Model	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
Balance	1.171	.584	.304	2.004	.052	.566	1.768
Astringent	-1.282	.569	-.269	-2.252	.030	.911	1.097
Complexity	1.226	.569	.317	2.154	.037	.602	1.660

Volatile drivers of price

Results of a stepwise multiple regression analyses of price on only volatile compounds are given in Table 8.8. Only one model was significant (Table 8.8). Ethyl 2-methylpropanoate was a significant driver of price in this stepwise regression analysis (Table 8.9); nonetheless, this compound explained only about 10% of price variance.

Table 8.8 Summary of stepwise multiple-linear regression analyses of price and volatile properties (ethyl 2-methylpropanoate).

Model	R	R Square	Adj. R Square	Std. Error Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	0.348	0.121	0.101	3.153	0.121	5.930	1	43	0.019

Table 8.9 Summary of model coefficients for best fit linear regression analysis of price on volatiles properties. . The unstandardized coefficients (B) are the regression coefficients with the corresponding standard error. Standardized coefficients are the regression coefficients when the data has been standardized. The collinearity statistics, tolerance and variance inflation factor (VIF) describe the degree of correlation between predictor variables.

	Unstandardized Coefficients		Standardized Coefficients			Collinearity Statistics	
Model	B	Std. Error	Beta	T	Sig.	Tolerance	VIF
Ethyl 2-methylpropanoate	0.024	0.010	.348	2.43	0.019	1.000	1.000

When analysed using the combined data (i.e., using wine sensory and volatiles composition), the stepwise multiple regression analysis identified balance and ethyl acetate as the significant predictors. A stepwise multiple linear regression yielded two candidate models (Table 8.10). Of these, model #2 was chosen as the better fit. It includes two variables (balance and ethyl acetate) to be significant drivers of price (Table 8.10, Table 8.11).

Table 8.10 Summary of stepwise multiple-linear regression analyses of price on sensory (balance) and volatile properties (ethyl acetate).

Model	R	R Square	Adj. R Square	Std. Error Estimate	R Square Change	F Change	df1	df2	Sig. F Change
1	0.584	0.341	0.326	2.729	0.341	22.279	1	43	0.000
2	0.67	0.448	0.422	2.528	0.107	8.141	1	42	0.007

Table 8.11 Summary of model coefficients and related statistics for linear regression analysis of price on sensory and chemistry composition. . The unstandardized coefficients (B) are the regression coefficients with the corresponding standard error. Standardized coefficients are the regression coefficients when the data has been standardized. The collinearity statistics, tolerance and variance inflation factor (VIF) describe the degree of correlation between predictor variables.

	Unstandardized Coefficients		Standardized Coefficients			Collinearity Statistics	
Model	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
Balance	2.363	3.811	0.614	5.336	0.000	0.992	1.008
Ethyl acetate	0.0001	0.00005	0.328	2.853	0.007	0.992	1.008

Vintage, site, and vigour effects

The analysis of results by MANOVA (Table 8.12) describe a distinct difference between both organoleptic properties and volatile composition across Vigour*Site*Vintage, Vigour*Site, Vigour*Vintage interactions, and the main effects of vintage and site. Interestingly, vigour on its own was not significant.

Table 8.12 Multivariate results of significant main effects and interactions from MANOVA. Pillai's Trace tests if differences exist between the means of the analysed variables. Partial Eta Squared is a measure of effect size. Observed Power is a measure of the statistical power of the test.

Effect	Pillai's Trace	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Observed Power
Vintage	1.0	368.5	28.0	3.0	.000	1.00	1.0
Site	1.992	37.0	56.0	8.0	.000	.996	1.0
Vigour	1.839	1.6	56.0	8.0	0.237	0.919	0.458
Site*Vintage	0.999	111.7	28	3.0	0.001	0.999	1.0
Vigour*Site	3.6	1.8	112.0	24.0	.047	.894	.948
Vigour*Vintage	2.0	8.6	56.0	8.0	.002	.984	.998
Vigour*Site*Vintage	1.9	3.5	56.0	8.0	.03	.961	.833

Astringent, balance, complexity, and red berry were all significantly different across sites. This is in line with earlier regression analysis and principal component analysis (PCA) (Figure 8.1) which implied the importance of these variables. All volatiles except ethyl decanoate were significant across site. This result is expected as one would predict that three vineyards from three climatically distinct regions would yield wines of significantly different volatile concentrations. Astringent, bitter, and canned vegetable significantly differed between the two vintages. This is not surprising as the optimal scaling showed the 2014 wines to be more astringent, bitter, and associated with green characteristics due to their young age. Ethyl propanoate and ethyl octanoate were the only non-significant volatiles between the vintages.

Sensory, volatile, and price associations

Optimal scaling biplot analysis of 2013 vintage wines yielded a 2 dimensional model with 30% of the variance explained by the first dimension and 24% explained by the second dimension (total 54%) (Appendix 2). Visual assessment of clustering in a biplot of 2013 vintage wines indicates an association between price, balance, red berry, ethyl 2 butanol, ethyl 3 butanol, and ethyl propanoate. Complexity is closely associated with jam and dark fruit. The Great Southern wines were characterised by high scores for balance, complexity, red berry, dark fruit, jam, and high concentrations of ethyl propanoate, and ethyl 2-methylbutanol. The Margaret River wines were characterised by high scores for astringency, and high concentrations of ethyl acetate, butanol, 2-methylpropyl acetate, 2&3-methylbutanol, and 2-methylpropanol. The Geographe wines were characterised by high concentrations of ethyl hexanoate, ethyl butanoate, ethyl octanoate, hexyl acetate, capsicum, ethyl decanoate, and hexanol.

Optimal scaling biplot analysis of 2014 vintage wines yielded a similar model with 2 dimensions with 33% and 23% of variance explained by each dimension (total 57%) (Appendix 3). Visual assessment of clustering in this biplot shows similar associations to the 2013 biplot. Price, balance, complexity, 2-methylpropyl acetate, and red berry are all tightly grouped. The Margaret River wines again are characterised by high scores for astringency, capsicum, and high concentrations of ethyl decanoate, hexanol, and 2-methylpropanol.

Geographe wines are characterised by high scores for dark fruit, jam, and interestingly, bitter; additionally these wines contained high concentrations of ethyl propanoate, ethyl 3-methylbutanol, and butanol. Great Southern wines were not made for 2014 vintage. Concentrations of ethyl 2-methylproponoate, ethyl 2 methylbutanoate, ethyl 3 methylbutanoate, and ethyl hexanoate were all consistently low in the 2014 vintage wines.

Principal Component Analysis (biplot analysis of both 2013 and 2014 vintages) showed a distinct difference between the two vintages, the three sites, and to a lesser extent the vigour zones (Figure 8.1). The first component accounted for 29% of the variance and the second PC explains 13% of the variance. Principal Component Analysis findings support earlier analysis which described the younger wines as more astringent and associated with undesirable characteristics like canned vegetable. Volatiles clustered around the 2014 wines include ethyl decanoate, 2&3-methylbutyl acetate, and 2-methylpropyl acetate. Interestingly, wines from the low vigour zone tended to be highest in ethyl propanoate which is positively correlated with red berry characteristics. The 2014 wines contained higher concentrations of 2&3-methylbutyl acetate than the 2013 wines.

When both vintages are analysed together (Figure 8.1), the Great Southern wines are tightly concentrated around the same loadings: balance, complexity, jam, red berry, and ethyl propanoate. There is some overlap between Margaret River and Geographe wines from the 2014 vintage. These wines are clustered around astringent, sour, ethyl decanoate, 2&3-methylbutyl, 2&3-methylbutanol, 2-methylpropyl acetate, bitter, canned vegetable, and hexyl acetate. Geographe wines from 2013 were more associated with ethyl hexanoate, ethyl butanoate, and hexanol. Margaret River 2013 wines were mostly grouped with capsicum, and eucalyptus; however wines made from the Margaret River high vigour zone were more closely associated with balance, complexity, jam, red berry, and price. This supports statements from earlier chapters indicating vigour zones in vineyards are temporally stable, but quality may vary annually.

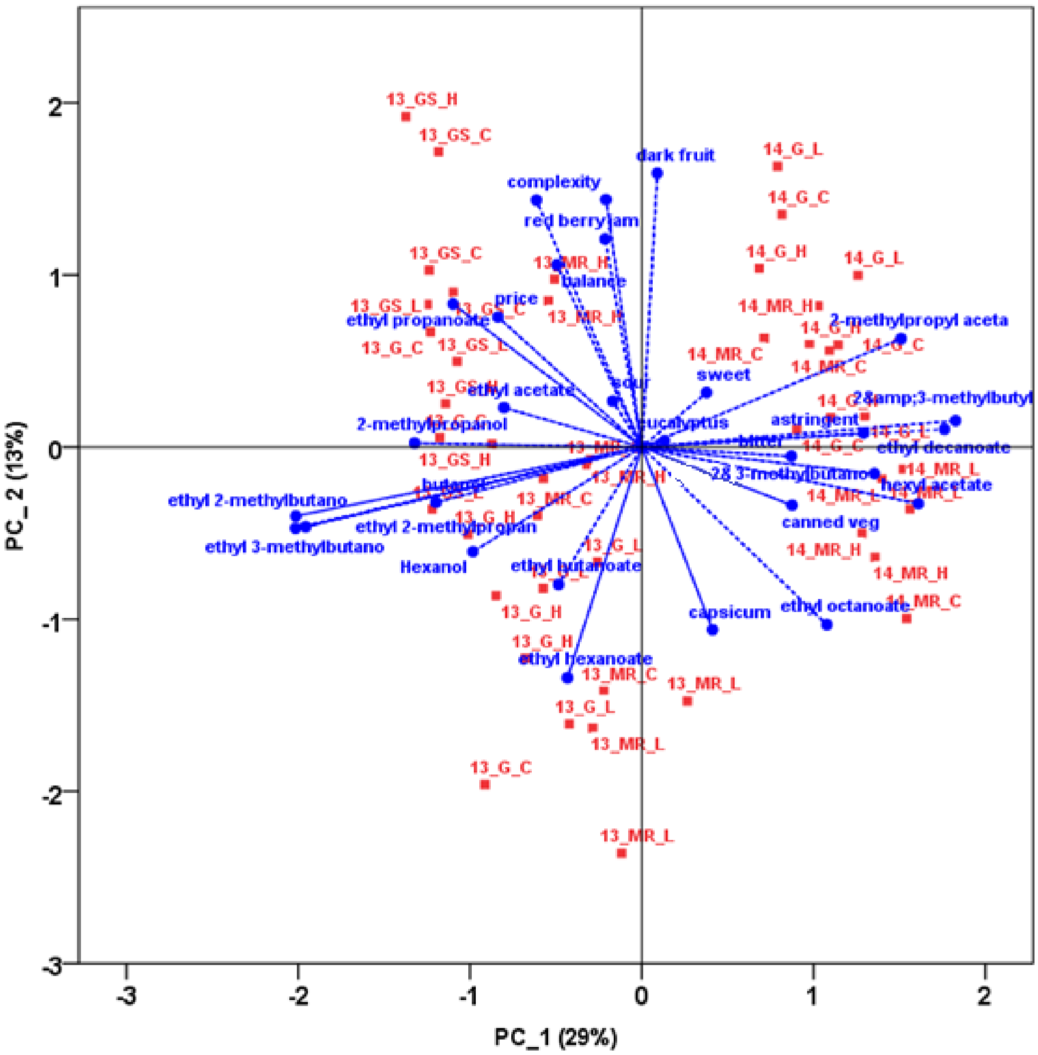

Figure 8.1 Principal Component Analysis (PCA) of wines, sensory properties, and volatile compounds. Codes for the small batch wines start with vintage (13 or 14), followed by site, (G=Geographe, MR=Margaret River, GS=Great Southern), and ending with zone (L or H) or control (C).

Partial Least Squares (PLS) Regression isolated a number of sensory and chemistry properties significant across each of the wines (Figure 8.2). The first dimension accounted for 57.8% of the variance of volatiles and 6.7% of the variance of sensory properties, while the second dimension explained 9.8% of the chemistry variance and 8.3% of the sensory differences. The segregation in Dimension 1 was characterised by, on the one hand bitterness, astringency, canned vegetable which were associated with hexyl acetate, 2&3-methylbutyl acetate, ethyl decanoate, and 2-methylpopyl acetate, and on the other by complexity and balance which were associated with ethyl propanoate. Dimension 2 was segregated by fruity and vegetative (capsicum) characteristics, PLS isolated ethyl propanoate as a significant compound that was correlated with the positive quality characteristics like red berry, complexity, and balance. To the best of the author's knowledge this is the first time this volatile has been shown to be associated with these sensory characteristics. Additionally, PLS regression found ethyl octanoate, 2&3-methylbutanol, and hexanol to be negatively correlated with fruity characteristics and more associated with capsicum. Overall PLS regression confirms the PCA and regression analysis, showing a grouping of fruity characteristics with balance and complexity (shown to be the primary drivers of price) and isolating ethyl propanoate as a significantly correlated volatile.

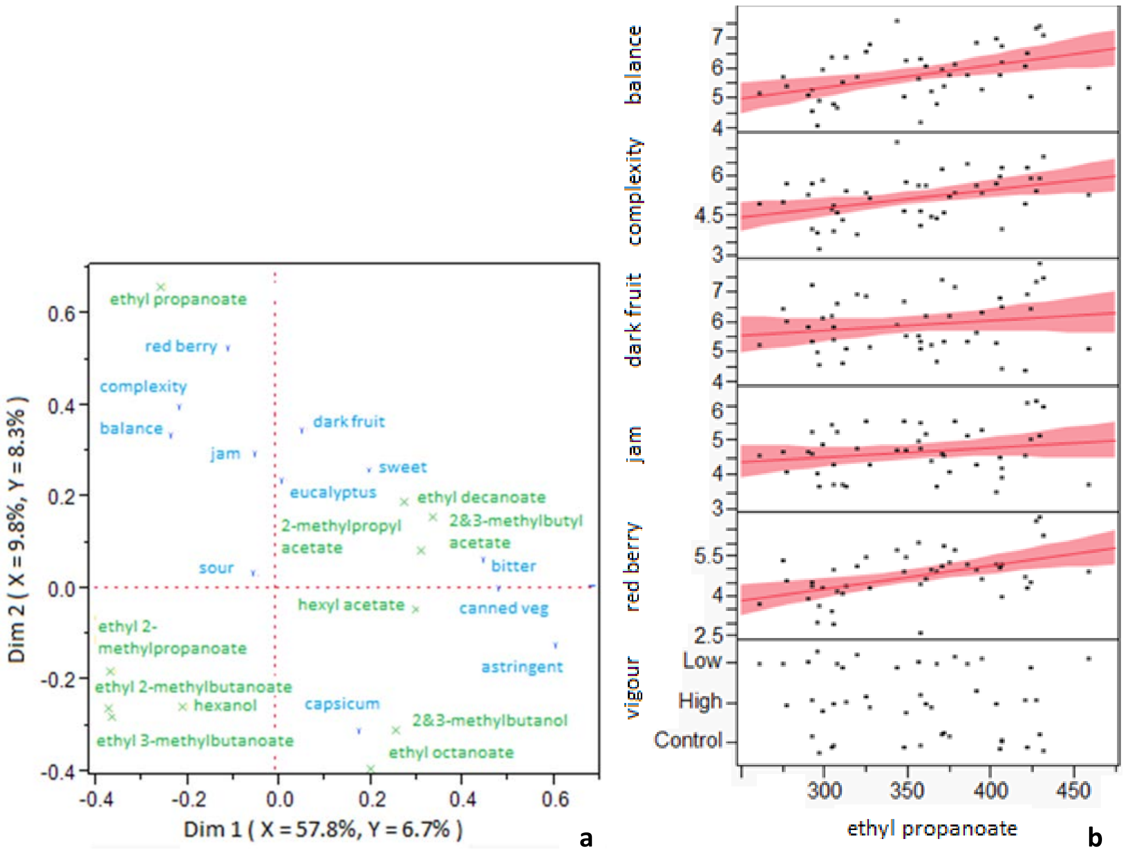

Figure 8.2 Partial Least Squares (PLS) regression results for significant sensory and chemistry properties. In figure (a) X=volatile compounds and Y=sensory properties. Specific analysis of ethyl propanoate against balance, complexity, dark fruit, jam, red berry, and vigour is included in figure (b). The regression equations and related coefficients of determination ($\boldsymbol{R^2}$) are as follows: Balance=3.15+0.007 EP (0.178); Complexity=2.73+0.007 EP (0.15); Dark fruit=4.43+0.003 EP (0.013); Jam=3.69+0.003 EP (0.02); Red berry=1.63+0.009 EP (0.227). EP is ethyl propanoate.

Discussion

One aim of this chapter was to identify the intrinsic characteristics of wine, specifically volatile and sensory properties, which are primary drivers of price. Of the variables examined here, a model containing balance, complexity, ethyl acetate, and ethyl 2-methylpropanoate was the best predictor of price. Yet, it needs to be noted that the model only accounts for just over 40% of the variance in wine price score suggesting factors other than those considered here influence wine pricing. Nonetheless, to the best of the author's knowledge, this is the first time the terms "balance" and "complexity" have been used in quantitative descriptive analysis of wine quality and price. It is also one of the first to investigate sensory and chemistry differences between regions and vigour zones. Complexity, fruity characteristics, green characteristics, and astringency were all significantly different organoleptic properties of wines from different vigour zones when compared by vintage and region. A number of volatile compounds were significantly different across these effects including: ethyl butanoate, 2&3-methylbutylacetate, butanol, ethyl hexanoate, ethyl octanoate, hexanol, ethyl 3-methylbutanoate, ethyl 2-methylbutanoate, 2-methylpropyl acetate, and ethyl acetate. To the best of the author's knowledge, this is the first time ethyl propanoate has been isolated as a significant volatile associated with fruity characteristics, balance, and complexity. Additionally, this research found 2-methylpropyl acetate, ethyl decanoate, and 2&3-methylbutyl acetate to be associated with bitterness and canned vegetable, and 2&3-methylbutanol and ethyl octanoate to be grouped with capsicum.

Another aim of this chapter was to examine the relationship between vigour and chemistry, sensory, and price. While small differences were found between vigour zones at the vintage, site, and vintage*site levels, these are far outweighed by regional (site) and vintage effects. Overall, low vigour zones tended to produce wines higher in red berry, dark fruit, jam, complexity, balance, price point, and ethyl propanoate. High vigour zones tended to produce wines higher in canned vegetable, bitter, ethyl decanoate, 2&3-methylbutyl acetate, and 2&3-methylbutanol.

This research confirms earlier findings, especially those of Bramley et al. (2011), identifying vintage, regional, and (smaller) vigour effects across sensory and chemistry properties. Additionally, Bramley et al. (2011) found that low vigour wines tended to be higher in fruity characteristics than high vigour wines. A similar trend was found in this research; however, the region effect again far outweighed the vigour effect. The relatively small overall vigour differences support prior research's assertions that a flat pay-off function exists (Pannell 2006). When processing fruit to wine, perhaps only very large variations are translated from fruit to wine.

The findings of this study support past research that demonstrated the importance of a number of volatiles as significant and powerful odorants. Ferreira et al. (2000) found ethyl octanoate and ethyl hexanoate to be among the most important potential aroma contributors and noted that these "are always found at concentrations higher than their odour thresholds." This could explain why these two volatiles were consistently significantly different across sample effects and treatments. Gürbüz et al. (2006) found ethyl 2-methylbutanoate, ethyl 3-methylbutanoate, ethyl octanoate, and ethyl hexanoate to be among the most intense odorants of Cabernet Sauvignon. This was echoed by Genovese et al. (2005) and Bramley et al. (2011) who both found each of these volatiles to be significantly powerful odorants. This chapter determined all of these compounds to be significantly different across vintage, region, and vigour effects.

These findings further support prior research, indicating that vigour zones within a vineyard are temporally stable, but quality of the harvested fruit may change annually. Proffitt et al. (2006) noted that vigour zones within a block tend to be temporally stable, but quality may change across vintages. This research found concentrations of ethyl 2-methylproponoate, ethyl 2-methylbutanoate, ethyl 3-methylbutanoate, and ethyl hexanoate to be consistently low in the 2014 vintage wines. Additionally, it found ethyl octanoate, hexanol, ethyl hexanoate, ethyl 3-methylbutanoate, ethyl 2-methylbutanoate, ethyl butanoate, 2-methylpropyl acetate, and ethyl acetate significantly differed between vigour zones and vintage. Wines from the 2013 vintage overall were preferred to the 2014 wines. A reason for this could be age; red wines, especially Cabernet Sauvignon, require more time to balance tannin and acidity than white wines. For this reason they tend to be consumed after a minimum of 1.5 to 2 years following harvest/vinification. Prior research has found that each of these compounds, with the exceptions of hexanol, ethyl butanoate, and 2-methylpropyl acetate, are important volatile compounds in Cabernet Sauvignon (Ferreira et al. 2000, Gürbüz et al. 2006). As wine grape and subsequent wine quality is based on aroma and flavour profiles, this suggests that vintage can play a major role in important volatile composition and therefore overall perceived quality. Bramley et al. (2011) noted differences in volatile composition between vintages, explaining that aging of wines may change chemical composition and environmental effects of different growing seasons may also contribute to the different volatile distributions.

Previous research has explored the concept of "terroir" in a sub-paddock context as opposed to a solely regional approach. Scarlett et al. (2014) found that the variation in rotundone concentrations in fruit harvested from a Shiraz vineyard in Victoria was spatially structured. Relationships were found between soil properties, vine characteristics (vigour as measured by PCD imagery), and rotundone concentration at harvest. Bramley et al. (2011) used remotely sensed vine vigour imagery, yield mapping, and soil sensing data to distinguish between areas of contrasting vine performance within a Cabernet Sauvignon vineyard in the Murray Valley region. Wines were made from low and high vigour zones (it is noted the fruit from each vigour zone was bulked together, not maintained separately) and analysed for volatile and non-volatile compounds that may be driving sensory properties. In general, it was found that low vigour vines produced wines with more fruity characteristics than did high vigour vines. Both Bramley et al. (2011) and Scarlett et al. (2014) recommended future research into the aspects of vine properties that may drive production of volatile compounds in wine grapes. This research supports this recommendation. In Chapter 7, it was determined that canopy structure could have a stronger influence on production of isobutyl-methoxypyrazine than overall vine vigour. This chapter investigated the effects of zonal vine vigour on wine chemistry and organoleptic properties. Furthermore, it included price point analysis and determined that fruity characteristics are positively associated with price and vegetative characteristics are negatively associated with price. If this relationship could be further classified (i.e. a tighter relationship established between vine properties like vigour or canopy structure and production of volatile or non-volatile compounds), then the potential for more detailed spatial economic maps of vineyards may become more viable.

Future research is recommended into the relationship between volatile precursors in the grape, their transformation throughout the growing season, and ultimate wine volatile composition, concentration, and quality. The implications for these further explorations and any link they may share with vine attributes (such as vigour) include the potential for viticultural manipulation to increase desired volatiles in the fruit that are directly correlated with wine quality and associated wine style.

Conclusion

This study provides a unique view of vine vigour (as determined by PCD) and corresponding wine sensory, chemistry, and price, and the relationship these attributes share across regions and vintages. Balance, complexity, astringency, ethyl acetate, and ethyl 2-methylpropanoate were influential on price. It found ethyl propanoate and fruity characteristics (red berry, jam, and dark fruit) to be positively associated with balance and complexity and green characteristics, bitterness, and astringency to be negatively correlated with balance and complexity. This supports prior findings in the literature. Additionally, a positive association was found between ethyl 2-methylpropanol, ethyl 3-methylbutanol, ethyl propanoate, ethyl 2-methylbutanol, price, balance, and red berry for the 2013 wines. The 2014 wines were associated mostly with astringency, bitterness, and green characters. This was most likely due to their young age as they were analysed just 6 months after completing secondary fermentation.

It is the first project to incorporate price into the analysis and successfully identifies fruity characteristics, balance, complexity, and ethyl propanoate as positively correlated with price. Although the vigour differences were small compared to the overall vintage and site effects, a general relationship was found between red berry, ethyl propanoate, and low vigour wines.

Chapter 9 Levelised Cost Analysis of Precision Viticulture

Introduction

Throughout this thesis, the concept of intrinsic quality of wine (sensory properties and chemical composition) has been explored. It has been shown that sensory properties, volatile, and non-volatile compounds have a relationship with wine price (Chapter 8). It is assumed, then, that quality manifests itself in price, and that increased quality should increase price; however, the extent of this relationship is unclear (Chapter 5). Currently, an adequate pricing matrix for fruit based on an objective quality scale is lacking (Jackson 2008).

At the core of economic evaluation of adoption of innovations is marginal analysis of the decision to adopt the innovation (i.e. Precision Viticulture). This marginal analysis (i.e. analysis of a change in the production system) leads logically to the use of the partial budgeting technique (Chapter 2). Partial budgeting (or partial gross margin analysis) can be used to analyse adoption of an innovation; however, this analysis is limited to one season and often only accounts for operating expenses (Chapter 4). Since many innovations that require significant investment last longer than one season and can incur capital and other adoption expenses, this partial budgeting analysis then becomes a capital budgeting exercise that uses “with and without scenarios” to analyse dynamic changes to capital, operating, and overhead expenses over the lifetime over a project (Chapter 2).

The aim of this chapter was to look at fruit quality as determined by cost, and define a Precision Viticulture adoption function that outlines optimal point of PV adoption for grape growers. A levelised cost approach has been undertaken that includes all costs, including capital costs, associated with fruit production. Levelised cost analysis is a method for performing a step-wise economic analysis of PV adoption that involves comparing profitability with and without the innovation and at the various rates of adoption. It is important to include every step from site establishment through harvest to understand all inherent costs incurred to produce one tonne of fruit. This chapter examines the “cost” of fruit quality, and how the price of fruit changes with and without an innovation (PV). The price considered is not calculated for only one growing season, as was done in Chapter 4, but considers total costs incurred over the lifetime of the vineyard. This sum can be used to determine the break-even price of fruit over the lifespan of the vineyard. A key aim of this study was to evaluate the relative merit of the economic analysis method of the levelised cost of grapes as compared with past econometric work which have assessed the importance of intrinsic fruit and wine quality through hedonic pricing (Chapter 2).

Precision Viticulture technologies can be conceptualised as an “innovation” (Chapter 2). Feder and Umali (1993) define an innovation “as a technological factor that changes the production function and regarding which there exists some uncertainty, whether perceived or objective (or both).” Therefore, an innovation must do at least one of the following: improve quality (resulting in a higher price for the good), improve yield, or reduce cost (Lindner 1987, Abadi and Pannell 1999). As noted by Cook and Bramley (1998) and Bramley (2001) among others, PV technologies can enhance the agricultural decision making process by enabling a more defined site specific management thereby increasing the potential to decrease input costs, increase fruit quality, and increase yield.

Adoption of an innovation can be considered an economic decision making process (Abadi and Pannell 2009, Feder and Umali 1993, Lindner 1987). This process can be viewed on a micro-economic level by examining the decisions of individual producers of “whether to adopt the innovation and its intensity of use if adopted” and on a macro-economic level by analysing adoption patterns of a technology across an industry (Feder and Umali 1993). Abadi and Pannell (1999) discuss the adoption of an innovation “as a dynamic decision problem spanning at least several years.” Their analysis incorporates a step-wise marginal analysis assessment of adoption as a learning process that varies with different managerial abilities and risk preferences.

Therefore, adoption of PV technologies can be considered an economic decision making process, and the decision of whether or not to adopt and at what rate a firm should adopt are only able to be answered through marginal economic analysis (Abadi and Pannell 1999, Abadi 2000). To do this it is necessary to examine profitability without the innovation (i.e. *status quo* or uniform management) and profitability at the various levels of adoption of the innovation (PV technologies) (Abadi and Pannell 1999). Essentially, the analysis is that of a controlled experiment that asks: “what is a firm’s profitability in the status quo (without the innovation) and how does profitability change with varying rates of adoption?" This approach to the economic analysis of adoption is supported by Marra et al. (2003) and Abadi and Pannell (1999) who advocate a methodical approach to assessing optimal rates of adoption, or if the innovation should be adopted at all.

Most of the prior economic analysis of PA and PV has included gross margin and cost benefit analysis (Brennen et al. 2007, Godwin et al. 2003, Lowenberg-DeBoer and Boehlje 1996, Robertson et al. 2007), finding overall that farmers believe PA (PV) is economically viable, though the effects have proven hard to measure (Robertson et al. 2012). Brennen et al. (2007) used a single grain field in northern New South Wales to observe the economic effects, both spatially and temporally, of variable nitrogen application. Scenario analysis concluded that "knowledge of seasonal variability is worth more than knowledge of spatial variability, but knowledge of both creates the greatest value" (Brennen et al. 2007). Godwin et al. (2003) trialled differential input of nitrogen at two wheat fields in the UK. Cost benefit analysis was undertaken to determine that the benefits of PA technologies outweigh the costs at a minimum farm size of 80 ha. It was noted that "to be cost effective, a farmed area of 250 ha of cereals, where 30% of the area will respond to variable treatment, requires an increase in crop yield in the responsive areas of between 0.25 and 1.00 tonnes/ha for the basic and most expensive precision farming systems, respectively" (Godwin et al. 2003). However, while most operating and capital costs were captured, the cost analysis was not as thorough as the levelised cost analysis undertaken in this study. For example, the costs of ground truthing and implementation were not considered. Additionally, only costs associated with PA technologies were included in the analysis. In a cost benefit analysis of six case studies from the Australian wheatbelt, Robertson et al. (2007) noted that farmers tended to recoup initial PA capital costs within a few years. Depending on the farmer circumstance, soil type, and management zone, "on a per paddock basis, benefits ranged from -$28 to +$57/ha per year" (Robertson et al. 2007). It should be reiterated that this cost benefit analysis was not a "thorough" cost analysis incorporating total costs incurred by either the farm under uniform management or with differential management in place. As with the other prior literature in the PA and PV fields, the economic analysis in Brennen et al. (2007) has been performed on a case-by-case basis.

Brennen et al. (2007) indicated the net profitability of PA, however, admitted the existence of a flat pay-off function as described by Pannell (2006). In a seminal paper, Pannell (2006) noted that in many agricultural pay-off functions, a flatness exists near the maxima, suggesting that a wide margin of error is possible and “for many types of problems, optimizing techniques are of limited practical relevance for decision support.” In a recent study by Ancev et al. (2015), a new metric, relative curvature (RC), was proposed to address the issue of differing “relative curvatures” to the production pay-off function. It was found “that there exists a high degree of variability in relative curvature of pay-off functions” and that this RC methodology is a highly efficient means to identify optimal fields for differential management.

Levelised cost analysis addresses these limitations. While this technique has been used in renewable energies (Kasmiouia and Ceulemans 2012), this approach has not been used before in the assessment of vineyards or broad-acre crops. By providing a structured framework that breaks down cost into subunits based on producer size (including dynamics of economies of scale), a unique view of cost-drivers in terms of levelised cost/tonne can be viewed. Additionally, full cost analysis of PV equipment, data acquisition, ground truthing, and implementation is crucial to complete analysis of response functions as determined through PV and vigour interactions. By meticulously “unpacking” cost, the final levelised cost/tonne of fruit production and cost of PV adoption is an objective measure that is attributable to specific items and actions in the production system. This provides a rigour in estimation not demonstrated in earlier research.

Another benefit of this approach is the ability to nominally (dollars/tonne) address “quality” of fruit. As fruit quality is a much debated parameter in the wine industry (Iland et al. 2011), the ability to assess fruit quality with a measurable unit (dollars/tonne) is necessary. While many have attempted to measure it, no objective scale has been derived to assess fruit quality. As discussed in Chapter 2, there is a large degree of conjecture in the literature with regard to fruit and wine quality and the roles of intrinsic and extrinsic factors on quality and price. Many econometricians have used hedonic regression to show that intrinsic characteristics (sensory and volatile properties of the wine) did not significantly affect price or quality (Lecocq and Visser 2006, Nerlove 1995, Schamel and Anderson 2001, Schamel and Anderson 2003). Others have argued that intrinsic characteristics drive overall quality and price (Cardebat and Figuet 2006, Combris et al. 1997, Combris et al. 2003, Lesschaeve 2007). Still others have acknowledged the short comings of hedonic analysis and recommended a move away from it (Miller et al. 2007, Palma et al. 2013).

Principles of production economics dictate that fundamental to the price of a commodity are a combination of the total cost of production, including operating and capital expenses, and a profit margin for the producer. Consequently, any difference between a price estimate derived from cost of production and the fruit price received by the grower (observed) can be labelled as "quality premium." Understanding how quality, as a subjective measure, may be monetised, will help define fruit quality and thus guide the contribution that PV can make to fruit quality.

As cost is the fundamental component of the fruit pricing matrix which is normally derived from the addition of cost/unit plus (usually) 20% profit margin, any discrepancy between observed price and modelled price can be described as "quality."

$$P = \frac{C_{total}}{Yield} + \pi$$

where

P = fruit price

C = total cost

π = profit margin

It is hypothesized that full PV adoption is likely to be more economical or worthwhile for larger producers.

Methodology

This experiment was designed to examine fruit quality as a measure of cost/unit. Additionally it sought to examine the benefits of PV adoption as a step-wise method across an array of producer sizes. It employed the creation of two levelised cost of vineyard production models able to directly compare alternative management practices in the vineyard. Furthermore, this experiment examined the potential return on investment (ROI) through step-wise integration of increasing technology as a function of producer size.

Modelling outline

The two levelised cost models (Figure 9.1) used in this chapter can be classified into two different model types: one that only considers production costs (uniform management or *status* quo) and one that considers costs and benefits of an innovation (PV). Each cost value was taken from a government report (i.e. Department of Primary Industries report) or an industry quote, and all costs were verified by multiple subject matter experts (SME's).

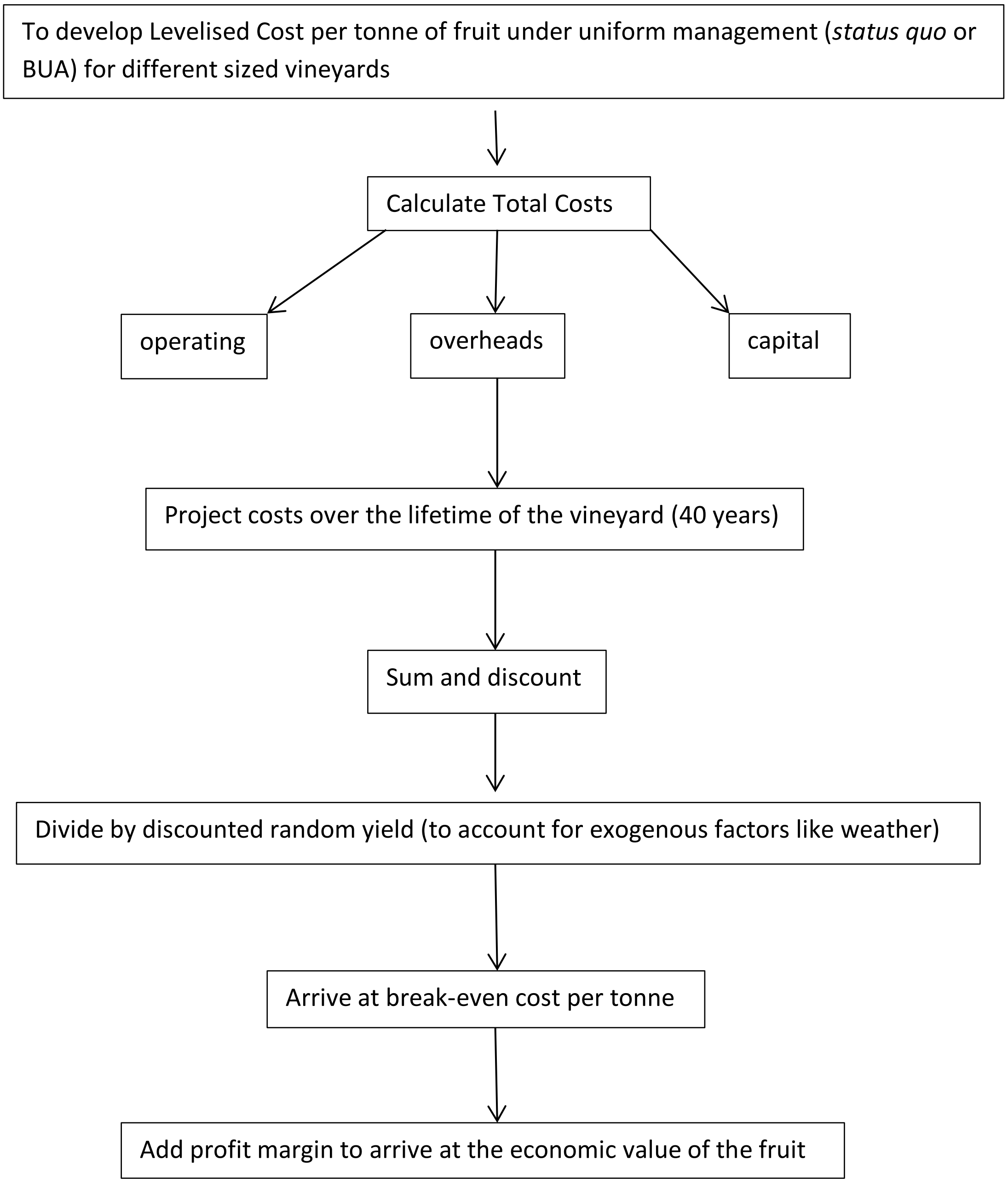

Figure 9.1 Levelised Cost model flow chart.

Production costs

Previous studies in the PV and PA literature have only considered production costs. This chapter includes total costs incurred throughout the lifecycle of a vineyard which is assumed to be 40 years. The total cost formula is included below and is the sum of total capital, overhead, and operating expenses incurred throughout the lifetime of the vineyard.

$$Total\ Cost = \sum_{j=1}^{n} C_{opex,}C_{capex,}C_{overheads}$$

where

n = number of periods (years)

j = time of cash flow (year)

C_{opex} = operating expenses

C_{capex} = capital expenses

$C_{overheads}$ = overhead expenses

Operating Expenses

Operating expenses are incurred annually and are split into two categories: those occurring in years 1 to 3 of the vineyard lifecycle (Table 9.2) and those occurring in years 4 to 40 (Table 9.3). The segregation in operating activities and expenses is due to the differing needs of a vine at different stages in the lifecycle. Cost collection includes both cost of resources (chemicals, fertilisers, etc.) and labour. Harvesting expenses (Appendix 6 Harvest) are incurred starting in year 4, as it is an assumption of the model that the vineyard will not yield commercial fruit until this time. It is acknowledged that some vineyards may yield fruit in year 3; however, not all vineyards will produce a commercially harvestable crop in year 3, hence the assumed first harvest occurs in year 4 (Iland et al. 2011). Harvesting expenses are the only operating expenses that vary with size as producers may choose to either manually or mechanically harvest the fruit. If the fruit is mechanically harvested, the producer must either own or rent a machine harvester. Depending on the harvesting strategy, various costs will be incurred.

Table 9.1 Operating expenses occurred in years 1 to 3 of the vineyard life.

Operating Expenses Years 1 to 3	$/ha
5 chemical applications	$524
1 fertiliser application	$345
0 canopy management/hedging passes	$0
0 netting passes	$0
2 cover cropping passes	$90
0 wire lifts	$0
3 training passes	$1,980 ($0.33/vine)
0 shoot thinning passes	$0

Table 9.2 Operating expenses occurred in years 4 to 40 of the vineyard life.

Operating Expenses Years 4 to 40	$/ha
6 chemical applications	$569
1 fertiliser application	$345
1 canopy management/hedging pass	$45
2 netting passes (on/off)	$90
2 cover cropping passes	$90
3 wire lifts	$180
1 pruning pass	$3,000 ($1.50/vine)
1 shoot thinning pass	$2,000 ($1/vine)

Capital Expenses and Overheads

Capital expenses are divided into one-off costs and costs that are incurred periodically. For example, the costs of vineyard establishment, including the costs associated with site development (Appendix 6 Vineyard Establishment), irrigation (Appendix 6 Irrigation), and trellising (Appendix 6 Trellising), are included only once. However, capital expenses like machinery (Appendix 6 Capital Expenses) are incurred periodically, depreciated over the asset's useful life years, and then replaced at a cost equal to the difference between the cost of a new asset and the salvage value of the existing asset. Since the cost model is a function of size, actual figures change with vineyard size. A list of capital expenses that could be incurred, depending on size and harvesting strategy is included in Table 9.3; however, as demonstrated in Table 9.4, many of the expenses either change with size or might not be included (i.e. not all sites use machine harvester). Overhead costs are incurred annually (Appendix 6 Overheads) and, again, vary with size. For example, a larger vineyard will require more full-time staff than a smaller vineyard.

Table 9.3 Capital Expenses included in vineyard levelised cost model. The model incorporates size, therefore, not all values in this table were included for each vineyard category. Additionally, some of these capital assets change with size.

Capital Expenses (an example as most values change with size and/or might not be included)			
Building, Plant, Machinery	New Value	Salvage Value	Useful Life Years
Tractor	See Table 9.4	45%	5
Machine harvester	$80,000	40%	5
Sprayer	$60,000	45%	5
Front end loader	$15,500	45%	5
Fertiliser spreader	$21,000	45%	5
4wd ute	$40,000	50%	7
Machinery shed	$20,000	0%	15
Coolroom	$20,000	0%	10
Mulcher	$8,500	45%	5
Mower	$14,500	45%	5
Green Trimmer	$43,000	45%	5
Sweeper (double sided)	$9,130	45%	5
Net Eagle	$13,500	45%	5

Table 9.4 Tractor size and costs relative to vineyard size. This table is an example of the varying cost figures of a capital asset as they change with vineyard size.

Vineyard size	Vineyard size (ha)	Tractor (hp)	Number of Tractors	New value ($)
Very small	<15	60	1	$30,000
Small	15-70	78-95	1	$84,428
Medium	71-360	78-95	2	$168,856
Large	361-1430	78-95	3	$253,284
Very large	>1430	78-95	3	$253,284

Discounted Cash Flow

A common feature of cost analyses of biological enterprises is discounted cash flow (DCF). DCF is used to express future cash flows of an enterprise (or investment) in their present value through discounting thereby accounting for the effects of time (Kasmioui and Ceulemans 2012, Jacobson 2003)." Due to the perennial nature of grapevines, the initial years of the vineyard investment are highly capital intensive with a four year lag until the first return (first harvest is in year 4). As Kasmioui and Ceulemans (2012) noted, DCF is necessary to "assess the absolute profitability" of biological enterprises lasting for many years. As may be surmised, the most critical variable of DCF is the discount rate (Kasmioui and Ceulemans 2012).

Pannell (2006, p. 26-36) noted the importance of discounting and its overall neglect in economic analysis. He emphasised the potentially misleading results of investment analysis without proper discounting. Kasmioui and Ceulemans (2012) described the effect of discount rate, noting that an increased discount rate increases the effect of initial costs (costs incurred early in the enterprise's lifecycle) and decreases the impact of future costs and benefits

The discount rate chosen for this analysis was 13%. As grapes are a value adding commodity and as there are often many extra-financial reasons a person may invest in a vineyard (especially very small-small producers), a low discount rate may be warranted. However, for larger size vineyards the behavioural reasons for entering the market are very different and return on investment (ROI) becomes an increasingly important aim. As vineyards are low risk investments with asset betas (risk coefficients) around 0.4 (NSW Government 2007), this discount rate is the best case scenario for encapsulating the degree of risk and quantifying potential opportunity cost across a wide range of producers with very different motives for entering the market. To ensure the chosen discount rate was not masking any potential relationships between model variables, sensitivity analysis was run on the discount rate.

Net Present Value

Net Present Value (NPV) is the sum of incoming and outgoing discounted cash flows (Boardman et al. 2006). Net Present Value has been used to assess production costs of biological enterprises (Goor et al. 2000, Jacobson 2003, Kasmioui and Ceulemans 2012). When only production costs are considered without analysis of enterprise profitability, future revenues are not considered (Kasmioui and Ceulemans 2012). Net Present Value in the cashflow analysis of adoption of innovations requires both the cashflows of revenues and costs. Because an objective measurement scale for fruit quality, and therefore price, does not exist, revenue cannot be calculated. Therefore, because revenue is yield multiplied by price, the levelised cost technique has been employed and a modified form of the NPV formula is included below:

$$NPV(\mathrm{i,n})=\sum_{j=1}^{n}\frac{X}{(1+i)^{j}}$$

where

i= discount rate

n= number of years

X= cash flow (revenues, operating, capital, or overheads)

j= time of cash flow (year)

Once total costs were aggregated, projected forward throughout the lifetime of the vineyard, and then discounted, net present value of total costs was then determined.

Levelised cost

Levelised cost has been used in renewable energies to calculate break-even unit price of energy when all costs incurred throughout the lifetime of an enterprise are considered (Branker et al. 2011, IPCC 2012, Kasmiouia and Ceulemans 2012). However, this approach has not been used before in the assessment of vineyards or broad-acre crops. The levelised cost formula below is a modified form of the NPV equation (IPCC 2012, Kasmioui and Ceulemans 2012, Moomaw et al. 2012, Stillwell et al. 2011).

$$LC = \frac{\sum_{j=1}^{n} \frac{TC}{(1+i)^{-j}}}{\sum_{j=1}^{n} \frac{Y}{(1+i)^{-j}}}$$

where

LC= levelised cost

TC= total cost

Y= Yield

$n =$ lifetime of the project

$i =$ discount rate

$j =$ time of cash flow (year)

The adapted NPV formula, when only costs are considered (not future revenues) is as follows (Kasmioui and Ceulemans 2012):

$$\text{NPV} = \sum_{j=1}^{n}(1+r)^{-j}.LC_j * Y_j - \sum_{j=1}^{n}(1+r)^{-j}.TC_j$$

Therefore, assuming the levelised cost value is constant and setting NPV equal to zero, the equation below is just another form of the levelised cost equation above (Kasmioui and Ceulemans 2012):

$$LC.\sum_{j=1}^{n}(1+r)^{-j} * Y_j = \sum_{j=1}^{n}(1+r)^{-j}.TC_j$$

Due to the adapted NPV formula, yield values are discounted in addition to projected costs (Kasmioui and Ceulemans 2012, Branker et al. 2011). Therefore, the levelised cost/unit is the break-even cost/tonne of wine grapes where discounted total costs throughout the lifecycle of the vineyard are divided by discounted yield throughout the entire lifetime of the vineyard.

Annual grape yield/ha was estimated using a randomised value/ha per year between a minimum of 4 tonnes/ha and a maximum of 9 tonnes/ha. This was done to simulate variability in yield due to exogenous factors such as growing season conditions. The minimum and maximum yield/ha values were used based on advice from subject matter experts (SME's) and observations from earlier chapters. A randomized yield/ha within the minimum and maximum parameters was then developed for each year of the project. These yields were then discounted in accordance with the above formulas.

Sensitivity analysis

Sensitivity analysis was carried out on the yield array to analyse how much the model results are impacted by the assumption about yield. Model simulations were repeated 200 times for each size category. Based on histograms and descriptive statistics, the yield array was determined to be accurate as the levelised costs its produced were within +/- \$10 (in most cases there was less than \$5 difference) of the mean and median values produced by the sensitivity analysis. Appendix 8 contains all histograms and descriptive statistics for each size category. To determine levelised cost/tonne, the sum of the NPV of total cost (variable + fixed) was divided by total discounted yield. Levelised cost/tonne was tested under two analysed concerning initial capital. The first included initial capital (i.e. cost of purchasing land, site development, etc.) and the second set of analyses excluded initial capital. As many growers do not factor recouping land and initial capital into their price/tonne valuation it was important to assess cost/tonne with and without this value. Additionally, due to the nature of discounting, costs or revenues incurred at the beginning of the project will be valued higher due to the exponential effect of discounting compounded by time.

Levelised cost (Precision Viticulture)

A decision tree was developed for Precision Viticulture technology based on guidelines published by Proffitt et al. (2006) which advocated a stepwise adoption process for PV technology in the vineyard. Only commercially available technologies (at the time of this research) were included: imagery, soil sensing, and yield monitoring. Variable rate spraying was not included due to its lack of use at the commercial level, and recycle sprayers were not included as this is considered to be more of an implement than a knowledge-based, decision-enhancing tool. For each element in the adoption of PV adoption, costs were measured: capital costs, data acquisition, ground truthing, and implementation. This study is the first to itemize and include the latter two costs associated with PV. Data acquisition costs were derived from industry quotes. Cost of ground truthing was assessed through observation, industry quotes, and information from subject matter experts (SME's). As the cost of implementing a decision is mostly incurred through staff training, implementation costs were estimated on the number of hours required to train individual personnel. It was assumed that 2 hours of training would be required per person at an opportunity cost of $20/hour, resulting in an implementation cost per person of $40. Larger producers will incur larger implementation costs as there are more personnel to be trained than small producers. Depending on the technology, these costs may be one-off's, annual, or some other increment.

All PV variable and capital costs were similarly projected across the 40 year project study and then discounted to the same discount rate as was used for the vineyard model. A levelised cost of PV in dollars/tonne was then estimated. A comprehensive overview of all previous economic analysis in PV was conducted and assessed on a case by case basis. This coupled with input from SME's and observations from the three case studies in this thesis were used to develop PV Response Functions which describe the effects of PV technologies on fruit price, yield, and costs (input and operating).

As noted above, all published economic analyses of PV have been considered in the construction of the PV response functions. Examples of cost savings through the use of PV indicated savings between $290 and $690/ha. Proffitt and Malcolm (2005) and Proffitt et al. (2006) noted costs savings from machine shoot trimming at $140/ha, hand crop thinning at $300/ha, and mechanical leaf plucking at $250/ha. Bramley (2010) estimated input costs to be reduced by $290/ha (11.6%). Examples of fruit price increasing from the literature have had a similar range of observations. Scollary et al. (2008) recorded price of uniformly harvested fruit to be $1000/tonne, fruit from the high vigour zone to be $1000/tonne, and fruit from the low vigour zone to be $1200/tonne. Bramley et al. (2011) noted fruit from the high vigour zone to be of the same price point as uniformly harvested fruit ($423/tonne), while fruit from the low vigour zone to be $520/tonne. Bramley et al. (2005) demonstrated uniformly harvested fruit to be $1200/tonne, while fruit from the high vigour zone received slightly less ($900/tonne). However, when the high vigour zone was harvested over multiple harvesting events, the price/tonne increased to $1200/tonne. Fruit from the low vigour zone of this section received $1800/tonne. In a separate case study, when a block was selectively harvested the fruit received $1800/tonne, whereas the uniformly harvested fruit received $1000/tonne (Bramley et al. 2005). Bramley and Hamilton (2005) noted that fruit from the high vigour zone received $1200/tonne, fruit from the low vigour zone received $2100/tonne, and the uniformly managed fruit received $1800/tonne. Bramley et al. (2003) and Bramley et al. (2005) both assess the economic benefits of differential management with selective harvesting at the wine level, noting that fruit from both the high vigour zone and fruit from the uniform control went into a wine priced at $18/bottle, while the low vigour fruit went into wine priced at $30/bottle. Price points were determined by the winemaker and viticulturist of the winery.

To assess the effect of cost savings generated from implementation of PV enhanced decisions on overall levelised cost/tonne, each case study was analysed individually. The specific cost savings was attributed to the relevant activity or input (*i.e.* less machine leaf plucking, shoot trimming, etc.), and then projected over the life of the study. It was similarly discounted and compared with the overall vineyard model's (uniform management) levelised cost/tonne.

Benefits received from PV technologies were lagged according to the technology. Adoption literature has shown that realisation of full potential benefits can take time especially when learning something that was previously unfamiliar (Abadi Ghadim 2000, Marra et al. 2003). This study anticipated commercial yield to be harvested for the first time in year 4. PV technologies are factored into the analysis from year 4 onwards. As benefits from PCD and soil sensing technologies can be incurred in the same year as data acquisition they are subjected to only a learning lag (no additional lags). However, yield monitoring benefits cannot be achieved until the following season; therefore any yield effects are lagged until year 5 in addition to the imposed learning lag. The learning lag involves a Bayesian approach to technology adoption and implementation which incrementally increases with usage. In the first year of usage a farmer can be expected to achieve only 10% of expected benefits, the second year 25%, the third year 75%, and the fourth year 99%.

Essentially, two models were built and then incorporated into one another. The first model is a cost model for vineyards incorporating economies of scale for vineyards of varying sizes under uniform management. Table 9.5 outlines the vineyard size categories. The second model is a cost and benefit model for PV involving a step-wise adoption process including a learning lag.

Table 9.5 Classifications of the vineyard size categories by tonnes and ha used in the modelling for this chapter.

Vineyard size	Tonnes	Hectares
Very small	<100	<15
Small	100-499	15-70
Medium	500-2,499	71-360
Large	2,500-9,999	361-1430
Very large	>10,000	>1430

As the first model calculates break-even and minimum price/tonne under uniform management it can be used to analyse quality. The minimum price calculated when total costs (including *all* capital, overheads, and expenses from the entire project lifespan) and profit margin are combined is the price at which 1 tonne of fruit is sold. This is the price of fruit that would enable the vineyard to cover its costs of production over the life of the project plus a modest profit margin. Any difference between this price and observed price can be labelled quality. Additionally, the levelised cost from the first model can be used to compare against the levelised cost calculated in the PV model. As it is a step-wise adoption process, uniform management can be compared to PV technologies in a comprehensive and transparent process.

Return On Investment

Overall return on investment (ROI) was calculated using the equation below:

$$ROI = \frac{C_{Lev(PV)} - C_{Lev(unif)}}{C_{Lev(unif)}}$$

where

$C_{Lev(PV)}$ = levelised cost under PV management

$C_{Lev(unif)}$ = levelised cost under uniform management

ROI calculations were used to compare the impact of adoption of PV on levelised cost/tonne.

Results

The results of this economic analysis examined levelised cost/tonne under uniform management for all sizes of producers employing different harvest strategies and across an array of discount rates and found an inverse relationship between levelised cost and producer size. These results include analysis of break-even price/tonne with and without initial capital, and found that initial capital weighs heavily on levelised cost/tonne. Additionally, levelised cost under PV management as a step-wise process of adoption was undertaken for all producer sizes and results indicate that all producers except very small would derive a net benefit from adoption of all 3 PV steps. ROI was determined at each PV step for each producer size and analysis was undertaken to determine the effect of the learning lag.

Levelised cost (uniform)

The levelised cost model under uniform management as a function of vineyard size showed that operating costs (Opex) did not change with size overall. The only activity that resulted in a change in Opex costs between small and large vineyards was harvesting method, either manual or mechanical harvesting. Overall, manual harvesting was found to be $155/tonne more expensive than mechanical harvesting (if owned). If the mechanical harvester was rented, the difference dropped to $49/tonne. However, the capital costs associated with a mechanical harvester make this option not feasible for very small vineyards (<15 ha). Appendix 9 includes an outline of the levelised cost/tonne under the two different harvesting strategies manual and mechanical (own vs rent). There are economies of scale which reduce overheads and capital expenses/tonne of fruit for larger properties.

To calculate levelised cost/tonne a range of discount rates was used from 5 to 20%. Table 9.6 and Table 9.7 display overall levelised cost/tonne with and without initial capital and land and accounting for each potential harvest method at discount rates ranging from 5 to

20%. As wine grapes require large initial capital and do not produce commercial fruit until year 4 of the project life, it was important to run the analysis with and without initial capital. Figure 9.2 shows the levelised cost/tonne breakdown (Opex, overheads, and capital expenses) for each vineyard size category when land and initial capital are included (at 13% discount rate). Figure 9.3 shows the levelised cost/tonne for each vineyard size category when land and initial capital are excluded (at 13 % discount rate).

Results included throughout the rest of this chapter used a discount rate of 13%. While the dollars/tonne results are sensitive to discount rate, the effect of discount rate on percentage change between producer sizes is negligible. These same model calculations, run at 5% discount rate, are included in Appendix 9 and share an almost identical relationship with the results presented in this chapter. This indicates that while value of grapes in dollars/tonne may change depending on the level of discounting (which is to be expected), the overall relationships between operating, capital, and overhead expenses, in addition to the effects of PV on levelised cost/tonne, are not sensitive to discount rate.

Levelised Cost/tonne results INCLUDING initial capital

Table 9.6 Levelised cost/tonne ($/tonne) including initial capital at various discount rates from 5 to 20%. For each size vineyard and potential harvest method the levelised cost/tonne was calculated (not including initial capital) for various discount rates ranging from 5 to 20%.

			Discount rate					
Vineyard size	Vineyard size (ha)	Harvest method	5%	7%	10%	13%	15%	20%
Very small	<15	Manual	$ 3,609	$ 4,057	$ 4,884	$ 5,903	$ 6,700	$ 9,210
Small	15-70	Manual	$ 2,261	$ 2,540	$ 3,057	$ 3,695	$ 4,195	$ 5,767
Small	15-70	Mechanical (rent)	$ 2,156	$ 2,433	$ 2,947	$ 3,580	$ 4,077	$ 5,639
Small	15-70	Mechanical (own)	$ 2,154	$ 2,437	$ 2,961	$ 3,607	$ 4,113	$ 5,705
Medium	71-360	Mechanical (own)	$ 1,963	$ 2,223	$ 2,703	$ 3,296	$ 3,760	$ 5,221
Large	361-1430	Mechanical (own)	$ 1,747	$ 1,981	$ 2,414	$ 2,949	$ 3,368	$ 4,686
Very large	>1430	Mechanical (own)	$ 1,699	$ 1,927	$ 2,350	$ 2,872	$ 3,281	$ 4,569

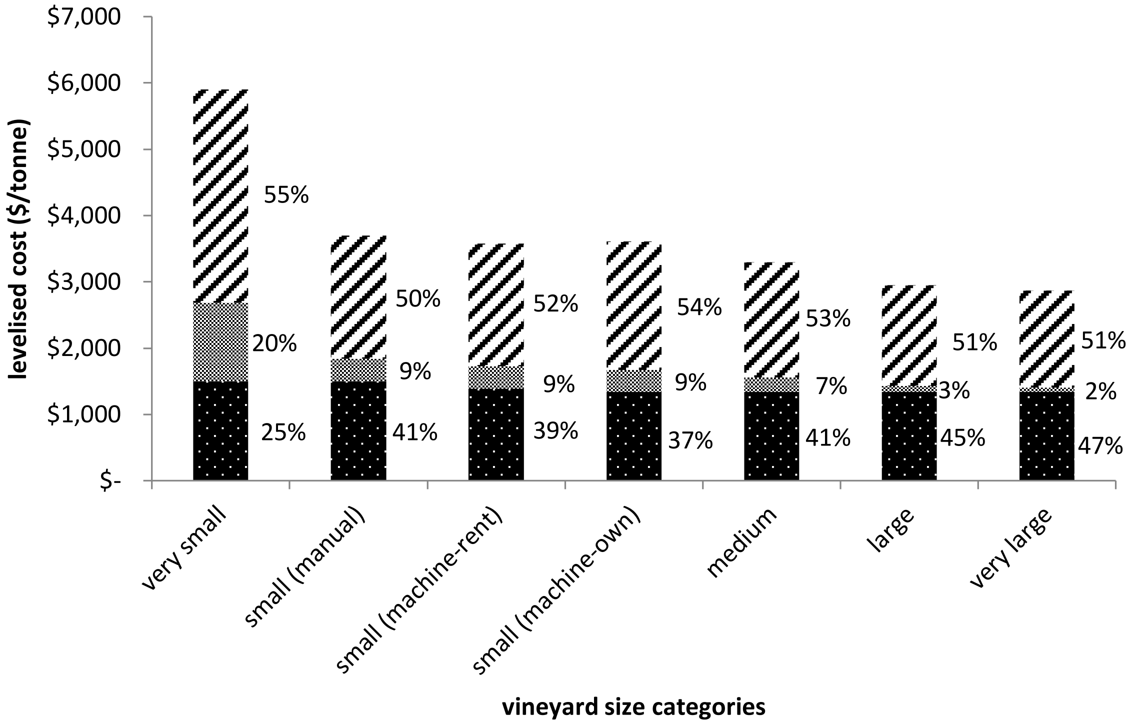

Figure 9.2 Levelised Cost/tonne breakdown for each vineyard category including initial capital and land purchases. Different harvest strategies are included where applicable. Each category of total cost/tonne has been broken down by percentages and is represented with a different pattern. Opex is classified by black with white dots, Overheads are grey, and Capital is black and white diagonal lines. Very small producers harvesting method is manual, medium to very large producers own a mechanical harvester, however, multiple harvesting scenarios have been considered for small producers including manual, renting a mechanical harvester, and owning a mechanical harvester.

It is clear that capital expenses weigh heavily on the levelised cost/tonne across all sizes of producers as they occur early in the life of the project. This is not surprising as viticulture is capital intensive in the start-up period and there is no commercial fruit or return on investment until approximately the fourth year after planting, although sometimes it is possible to produce a viable crop in year 3. Due to the exponential nature of discounting, costs and revenue (in this case yield) incurred in the beginning are weighted more heavily than costs at the end of the project lifetime. As many farmers do not factor recouping initial land purchases and capital into their ultimate return on investment, further levelised cost/tonne not including initial capital and land purchases has been analysed as well.

Levelised Cost/tonne NOT including initial capital

Although operating expenses did not change much with size, fixed costs (capital expenses and overheads) decreased with increasing size. When not including initial capital, shifting from very small to small size farm, results in a decrease in capital of 9% and in overheads of 20%/tonne. Between small and medium farms the decrease in capital was only about 1 to 3% and overheads decreased between 2 to 4%. The shift from medium to large size results in a decrease in capital expenses/tonne of 3% and overheads of 8%. Growing from large to very large size decreases capital/tonne of 1% and overheads/tonne of 1%. However, as operating expenses, especially in small to very large vineyards, create the bulk of the cost/tonne, overall the levelised cost/tonne decreases steadily until a large size farm is reached. This suggests that economies of scale are most prevalent early on, and that after reaching a certain size (about 360 ha) the increased benefits of operating at a larger size become negligible. For the purposes of this research, no initial capital (capital expenditure from year one) was included in subsequent analysis.

Table 9.7 Levelised cost/tonne ($/tonne) not including initial capital at various discount rates from 5 to 20%. For each size vineyard and potential harvest method the levelised cost/tonne was calculated (not including initial capital) for various discount rates ranging from 5 to 20%.

			Discount rate					
Vineyard size	Vineyard size (ha)	Harvest method	5%	7%	10%	13%	15%	20%
Very small	<15	Manual	$ 2,616	$ 2,724	$ 2,923	$ 3,166	$ 3,355	$ 3,943
Small	15-70	Manual	$ 1,630	$ 1,693	$ 1,812	$ 1,956	$ 2,069	$ 2,421
Small	15-70	Mechanical (rent)	$ 1,525	$ 1,586	$ 1,701	$ 1,842	$ 1,951	$ 2,293
Small	15-70	Mechanical (own)	$ 1,506	$ 1,567	$ 1,682	$ 1,822	$ 1,930	$ 2,270
Medium	71-360	Mechanical (own)	$ 1,366	$ 1,422	$ 1,525	$ 1,652	$ 1,751	$ 2,058
Large	361-1430	Mechanical (own)	$ 1,205	$ 1,253	$ 1,343	$ 1,454	$ 1,541	$ 1,810
Very large	>1430	Mechanical (own)	$ 1,168	$ 1,215	$ 1,303	$ 1,410	$ 1,494	$ 1,755

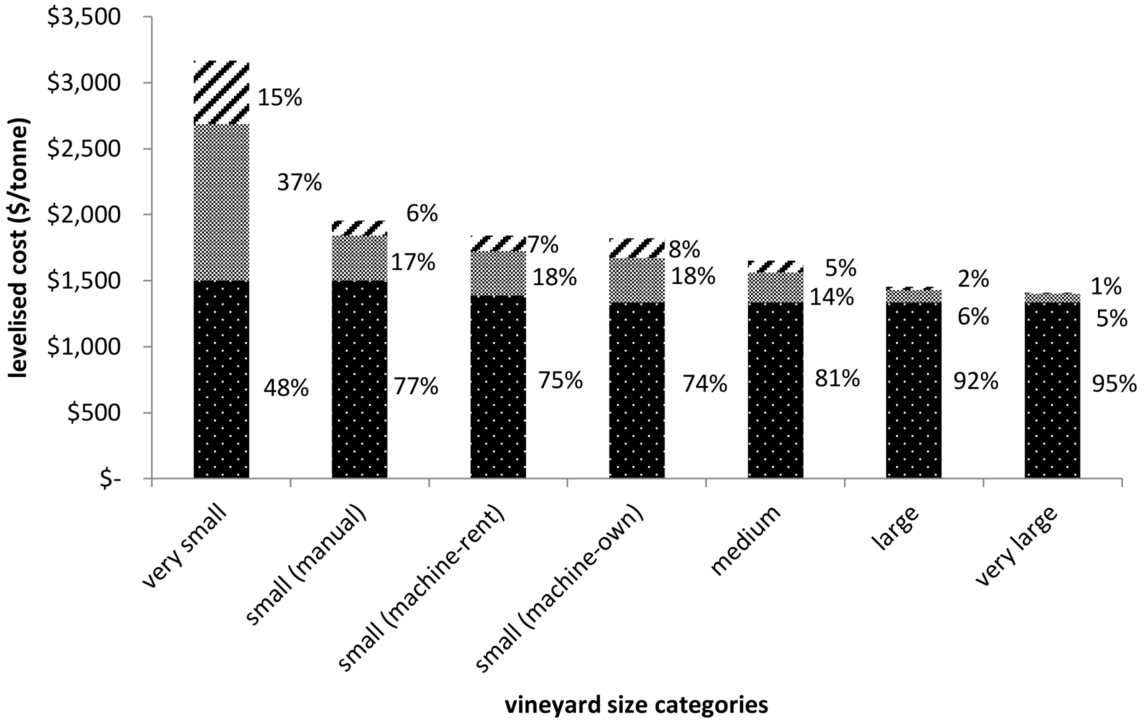

Figure 9.3 Levelised cost/tonne breakdown for each vineyard category NOT including land and initial capital. Each category of total cost/tonne has been broken down by percentages and is represented with a different pattern. Opex is classified by black with white dots, Overheads are grey, and Capital is black and white diagonal lines. Very small producers harvesting method is manual, medium to very large producers own a mechanical harvester, however, multiple harvesting scenarios have been considered for small producers including manual, renting a mechanical harvester, and owning a mechanical harvester.

At this stage it is possible to examine fruit quality as it relates to price. First principles dictates that fruit price should be a measure of total cost/unit plus a modest (20%) profit margin. Table 9.8 contains the minimum prices (levelised cost + 20% profit margin) for each of the vineyard sizes and harvest methods (where applicable). Any discrepancy between the calculated minimum price and the observed prices in the market can be labelled "quality." This research does not attempt to classify what exactly quality is and which factors of quality are most responsible for driving price up or down. However, for the first time, a dollar value can be attributed to quality through cost. Although it cannot be stated exactly what quality is, it is clear that quality does exist and in a measurable form.

Table 9.8 Minimum price (levelised cost/tonne (no initial capital) + 10%, 20%, and 30% profit margins) for each vineyard size category and harvesting method (for small producers).

	Minimum price at different profit margins		
Vineyard size	10%	20%	30%
Very small	$3,483	$3,799	$4,116
Small (manual harvest)	$2,152	$2,348	$2,543
Small (mechanical own)	$2,004	$2,186	$2,369
Medium	$1,817	$1,982	$2,148
Large	$1,599	$1,745	$1,890
Very large	$1,551	$1,692	$1,833

Precision Viticulture adoption analysis

At this stage it is possible to examine the differences in levelised cost/tonne between vineyards under uniform management and vineyards under each step of PV. It is clear from Figure 9.4 that PV is not economically viable for very small producers (<15 ha). However, as producer size increases, overall net benefits of PV adoption positively increase. It is interesting that harvesting methods play a huge importance in full adoption of PV. Small producers who manually harvest or rent a mechanical harvester will notice less benefit as compared with small producers who own a mechanical harvester. This is due to the harvesting techniques of smaller producers. Vineyards of a very small to small size tend to manually harvest their fruit or rent a mechanical harvester as the capital costs associated with owning a mechanical harvester make this option prohibitively expensive. Perhaps due to the low capital and operating expenses incurred through soil sensing (as it is only done once and requires no capital outlay if the data is acquired by a service provider), the overall difference between Step 1 and Step 2 for even manually harvesting small producers is very large.

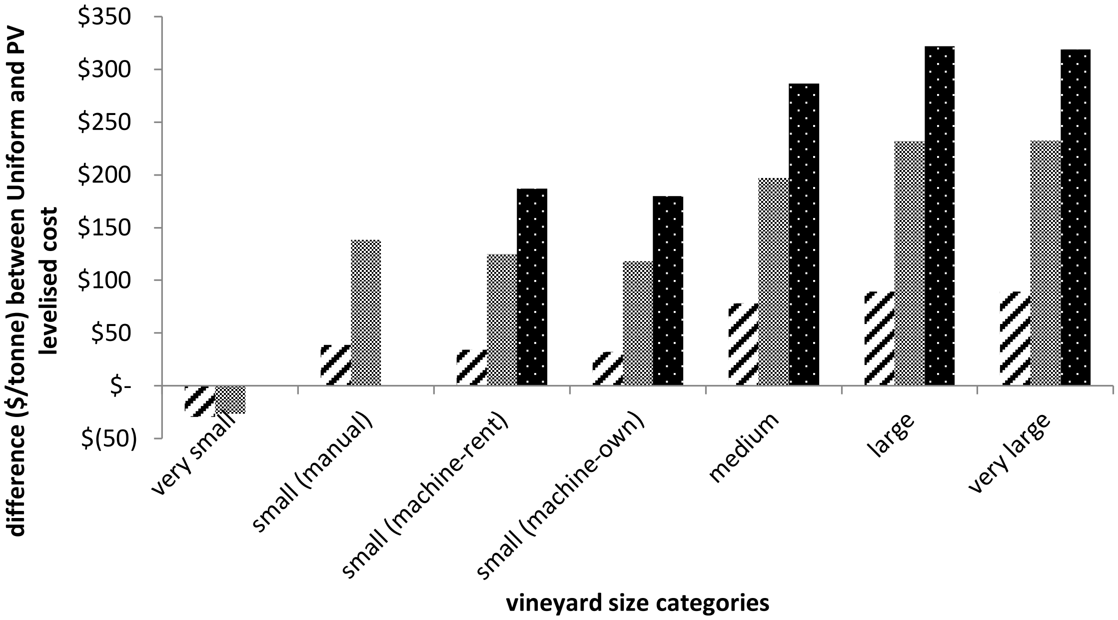

Figure 9.4 Benefits of stepwise adoption of Precision Viticulture according to producer size and harvest strategy as compared with uniform management. Very small producers incur a negative impact to adopting PV, however, even small producers (>15 ha) incur a positive return from full PV adoption. Step 1 (imagery) benefits are coloured with black and white diagonal lines. Step 2 (imagery + soil sensing) benefits are grey. Step 3 (imagery + soil sensing + yield monitoring) benefits are black with white dots.

As noted earlier, the only difference in operating expenses under uniform management are the costs incurred through harvesting methods. This same pattern is observed in PV benefits and adoption. As can be seen in Figure 9.4, depending on whether or not a producer owns a mechanical harvester, Step 3 of PV adoption may or may not be viable. Yield monitors are attached to mechanical harvesters and the technology to use them alongside manual harvesting methods is not widely available or economically feasible. Due to these technical challenges, producers who manually harvest fruit are unable to adopt yield monitoring technology and therefore unable to benefit from this technology.

The effect of harvesting practice, manual or mechanical, is clearly visible in Table 9.6. When a small producer uses a mechanical harvester, full adoption of all three PV steps is advantageous, however, when manually harvesting the last step is unviable. As the overall levelised cost/tonne of fruit is greater when a producer rents a mechanical harvester when compared to owning a mechanical harvester, PV benefits appear to be slightly reduced. However, economic analysis of owning vs renting a mechanical harvester indicates a lower overall levelised cost/tonne (under uniform and PV management) when the mechanical harvester is owned. For this reason further analysis of small producers renting a mechanical harvester has been omitted.

Overall benefits generated from PV increase with increasing size, however, a similar trend to levelised cost/tonne under uniform management is observed. Very small producers realise no benefit from PV adoption (in fact, they do not break even), whereas small to very large producers gain positive net benefits from PV adoption. Increased benefits are substantial when shifting from very small to small and small to medium in size; however there is no difference in PV benefits from large to very large size vineyards. For all producers (small to very large) when incorporating mechanical harvesting, full adoption of PV is recommended. Table 9.7 shows a clear visualization of the benefits generated from PV (as compared with uniform management) for each size category of producer.

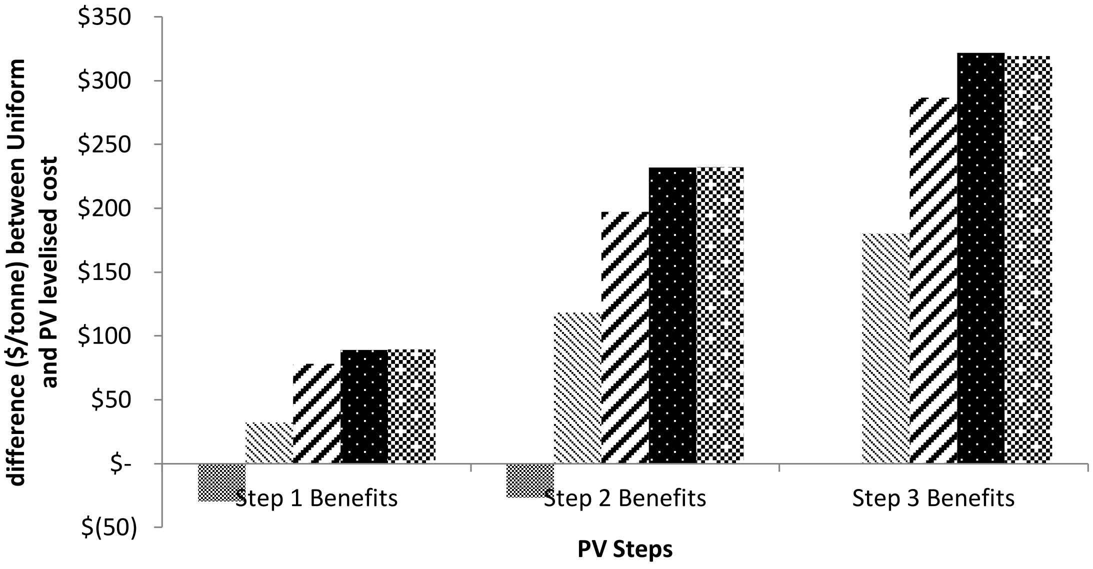

Figure 9.5 PV Benefits received to each producer size from each of the three steps. Step 1 is imagery, Step 2 is imagery + soil sensing, Step 3 is imagery + soil sensing + yield. The bars at each step move from left to right by size (very small to very large). Very small producers are shaded in grey. Small producers are shaded with thing grey diagonal lines. Medium producers have thick black diagonal lines. Large producers have black with white dots. Very large producers are grey with white dots. The very small producer’s harvesting method is manual while all other size producers own a mechanical harvester.

PV benefits increase with producer size until flattening off between large (361-1430 ha) and very large (>1430 ha) producers indicating a flatness in the payoff function with regard to size at this point. As noted earlier, very small producers achieve no benefit to adopting PV technology. Since yield monitoring technology (at the time of this writing) is not commercially available for manually harvesting methods, only producers using mechanical harvesting methods are able to achieve full PV adoption (imagery + soil sensing + yield monitoring).

Return On Investment (ROI) to Precision Viticulture

The ROI from PV implementation increased with increasing producer size. As this calculation of ROI is based on cost, positive percentages indicate a decrease in levelised cost/tonne (break even cost), and negative percentages indicate an increase in levelised cost/tonne. It was found that very small producers incur an increase in total cost/tonne through PV adoption, reiterating findings from earlier in this chapter. However, all other producer sizes gain benefits to full PV adoption (where applicable), with very large producers realising up to 23% ROI. Table 9.9 outlines the ROI for each PV step for all producer sizes and harvest strategies (where applicable).

Table 9.9 Return on Investment (ROI) from each Precision Viticulture step for all producer sizes. ROI was calculated using levelised cost under uniform management compared with levelised cost under PV management.

Vineyard size	Step 1	Step 2	Step 3
Very small	-1%	-1%	N/A
Small (manual)	2%	7%	N/A
Small (mechanical -rent)	2%	7%	10%
Small (mechanical -own)	2%	6%	10%
Medium	5%	12%	17%
Large	6%	16%	22%
Very large	6%	16%	23%

Effect of learning lag rates

Sensitivity analysis was run on the learning lag and determined that levelised cost is only marginally sensitive to the rate of learning. Results presented in this chapter incorporate a 4 year learning lag. However, the model was tested with a 2 year learning lag as well. A farmer who is able to utilise the technologies from each step within two years will gain benefits only marginally greater than those received by a farmer who requires 4 years to use the technologies to their full potential. Table 9.10 details the percentage increase in benefits (as determined through comparison of levelised cost/tonne at the 2 different learning speeds) received by a farmer when he or she is able to receive full benefits from PV technology in 2 years as opposed to 4. Producers using only the first step of PV realise almost no difference between the two speeds (up to 1%). Those using imagery + soil sensing data gain between 1-4% differences (depending on producer size) between the 2 learning rates, while full PV adopters realize 3-6% increase in benefits through faster learning.

Table 9.10 Difference (%) in overall benefits received between 2 and 4 year learning lags. Percentages were determined by comparing the overall levelised cost/tonne with a 4 year learning lag against the levelised cost/tonne with a 2 year learning lag.

Vineyard size	Step 1	Step 2	Step 3
Very small	0%	0%	0%
Small (mechanical-own)	0%	1%	3%
Medium	1%	3%	4%
Large	1%	4%	6%
Very Large	1%	4%	6%

Discussion

The aim of this chapter was to examine fruit quality through cost and to establish a dollar value for quality. Using the basic fruit pricing assumption (that fruit price should be break-even cost/unit plus a profit margin), any discrepancy between modelled price and actual price can be labelled as "quality." The ultimate "cost of quality" included economies of scale, indicating production costs drive inflated prices for fruit from smaller producers. However, with an array of price points on the market, (in this research observed price points varied from $1,400 to $10,000), this dollar value assessment of quality can change radically.

A further aim of this study was to determine an adoption function for Precision Viticulture technology that outlines the optimal point of PV adoption for grape growers of all size categories, from very small (<15 ha) to very large (>1430 ha). While it is clear that very small producers (<15 ha) are unlikely to benefit from PV, however, all other size producers may experience a benefit. Diminishing marginal returns to size or diminishing economies of scale is maximised at the medium size vineyard, indicating that medium size farms realize maximum marginal benefit/ha from PV adoption.

These results support findings throughout this thesis which suggested that the very small Geographe site, 0.27 ha block on a property <15 ha in size, did not benefit from PV zonal management. Whereas results from the other two sites, Margaret River and Great Southern, both substantially bigger and part of vineyards of small and medium size categories respectively, showed clear relationships between PCD and manual sampling measurements (trunk circumference, canopy surface area, berry chemistry, and average bunch weight) and demonstrated positive economic benefits from PV zonal management.

The findings of this study confirm past econometric work which has shown the importance of intrinsic fruit and wine quality and the need for a different methodological approach for analysing quality and price. In an analysis (hedonic pricing) of Bordeaux wine pricing, Cardebat and Figuet (2006) found that sensory characteristics played a strong role in price determination. In a similar hedonic pricing analysis of Bordeaux wines, Combris et al. (2003) found that “quality is essentially determined by the sensory characteristics.” Miller et al. (2007) realized the inabilities of econometric modelling to account for the wine market’s imperfect competition and information asymmetries and recommended a move away from typical hedonic regression. Palma et al. (2013) acknowledged the complexity of wine and the inherent heterogeneity of consumers’ preferences create modelling difficulties. Levelised cost addresses these deficits through an unbiased, methodical approach to quantifying the unit cost of production, thereby achieving a dollar value for “quality premium.”

This research supports prior studies which indicated potential economic benefits to PV (PA) adoption. Most of the prior economic analysis of PA and PV has included gross margin and cost benefit analysis (Brennen et al. 2007, Godwin et al. 2003, Lowenberg-DeBoer and Boehlje 1996, Robertson et al. 2007), finding overall that farmers believe PA (PV) is economically viable, though the effects have proven hard to measure (Robertson et al. 2012). Brennen et al. (2007) used a single grain field in northern New South Wales to observe the economic effects, both spatially and temporally, of variable nitrogen application. Scenario analysis concluded that “knowledge of seasonal variability is worth more than knowledge of spatial variability, but knowledge of both creates the greatest value” (Brennen et al. 2007). Godwin et al. (2003) trialled differential input of nitrogen at two wheat fields in the UK. Cost benefit analysis was undertaken to determine that the benefits of PA technologies outweigh the costs at a minimum farm size of 80 ha. It was noted that “to be cost effective, a farmed area of 250 ha of cereals, where 30% of the area will respond to variable treatment, requires an increase in crop yield in the responsive areas of between 0.25 and 1.00 tonnes/ha for the basic and most expensive precision farming systems, respectively” (Godwin et al. 2003). However, while most operating and capital costs were captured, the cost analysis was not as thorough as the levelised cost analysis undertaken in this study. For example, the costs of ground truthing and implementation were not considered. Additionally, only costs associated with PA technologies were included in the analysis. In a cost benefit analysis of six case studies from the Australian wheatbelt, Robertson et al. (2007) noted that farmers tended to recoup initial PA capital costs within a few years. Depending on the farmer circumstance, soil type, and management zone, “on a per paddock basis, benefits ranged from -\$28 to +\$57/ha per year” (Robertson et al. 2007). It should be reiterated that this cost benefit analysis was not a “thorough” cost analysis incorporating total costs incurred by either the farm under uniform management or with differential management in place. As with the other prior literature in the PA and PV fields, the economic analysis in Brennen et al. (2007) has been performed on a case-by-case basis. This chapter used a levelised cost model incorporating response functions observed in the pertinent literature (in addition to observations from this thesis) to provide a worthwhile and measurable assessment that can be applied to multiple growers, not just a single case. The levelised cost approach undertaken in this research shows that PV is worthwhile for most grape and wine producers.

This study supports prior research which found that size and variability can have effects on return from PV (PA). Godwin et al. (2003) noted the benefits of PA outweigh the costs in cereal production; however, the overall return is proportional to size and inherent variability of the farm. Monsó et al. (2013) developed an Opportunity Index (OI) that incorporated size and spatial variability as criteria for PV-encouraged use. Arnó et al. (2009) noted increased economic return from PV technologies as size and variability increased. Results from this study found increasing benefits with larger producer size, with marginal return from size occurring at the medium size category. Additionally, it was found that very small producers (<15 ha) see no benefit to adoption of PV technologies.

The results of this study confirm findings from past work in the field which found a flat pay-off function and diminishing marginal returns to PV (PA). Brennen et al. (2007) indicated the net profitability of PA, however, admitted the existence of a flat pay-off function as described by Pannell (2006). In a seminal paper, Pannell (2006) noted that in many agricultural pay-off functions, a flatness exists near the maxima, suggesting that a wide margin of error is possible and "for many types of problems, optimizing techniques are of limited practical relevance for decision support." In a recent study by Ancev et al. (2015), a new metric, relative curvature (RC), was proposed to address the issue of differing "relative curvatures" to the production pay-off function. It was found "that there exists a high degree of variability in relative curvature of pay-off functions" and that this RC methodology is a highly efficient means to identify optimal fields for differential management. This study noticed growing returns with increased size, with a flatness to the payoff curve occurring between large and very large size. The results of this study demonstrate that marginal benefits to size are maximised at medium size. As the levelised cost methodology is not an optimizing technique, but rather a view of unitary cost, the adoption functions are based on cost, not scenario analyses and, hence, provide traceable outputs.

While this research was able to quantify a "quality" figure, further segregation of the constituent variables driving "quality" was outside the scope of this research. Future research is encouraged into individual aspects of quality and their proportional relationship with price. As a dollar value for quality has been obtained, it would be interesting to segregate intrinsic and extrinsic properties and determine their individual weights on quality and price.

Conclusion

This research has enable measurement of quality on an objective, universally acknowledged scale. This research examined quality through cost, using the first principles assumption that price is a measure of cost (per unit) plus profit. Any difference between the minimum price as developed through the levelised cost model and the observed price can be classified as quality. It found that capital and overheads expenses decreased with increasing producer size and that operating expenses remained almost unchanged. Harvesting method was the only activity that changed operating expenses ($/tonne) across all producer sizes. For very small producers it is not economically viable to own or rent a mechanical harvester. For small to very large producers, it is more economically efficient to own rather than rent a mechanical harvester. However, it is acknowledged that often a price premium is paid for manually harvested fruit, hence some small producers, depending on overall size and desired fruit price, may incur the extra cost of manual harvesting to achieve a greater fruit price, as the difference between the two is $125/tonne.

The PV adoption model developed in this study shows that full PV adoption is worthwhile for small to very large producers, and uneconomical for very small producers. It should be noted that at the time this thesis was written, yield monitor technology for manually harvesting methods was not commercially available. Therefore, only producers owning a yield monitor are able to gain benefits from the third step of PV adoption (imagery + soil sensing + yield monitoring). As soil sensing is an operation performed only once and requires no capital purchases not incurred through imagery acquisition, all producers (small to very large) saw a measurable increase in benefits from Step 1 to Step 2. Small to very large producers noted differences in ROI from 1 to 23% (decrease in levelised cost/tonne). It is therefore highly encouraged to adopt imagery and soil sensing technologies and use the data together to make more informed management decisions. Benefits of PV adoption directly increase with size until the large producer category (361 to 1430 ha) is reached. There is no change in PV benefits between large and very large (<1430 ha), suggesting a flatness to the pay-off function with regard to size.

Chapter 10 Conclusion

Research into and use of Precision Viticulture technology has been growing since the 1990's, however, it has experienced a relatively slow adoption rate. One of the main obstacles to adoption of Precision Agriculture technologies cited by farmers is the lack of economic analysis of the costs and benefits associated with these technologies. This research was aimed at analysing the economic effects of different management practices, specifically Precision Viticulture, in the vineyard and their overall effect on Cabernet Sauvignon fruit and wine quality and price. The following main outcomes were realised through this research:

1. The role of PCD imagery as a tool to identify areas of divergent vigour within a vineyard block was established.
2. Case studies in the vineyard proved PV's ability to decrease operating expenses and increase fruit price and yield.
3. Experimental wines are representative of commercial scale wines.
4. Methoxypyrazines do not necessarily share a direct relationship between climate or region.
5. Sensory and chemistry drivers of and associations with price were isolated across regions, sites, and vigour zones across two vintages
6. Fruit quality was quantified on a universally acknowledged, objective, and repeatable scale through levelised cost analysis.
7. PV adoption function was developed to determine the optimum adoption rate for producers of all sizes.

Relationship between high density and manual sampling measures indicating economic efficiency/viability of Precision Viticulture

A weak positive linear relationship was found between imagery (PCD), trunk circumference, and canopy surface area. While these findings support prior research in the field, this experiment was more robust than previous studies due to a much larger population sample that was acquired for this analysis. It involved 25% population sampling at two sites and 13% population sampling at a third site. At one site, significant relationships between PCD and pH, titratable acidity, total soluble solids, and average bunch weight were found.

However, the third site which was much smaller in size (0.27 ha), no significant relationship was found between PCD and TSS or average bunch weight. Even in the absence of strong linear relationships, clear visual patterns were evident when the data is portrayed through GIS.

When the data set was stratified to incorporate only target vines within distinct high and low vigour zones, relationships between PCD and trunk circumference, canopy surface area, and to a lesser extent average bunch weight (statistically significant at one site). This indicates that PCD's role in distinguishing between high and low vigour zones is marked, however the utility of using PCD values in per vine regression analysis may be limited. Also, it is possible that vines of a medium vigour are not statistically significant from either high or low vigour vines. This upholds findings from Bramley et al. (2011) who noted that trunk circumference values from the middle vigour zone were not statistically significantly different from trunk circumference measures of vines from either low or high vigour zones.

It was determined that the cost of producing a manual sampling map that is clear enough to distinguish between low and high vigour zones is \$180/ha. It should be noted that the map generated using trunk circumference and canopy surface area measurements is not as clear or as accurate as PCD imagery and therefore the range of decisions that can be made based on the map are greatly diminished. This cost does not include staff training or GIS software package costs. PCD imagery acquisition ranges from \$32 to \$40/ha. The positive economic benefits of using PCD over manual sampling (about \$140 cheaper) to make more informed decisions are clear.

Case studies of the economic effects of Precision Viticulture technologies on vineyard gross margin through revenue increases (increase in fruit price and/or yield) and cost savings

This research identified potential profitability of PV implementation through an increase in revenue due to a fruit price increase and/or yield increase and potential savings to the cost of production. Over the course of the 2012-2013 growing season costs were traced to the high and low vigour zones at three different vineyard sites. Two of the vineyards that implemented PV noted a reduction in input costs (fertiliser, irrigation, etc.) and/or a fruit price increase. At the Margaret River site, the winery differentially managed to homogenize the fruit and the resulting batches of fruit from the low and high vigour zones were deemed of equal quality. Fruit from the Great Southern site was selectively harvested and allocated to different product streams resulting in a gross margin increase of $3,134/ha. The Geographe site was the only site not to generate a benefit in gross margin through PV implementation. This may be due to the relatively small size of the block (0.27 ha).

To analyse the experimental wines for price and quality, 27 winemakers or other professionally qualified and experienced industry personnel were asked to rate the wines on these parameters. In a blind tasting, the winemakers were unable to accurately rank/identify wines with no prior information. Additionally, the winemaker and viticulturist from each site participated in the study. When asked to identify the flight of wines made from that site's fruit, they were unable to correctly identify the group of wines. This potentially calls into question prior PV research relying on winemaker input for price point determination. It further supports the need for a more rigorous and transparent assessment of price point allocation.

Two interesting observations were made through the winemaker sensory analysis. Firstly, it was noticed in this sensory analysis involving price point that participants tended to score wines between $15 to $25. This leads to the question: is there a bias to score wines within a certain range? Secondly, while winemakers and experienced industry personnel were unable to accurately rank wines, the overall price and quality scores shared a strong positive relationship, suggesting that intrinsic quality attributes do exist and are dominant drivers of price. Further research into this potential bias and price/quality relationship is warranted.

Experimental wines are representative of their commercial scale counterparts

Most prior economic analysis of PV relied on the use of experimental wines. However, to the best of the author's knowledge, no published research has ever detailed the full methodology and outcome of a direct comparison of experimental and commercial wines to determine if experimental wines are comprehensive substitutes for commercial wines. A semi-trained panel determined that experimental wines are representative of their commercial scale counterparts. Paired discrimination sensory analysis determined no significant differences between experimental and commercial wines. Marginal means indicate a slightly higher overall quality score for the experimental wines (0.48) as compared with the commercial wine score of 0.41.

Methoxypyrazines (MP) do not always share a direct relationship with climate or region

Previous research found that IBMP concentrations in wines were typically higher from cool climate regions and lower from warmer regions. This research did not support this trend. Wines from the cool climate Great Southern vineyard did not detect any methoxypyrazines (IBMP, IPMP, SBMP), whereas wines from the warmer Margaret River and Geographe vineyards had IBMP concentrations between 7 and 12 ng/L. This indicates vineyard attributes (i.e. meso- and micro-climates) or canopy structure could be of greater importance than regional macro-climates.

A negative linear relationship was found between PCD value and IBMP concentration in wines. Additionally, a relatively weak relationship was found between vigour zone and methoxypyrazine concentration, with wines made from low vigour zones tending to be slightly higher in IBMP concentration than wines made from high vigour zones. Though, it was determined that canopy structure may have a greater effect on IBMP concentration in fruit than overall vine vigour.

Sensory and chemistry drivers of and associations with price were isolated across vigour zones, sites, and regions across two vintages

To the best of the author's knowledge, this is the first study to incorporate price point analysis into the study of chemistry and sensory characteristics. Linear regression analysis determined balance and complexity to be the strongest organoleptic determinants of price. Ethyl acetate and ethyl 2-methylpropanoate are the strongest volatile determinants of price. This research is the first to use the sensory descriptors *balance* and *complexity* in an experiment of this kind.

Principle component analysis, optimal scaling, and Partial Least Squares regression found that fruity characteristics tended to be associated with price, balance, and complexity. While prior research has found a positive relationship between fruity characteristics and quality, this is the first project to include price point analysis.

While fruity characteristics tended to be positively associated with price, green characteristics such as capsicum and canned vegetable were negatively correlated with price. This research supported prior findings that demonstrated that wines made from high vigour zones tended to be associated with astringent, bitter, and vegetative/green characteristics. The results of this research showed that wines made from high vigour zones were negatively associated with price, balance, and complexity. Again, it is believed that this research is unique in training a sensory panel on price point assignment and to successfully include price point into the sensory and volatile profiling.

Surprisingly, due to the cool climate nature of the region, wines from the Great Southern tended to be positively associated with price, balance, and complexity while wines from Margaret River and Geographe were associated with vegetative and green characteristics. This is somewhat surprising as prior research indicated a potential relationship between IBMP, which is known to be a driver of green characteristics in Cabernet Sauvignon, and climate.

Quality is able to be measured for the first time on a universally acknowledged, objective scale (dollars) through a levelised cost approach

A range of price points exists in the wine grape market. The case studies in this research observed prices of Cabernet Sauvignon fruit range from $1,400 to $10,000/tonne. As no objective measurement scale exists for directly measuring fruit quality, a need is evident for a transparent, repeatable assessment of quality and price.

This research resulted in the first full economic analysis of wine grape price/tonne. It includes a thorough and comprehensive levelised cost analysis which involves total cost (including hidden capital and initial start-up costs) collection and projection over the lifetime of the vineyard (40 years). The costs are broken down into constituent categories, operating expenses, overheads, and capital, and then discounted. Once net present value has been assessed, costs are then evenly spread over the years and divided by a discounted yield to determine a levelised cost/tonne. This levelised cost is the first of its kind and is able to provide a complete view of cost/tonne of fruit.

By adding a profit margin (20%) to this levelised cost/tonne (or break-even) value, a unique assessment of quality can be made on a universally acknowledged, objective scale (dollars). Basic economic assumptions of agricultural fruit pricing dictates that minimum fruit price should be total cost/unit plus a profit margin (normally about 20%). Using this assumption, comparisons between the modelled minimum price and the observed price on the market can be made and the difference between the two can be labelled as quality premium. This research does not attempt to further subdivide quality based on intrinsic and extrinsic factors. Rather it provides a scale by which quality can be measured and compared across sites, regions, and climates.

Overall the levelised cost/tonne was slightly higher than anticipated. It also found that operating expenses (Opex) do not include economies of scale, and the only activity that affected overall Opex was harvesting method. Manual harvesting was found to be about $150 more per tonne than mechanical harvesting. As a price premium may be gained through manual harvesting, this added expense may be opportune if the price bonus accounts for the added expense. Vineyards from 1-30 ha are advised to either manually harvest or rent a mechanical harvester, producers of 30 or more ha are encouraged to own a mechanical harvester as the price/tonne makes this option more economically efficient. While Opex were not found to change with size, capital (capex) and overhead expenses do include economies of scale. As might be imagined, capex and overheads are proportionally larger (as a percent of levelised cost) for smaller vineyards than larger vineyards.

A Precision Viticulture adoption function was created to determine optimum adoption rate for producers of all sizes

This research offers the first full economic analysis of Precision Viticulture which is able to determine optimal adoption rates for wine grape producers of all vineyard sizes. To do this, another levelised cost model was created that involved total cost collection for Precision Viticulture technologies in a step-wise process.

This research acknowledges that PV technologies incur multiple costs: capital expenses, data acquisition, ground truthing, and implementation (ground truthing is not required for yield monitoring). The latter two expenses have not been considered in previous PV economic analysis. For each PV step (addition of new technology) total costs were collected and aggregated to the costs collected in the original levelised cost under uniform management. Using all published case studies, information from subject matter experts (SME's), and data collected throughout this research, response functions were created for each technology (imagery, soil sensing, and yield monitoring) based on the technology's ability to either decrease costs, increase fruit price (through homogenization or product differentiation), or increase yield. Probabilities of achieving this benefit were assigned based on vigour and number of technologies incorporated. Using these probabilities, weighted averages were created for each of the vineyard size categories stipulated in the levelised cost model (very small, small, medium, large, and very large). Adoption literature (i.e. Abadi Ghadim 2000, Abadi Ghadim and Pannell 1999, Abadi Ghadim et al. 2005) has shown that any new technology experiences a learning lag which hinders full receipt of benefits while the industry learns how to use and trust it. For this reason a four year learning lag was installed in the model, so full benefits from each PV step are not realized straight away.

For each PV step (imagery, imagery + soil sensing, imagery + soil sensing + yield monitoring), cost savings and fruit price increases were discounted, then aggregated and subtracted from the total cost. For Step 3, yield increases were subsequently discounted and used to divide the total costs and generate a levelised cost/tonne of fruit under the different stages of PV and incorporating different size vineyards. Using the levelised cost under uniform management (without PV) produced through the levelised cost model, the break-even cost under PV can be directly compared.

It was found that very small producers (<15 ha) do not benefit from PV adoption; however, all other producers (small to very large) notice clear benefits from full adoption. At the time of writing, yield monitoring technology for manual harvesting methods was not commercially available, therefore, growers who do not mechanical harvest cannot fully adopt PV (Step 3). All producers (small to very large) achieve the greatest marginal benefits to adoption at Step 2 (imagery + soil sensing). As soil sensing technology requires no additional capital outlay (other than that incurred for imagery adoption) and is only performed once throughout the life of the vineyard, this is not surprising. The benefits to all producers slow after Step 2; however, where applicable, Step 3 is encouraged for all sizes. Medium sized vineyards (71-360 ha) achieve the greatest marginal benefits to PV adoption.

There are no increased benefits from large (361-1430 ha) to very large (>1430 ha) vineyards, indicating a flatness to the relative benefits to size payoff curve.

Future Research

This research proves the assumption stated at the beginning of this thesis: that intrinsic fruit and wine quality does exist and that, at least in part, is directly translated back to the vineyard and therefore can be manipulated using PV techniques and technologies. Additionally, it successfully isolated quality as a dollar value with respect to cost. A general relationship between quality and price was identified and supported through sensory and GCMS analysis. However, more research is necessary both at the fruit and wine level to understand:

- Sensory properties that drive price,
- Volatile properties that drive sensory characteristics,
- Vine characteristics that create relevant volatiles,
- Vineyard management techniques that can alter these characteristics,
- And, PV technology in the vineyard that can create a more efficient and informed management strategy to target vine characteristics for a specific desired wine style, quality, and price point.

Bramley et al. (2011) proposed the idea of tracing the formation of volatile compounds back to the vine. If more is known about the production of volatiles in berry development, potential exists to trace these compounds to certain physiological traits of the vine. If this relationship can be established, the possibilities for PV technologies to surrogately measure volatile compounds expands. This research progresses this idea to the next level by introducing price. If a relationship between vine physiological traits can be traced to volatile compound production and if these volatiles can be successfully attributed to sensory properties that have a relationship with price, then there is potential to generate economic maps of vineyard blocks at a per vine resolution.

Limitations of Precision Viticulture agronomic analysis

Previous studies have shown that it can be economically feasible to divide a vineyard into 2 or 3 management zones, though there has been little research into the economic viability of more than 3 management zones in a vineyard. While most case studies have used PCD or NDVI imagery as a means to identify and divide a vineyard block into 2 management zones (low and high vigour) (Bramley and Hamilton 2005, Bramley et al. 2008, Bramley 2010, Bramley et al. 2011, Proffitt and Malcolm 2005, Scollary et al. 2011), Bramley (2005) divided one of the sites in the study into 3 management zones (low, medium, and high vigour). To the best of the author's knowledge, no more than 3 management zones have been used in a published case study of PV economic analysis. In a study of grain in Missouri, Fridgen et al. (2004) noted that "measures of cluster performance indicated no advantage of dividing these fields into more than four or five management zones." However, even in the grain and wheat industries, many of the PA economic analysis case studies use no more than 3 management zones (for example, Godwin et al. 2003, Brennen et al. 2007).

This research, in addition to Bramley et al. (2011) has advocated the exploration of economic response functions. In particular, it has been advised that future research investigate vine properties that increase (or decrease) compounds that increase (or decrease) price. If the relationships between certain (currently unknown) combinations or concentrations of compounds and price were accurately understood, then it may be possible to generate economic maps at the per vine level. These maps would reflect the intrinsic value of the fruit as determined by chemical composition as it is manifested by vine physiological traits.

However, it should be noted that the principle limitations of generating economic maps at the per vine level are market structure and commercial capability. Currently, economic maps are limited to zones, as fruit is sold not per vine but rather per zone (or per block). Therefore, even if response functions between vine parameters, chemical compounds, and price could be accurately refined and used for economic analysis at the per vine level, market conditions have not evolved and advanced enough to allow for the logistical coordination of fruit purchase at the vine level. It has been shown that a maximum of 3 management zones in a vineyard is possible (Bramley 2005, Bramley and Hamilton 2005, Bramley 2010, Bramley et al. 2011, Proffitt et al. 2006); therefore, agronomic analysis is limited to zones not vines. In addition to market structure, commercial harvesting technologies and logistics have not advanced enough to allow for the harvesting and segregation of more than 3 to 5 zones. As noted earlier, the PV literature has demonstrated the economic viability of 3 zones, but, given current technologies, it is not possible to differentially harvest individual vines. Therefore, until the grape market structure and viticultural harvesting technologies are able to support the harvesting and selling of fruit at the per vine level, economic maps of vineyards will be constrained to the number of zones in the vineyard.

Levelised cost analysis across industries

The levelised cost methodology proposed in this research has potential implications in not just wine but also across other production industries where the relationship between price and quality is similarly ambiguous. Examples of industries that may benefit from this cost analysis of quality could include: fashion, automobiles, and electronics.

Glossary of Terms

BCA : benefit cost analysis

BUA : business as usual

C : Control

CAPEX: capital expenses

G : Geographe

GBP : Great British Pound

GC/MS : gas chromatography mass spectrometry

GI : Geographical Indication

GIS : Geographical Information Systems

GM : gross margin

GS : Great Southern

H : High

IBMP : isobutyl methoxypyrazine

IPMP : isopropyl methoxypyrazines

IR: infrared

L : Low

MLF : malolactic fermentation

MP : methoxypyrazines

MR : Margaret River

NIR : near infrared

NPV : Net Present Value

OPEX: operating expenses

P : price

PCD : Plant Cell Density

PV : Precision Viticulture

ROI : return on investment

SBMP : secbutyl methoxypyrazine

VRA : Variable Rate Application

VR : Variable Rate

VSP : Vertical Shoot Position

Y : yield

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Appendix

Appendix 1

Methoxpyrazine concentration (ng/L) and Plant Cell Density (PCD) values by harvest zone across each of the 2013 and 2014 vintages. PCD (mean) for controls was generated from the corresponding high and low harvest zones (i.e. Control 1=Mean (Low 1 and High 1), etc.). As noted previously, PCD results are not to be compared between seasons or sites. They are only meaningful within a site (for comparing relative differences across a block for measurements acquired at the same time. Cross site and season comparison requires either normalisation or calibration or use of active sensors. It should be noted that the same harvest zones were used for consecutive seasons. While the 2013 data show the expected pattern (higher PCD values for high vigour zones and lower PCD values for low vigour zones), this pattern does not hold true for the 2014 data from the Geographe site only. This is most likely due to the very small size of the block (0.27 ha). The 2014 data for the Margaret River site follows the expected trend.

Geographe

Vintage	Harvest Zone	PCD (mean)	IBMP (ng/L)	IPMP (ng/L)	SBMP (ng/L)
2013	Low 1	98	8	nd	nd
2013	Low 2	79	9		
2013	Low 3	115	9		
2013	High 1	201	7		
2013	High 2	188	9		
2013	High 3	184	10		
2013	Control 1	149	8		
2013	Control 2	133	9		
2013	Control 3	149	8		
2014	Low 1	183	9	nd	nd
2014	Low 2	89	10		
2014	Low 3	159	11		
2014	High 1	128	7		
2014	High 2	142	9		
2014	High 3	94	8		
2014	Control 1	155	9		
2014	Control 2	116	8		
2014	Control 3	126	8		

Margaret River

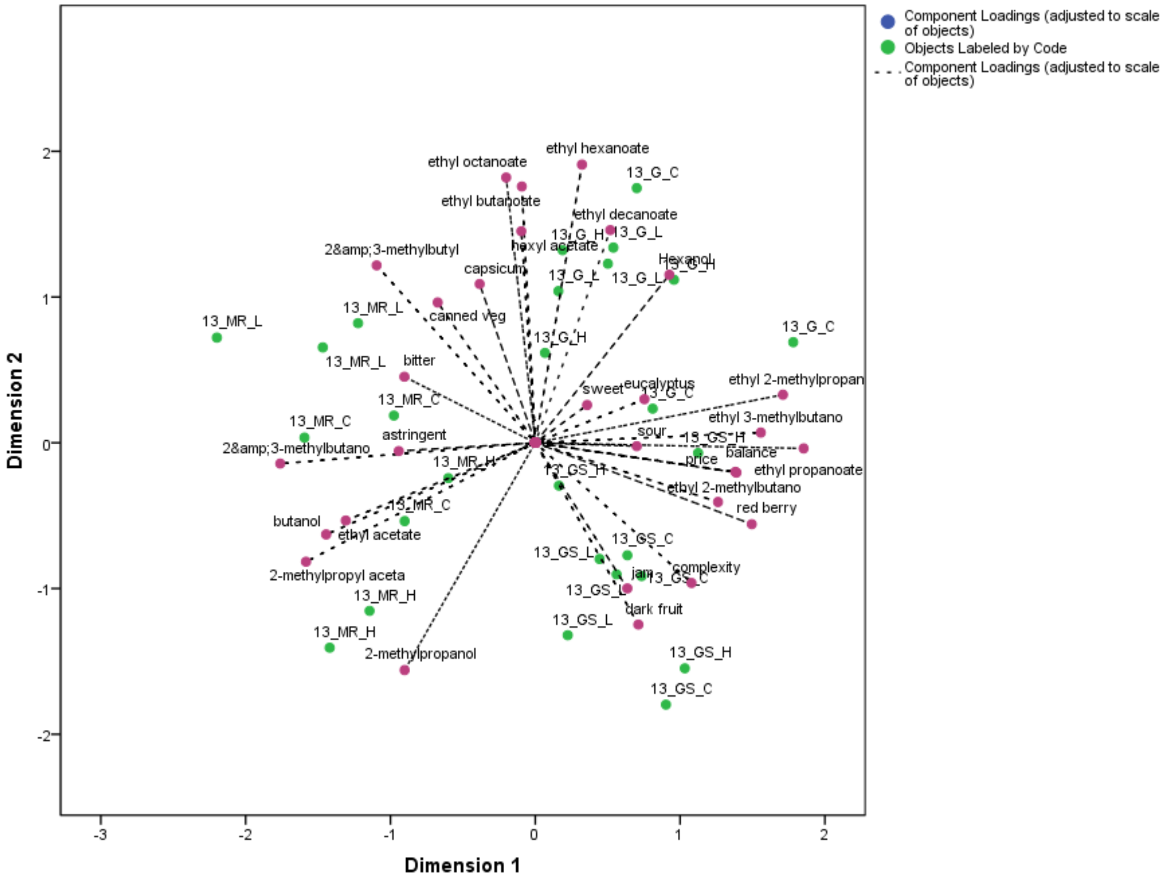
Vintage	Harvest Zone	PCD (mean)	IBMP (ng/L)	IPMP (ng/L)	SBMP (ng/L)
2013	Low 1	42	9	nd	nd
2013	Low 2	88	11		
2013	Low 3	61	11		
2013	High 1	166	10		
2013	High 2	162	8		
2013	High 3	138	9		
2013	Control 1	104	10		
2013	Control 2	125	9		
2013	Control 3	100	10		
2014	Low 1	656	9	nd	nd
2014	Low 2	648	8		
2014	Low 3	675	12		
2014	High 1	830	6		
2014	High 2	868	8		
2014	High 3	691	7		
2014	Control 1	743	8		
2014	Control 2	758	9		
2014	Control 3	683	10		

Great Southern

Vintage	Harvest Zone	PCD (mean)	IBMP (ng/L)	IPMP (ng/L)	SBMP (ng/L)
2013	Low 1	91	nd	nd	nd
2013	Low 2	79			
2013	Low 3	153			
2013	High 1	193			
2013	High 2	154			
2013	High 3	154			
2013	Control 1	142			
2013	Control 2	116			
2013	Control 3	153			

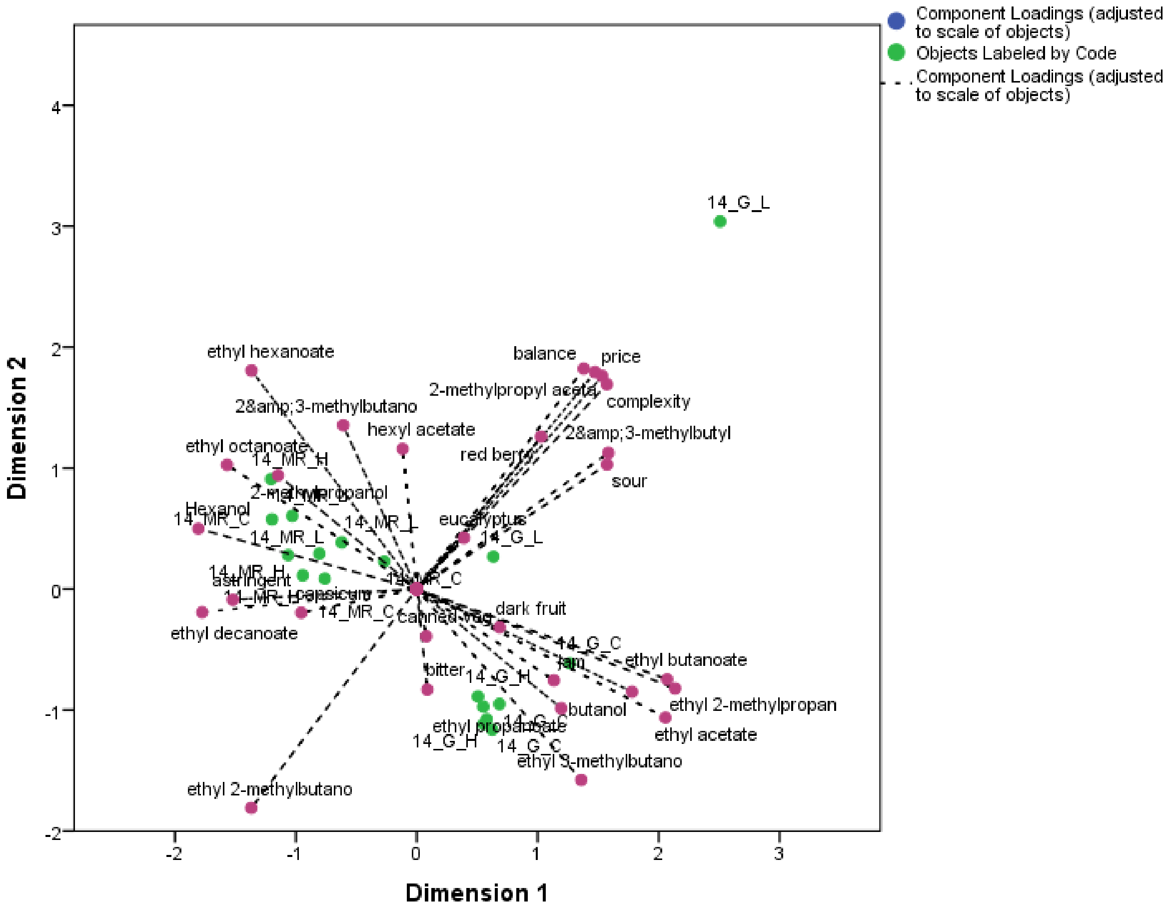
Appendix 2

Biplot of 2013 wines, sensory characteristics, and volatiles.



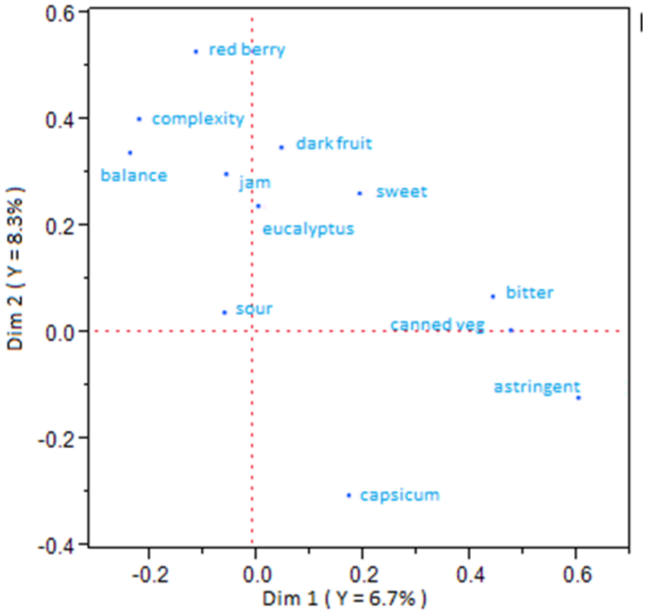
Appendix 3

Biplot of 2014 wines, sensory characteristics, and volatiles. Codes for the small batch wines start with vintage (13 or 14), followed by site, (G=Geographe, MR=Margaret River, GS=Great Southern), and ending with zone (L or H) or control (C).


Component Loadings (adjusted to scale of objects)
Objects Labeled by Code
Component Loadings (adjusted to scale of objects)
Dimension 2
Dimension 1
4
3
2
1
0
-1
-2
-2
-1
0
1
2
3
14_G_L
ethyl hexanoate
balance
price
2-methylpropyl aceta
complexity
2&3-methylbutano
hexyl acetate
2&3-methylbutyl
red berry
sour
ethyl octanoate
14_MR_H
2-methylpropanol
14_MR_L
Hexanol
14_MR_C
14_MR_L
eucalyptus
14_MR_L
14_G_L
14_MR_H
astringent
14_MR_H
capsicum
14_MR_C
14_MR_C
canned veg
dark fruit
ethyl decanoate
14_G_C
jam
ethyl butanoate
bitter
14_G_H
butanol
ethyl 2-methylpropan
ethyl propanoate
14_G_C
ethyl acetate
14_G_H
14_G_C
ethyl 3-methylbutano
ethyl 2-methylbutano

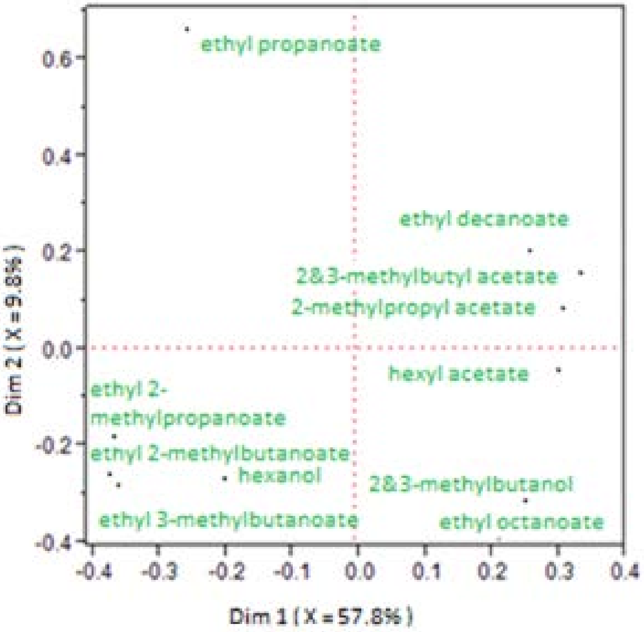
Appendix 4

PLS regression biplot of sensory attributes. Dim 1 explains 6.7% of the variance and separates bitter and canned vegetable characteristics from sour. Dim 2 explains 8.3% of the variance and is characterised by fruity characteristics and balance and complexity.



Appendix 5

PLS regression biplot of volatiles from both 2013 and 2014 wines. The first dimension explains 57.8% of the variance and groups hexyl acetate, 2-methylpropyl acetate, and ethyl decanoate against ethyl 2-methylpropanoate, ethyl 2-methylbutanoate, and ethyl 3-methylbutanoate.



Appendix 6

Vineyard Levelised Cost Model

It is noted to the reader that the levelised cost model created accounts for economies of scale as incurred as a function of size. The examples included throughout this Appendix are costs incurred for a 100 ha vineyard; however, vineyard size and harvesting strategy have a large effect, as noted in Chapter 9. As such, if the model was run at a different size or harvesting strategy, these numbers would correspondingly change. Each cost value has been verified by at least one source, many have multiple sources. These examples are included only to emphasize to the reader the comprehensive nature of the total vineyard costs included in the Levelised Cost model.

Vineyard Establishment

Development Expenses		Unit	Rate units/ha	Price $/unit	Cost $/ha	Cost for Vineyard	
Cost of Land					$ 18,000	$ 1,800,000	
Survey Block					$ 1,500	$ 1,500	
fertilizer	tractor	hours	2	$ 36	$ 72	$ 7,200	
	labour	hours	2	$ 20	$ 40	$ 4,000	
	fertiiliser-pre vine planting	tonnes	1.5	$ 100	$ 150	$ 15,000	$ 26,200
Planting	materials	rootlings	2000	$ 1	$ 2,200	$ 220,000	
	labour	rootlings	2000	$ 1	$ 1,000	$ 100,000	$ 320,000
Land preparation-contract tasks							
Dozer - Ripping		hours	$ 7	$ 35	$ 245	$ 24,500	
Dozer - Mobilisation		fixed cost		$ 600	$ 6	$ 600	$ 25,100
rock/stick pick up		hours	$ 40	$ 30	$ 1,200	$ 120,000	
rotary hoe		hours	$ 4	$ 120	$ 480	$ 48,000	
gridding		hours	$ 17	$ 30	$ 510	$ 51,000	
Total					$ 25,403.00	$ 2,391,800.00	

Irrigation

Water requirement per vine	750 L/vine/yr
Water requirement per ha	1500000 L/ha
Cost of Water	0 $/L

Dam				
Per farm items:	Unit	Rate units/ha	Price $/unit	Cost $
Dam	cu.m	1500	3	450000
Pump and electric motor				11000
Sand filter, back-up filter, & controller				140000
Mainline	m	100	100	10000
Design & Install				1500
Total				612500

Variable irrigation installation costs					
Per hectare items:	Unit	$/unit	Units/ha	$/Ha	Cost for vineyard
Sub-main	m	5	100	$ 500.00	$ 50,000.00
Lateral (16mm),in-line drippers @0.5m	m	1	4000	$ 4,000.00	$ 400,000.00
Fittings (tees, valves, couplings, bushes)				$ 200.00	$ 20,000.00
Installation Labour	hrs				
dripper pipe	$/m	0.05	4000	$ 200.00	$ 20,000.00
clip up dripper	$/m	0.15	4000	$ 600.00	$ 60,000.00
Total				$ 5,500.00	$ 550,000.00

Irrigation cost per annum		
Irrigation maintenance - materials	15	per ha
includes: labour, electricity, repairs, cleaning/maintenance, flushing the system before use programming the systems, and checking soil moisture equipment		

size	tonnes*	vineyard size (ha)	Pump size kW	No of Pumps	Cost of Pump ($)	Cost of Starter	Mainline size (mm)	Mainline cost ($/m)	Sub-main size (mm)	Sub-main Cost ($/m)
very small	<100	<15	7	1	2500	1000	100	15	40	5
small	100-499	15-70	50	1	7000	2000	100	15	40	5
medium	500-2,499	71-360	100	3	11000	5000	300	100	80	10
large	2,500-9,999	361-1430	100	4	11000	5000	700	200	200	50
very large	>10,000	>1430	100	5	11000	5000	700	200	200	50

Trellising

Trellising costs		
rows per ha	40	
Row Width	2.5	meters
Vine Spacing	2	meters
Total Ha	100	
Average row length	100	meters

vines per post	4	vines/post
strainer posts per row	2	str post/row
km trellis per ha	4	km/ha
posts per row	12	posts/row
vines per row	50	vines/row
posts per ha	480	posts/ha
strainer posts per ha	80	str post/ha
total posts per ha	560	total posts/ha

Item cost		**unit**	**unit cost**	**per post**	**$/post**		**$/Ha**	Cost for Vineyard
posts		1 post	12.4		$ 12.40		$ 5,952.00	$ 595,200.00
strainer post		1 post	29.2		$ 29.20		$ 2,336.00	$ 233,600.00
staples (25kg)		2500 staples	132	2	$ 0.11	post	$ 50.69	$ 5,068.80
				2	$ 0.11	strainer post	$ 8.45	$ 844.80
	gauge mm	unit	**unit cost**	per vine	$/km		$/Ha	
growire	2.65	1000 m	128.7	1	$ 128.70		$ 514.80	$ 51,480.00
folliage	2.5	1500 m	198	5	$ 660.00		$ 2,640.00	$ 264,000.00
dripper	2	2000 m	148.5	1	$ 74.25		$ 297.00	$ 29,700.00
								$ -
labour				hours per post	$/post	Hours/Ha	$/Ha	
	drop out posts			0.09	$ 1.80	50.4	$ 1,008.00	$ 100,800.00
	Install strainer			0.9	$ 18.00	72	$ 1,440.00	$ 144,000.00
	Install post			0.125	$ 2.50	60	$ 1,200.00	$ 120,000.00
	staple off			0.01	$ 0.20	5.6	$ 112.00	$ 11,200.00
				hours per km wire	$/km trellis			
	install wire	7 wires		0.25	$ 35.00	7	$ 140.00	$ 14,000.00
						Total	$ 15,698.94	$ 1,569,893.60

Capital Expenses

Building, Plant, Machinery (PBM)	**Included Y/N**	**New Value**	**Disposal Value %**	**Useful Life Yrs**	**Salvage value**	**Depreciation per year**	**Cost per year**
tractor	**Y**	$ 168,856	45%	5	$ 75,985	$ 18,574	$ 18,574
machine harvester	**Y**	$ 80,000	40%	5	$ 32,000	$ 9,600	$ 9,600
sprayer	**Y**	$ 60,000	45%	5	$ 27,000	$ 6,600	$ 6,600
front end loader	**Y**	$ 15,500	45%	5	$ 6,975	$ 1,705	$ 1,705
fertilizer spreader	**Y**	$ 21,000	45%	5	$ 9,450	$ 2,310	$ 2,310
4wd ute	**Y**	$ 40,000	50%	7	$ 20,000	$ 2,857	$ 2,857
machinery shed	**Y**	$ 20,000	0%	15	$ -	$ 1,333	$ 1,333
coolroom	**Y**	$ 20,000	0%	10	$ -	$ 2,000	$ 2,000
mulcher	**Y**	$ 8,500	45%	5	$ 3,825	$ 935	$ 935
mower	**Y**	$ 14,500	45%	5	$ 6,525	$ 1,595	$ 1,595
Green Trimmer	**Y**	$ 43,000	45%	5	$ 19,350	$ 4,730	$ 4,730
Sweeper (double sided)	**Y**	$ 9,130	45%	5	$ 4,109	$ 1,004	$ 1,004
Net Eagle	**Y**	$ 13,500	45%	5	$ 6,075	$ 1,485	$ 1,485
total depreciation PBM per year							$ 54,729

Tractor-type dependent on farm size

size	tonnes*	vineyard size (ha)	Tractor (hp)	New Value ($)	Disposal Value %	**Useful Life Yrs**	**Salvage value**	**Depreciation per year**
very small	<100	<15	60	$ 30,000	45%	5	$ 13,500	$ 3,300
small	100-499	15-70	78-95	$ 84,428	45%	5	$ 37,993	$ 9,287
medium	500-2,499	71-360	150-200	$ 168,856	45%	5	$ 75,985	$ 18,574
large	2,500-9,99	361-1430	242-295	$ 253,284	45%	5	$ 113,978	$ 27,861
very large	>10,000	>1430	242-295	$ 253,284	45%	5	$ 113,978	$ 27,861

1

tractor operating costs (fuel, oil, grease, maintenance)	36 $/hour	**Diesel Price**	1.536 $/L

2

3 Harvest

Harvest

Owned/rented	Owned	
Rate of machine harvesting	1.5	hr/ha
Rate of manual Harvesting	5	Hr/Tonne
Pickers per runner	15	

4

Machine Harvesting	$/Hr	Unit ($/Ha)	Cost for vineyard
Contract rate	$ 500	$ 333	$ 33,333
Mobilisation of harvester			$ 500
Tractor (fuel, oil, repair + maint)	$ 36	$ 24	$ 2,400
Operator	$ 20	$ 13	$ 1,333
Total		$ 37	$ 3,733

5

Manual Harvesting	$/hr	Hrs/Tonne	$/Tonne	$/Ha	Cost for vineyard
Picking labour	$ 20	5.00	$ 100	$ 800	$ 80,000
Runner	$ 20	0.33	$ 7	$ 53	$ 5,333
Tractor	$ 56	0.33	$ 19	$ 149	$ 14,933
TOTAL				$ 1,003	$ 100,267

6

7 Operating Expenses

Tractor speed	km/hr	5
Chemical Application rate	kg/Ha	25
Cost of Chemicals	$/kg	12
Fertiliser Application rate	kg/Ha	25
Cost of Fertiliser	$/kg	12

8

Years 1 - 3

OPERATING					hrs/km	$/km	$/Ha	Cost for Vineyard
Chemicals							$ 300	$ 30,000
Applying Chemicals (pass with tractor)			5	Applications / yr	0.2	$ 11	$ 224	$ 22,400
Fertiliser							$ 300	$ 30,000
Fertiliser Application (pass with tractor)			1	Applications / yr	0.2	$ 11	$ 45	$ 4,480
Canopy Mgt & Hedging			0	pass(es)	0.2	$ 11	$ -	$ -
Netting on/off			0	pass(es)	0.2	$ 11	$ -	$ -
Cover Cropping/Mid row maint			2	pass(es)	0.2	$ 11	$ 90	$ 8,960
Wire Lifting	No of passes	0	3	Hrs/Ha			$ -	$ -
Training	No of passes	3	0.33	$/vine			$ 1,980	$ 198,000
Shoot thining				$/vine			$ -	$ -
Irrig'n Operation & Maint							$ 15	$ 1,500
SUB TOTAL							$ 2,953	$ 295,340

Years 4-20

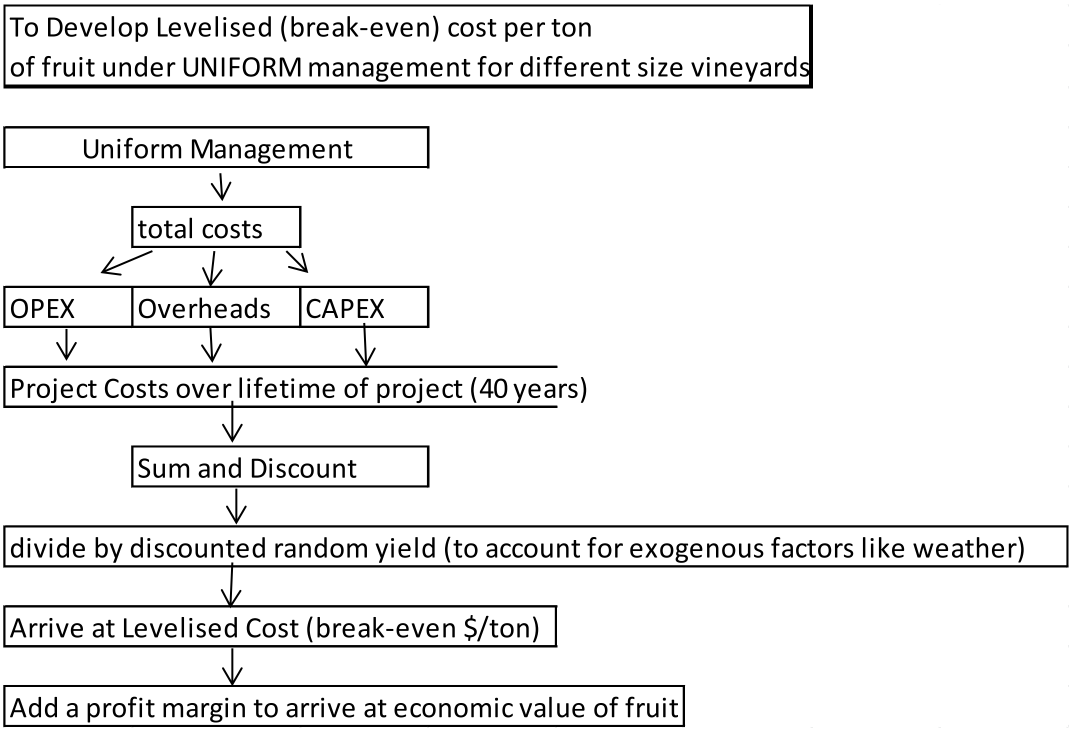
OPERATING					hrs/km	$/km	$/Ha	Cost for Vineyard
Chemicals							$ 300	$ 30,000
Applying Chemicals			6	Applications / yr	0.2	$ 11	$ 269	$ 26,880
Fertiliser							$ 300	$ 30,000
Fertiliser Application			1	Applications / yr	0.2	$ 11	$ 45	$ 4,480
Canopy Mgt & Hedging			1	pass(es)	0.2	$ 11	$ 45	$ 4,480
Netting on/off			2	pass(es)	0.2	$ 11	$ 90	$ 8,960
Cover Cropping			2	pass(es)	0.2	$ 11	$ 90	$ 8,960
Wire Lifting	No of passes	3	3	Hrs/Ha			$ 180	$ 18,000
Pruning	No of passes	1	1.5	$/vine			$ 3,000	$ 300,000
Shoot thining			1	$/vine			$ 2,000	$ 200,000
Irrig'n Operation & Maint							$ 15	$ 1,500
SUB TOTAL							$ 6,333	$ 633,260

Overheads

Cost of contract labour		$/hour	$ 20
Salary of permanent manager		$ / year	$ 70,000
Consultancy fees		$ / year	$ -
Accountancy and Admin (10% of opex costs)		$/ year	$ 12,500
Fuel and Oil			$ 1,500
Utilities (electricity, gas)			
Repairs and Maintenance			
	equipment	2500	
	firebreaks/clearing	3000	$ 5,500
TOTAL			$ 89,500

		vineyard	Salary of	Consultancy
size	tonnes	size (ha)	permanent manager	Cost per annum
very small	<100	<15	40,000	$ 5,000
small	100-499	15-70	50,000	$ 7,000
medium	500-2,499	71-360	70,000	$ -
large	2,500-9,999	361-1430	90,000	$ -
very large	>10,000	>1430	100,000	$ -

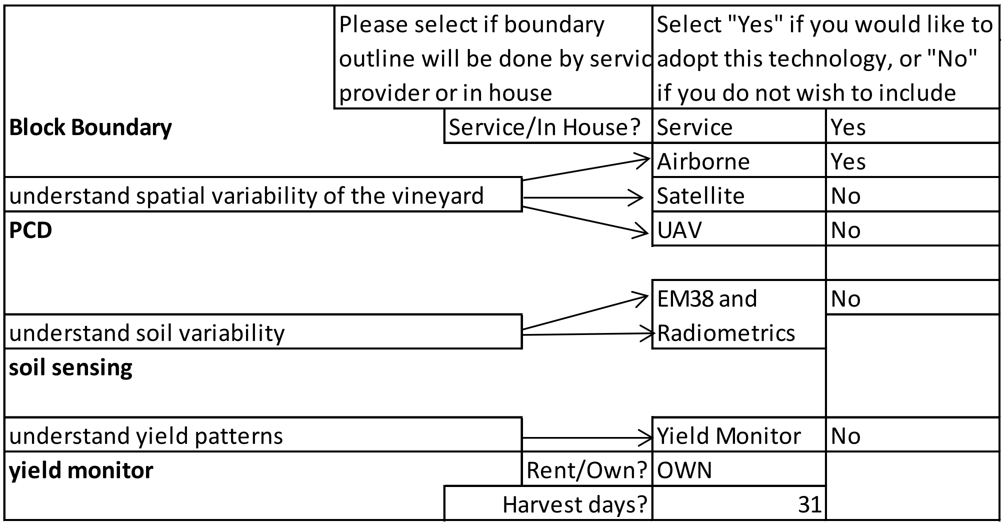
Uniform Management Summary Model Flowchart



Appendix 7 Precision Viticulture

Decision Tree

3 steps to PV-enhanced decision making
1. data acquisition
2. data processing/ground truthing
3. implementation



	Please select if boundary outline will be done by servic provider or in house	Select "Yes" if you would like to adopt this technology, or "No" if you do not wish to include	
Block Boundary	Service/In House?	Service	Yes
		Airborne	Yes
understand spatial variability of the vineyard		Satellite	No
PCD		UAV	No
		EM38 and	No
understand soil variability		Radiometrics	
soil sensing			
understand yield patterns		Yield Monitor	No
yield monitor	Rent/Own?	OWN	
	Harvest days?	31	

PCD Costs

PCD data acquisition Pricing

size	tonnes	vineyard size (ha)	Airborne $ per Ha
very small	<100	<15	$ 50
small	100-499	15-70	$ 43
medium	500-2,499	71-360	$ 41
large	2,500-9,999	361-1430	$ 37
very large	>10,000	>1430	$ 37

*includes data acquisition, processing and delivery costs

PCD ground truthing

Ground Truthing	$/hour	hours/ha	$/ha	
service provider	40	0.16	6.4	*NB: This is 10 minutes/ha. This number was generated through experience combined with the industry quoted average of $40/block.
in house	20	0.16	3.2	

PCD cost of implementation

implementation cost of training employee	
hours of training required	2
opportunity cost of labour ($/hr)	20
per person implementation cost	40

Staff to Train Relative to site size			implementation	implementation
		vineyard	No of personnel	cost
size	tonnes	size (ha)	to be trained	$
very small	<100	<15	1	$ 40
small	100-499	15-70	3	$ 120
medium	500-2,499	71-360	6	$ 240
large	2,500-9,999	361-1430	10	$ 400
very large	>10,000	>1430	10	$ 400

Block boundary survey	$/hour	hour/ha	$/ha	
service provider	40	0.08	3.2	*NB: This is 5 minutes/ha. This number was generated through experience combined with the industry quoted average of $30/block.
in house	320	0.08	25.6	

Soil Sensing Costs

Soil Sensing cost of data acquisition

		vineyard	EM 38 and Radiometrics
size	tonnes	size (ha)	$ per Ha
very small	<100	<15	$ 30
small	100-499	15-70	$ 25
medium	500-2,499	71-360	$ 25
large	2,500-9,99	361-1430	$ 25
very large	>10,000	>1430	$ 25

Soil Sensing cost of ground truthing

Ground Truthing

approx $80/ha includes cost of coring and 6 full lab analyses and 5 basic lab analyses

Soil Sensing cost of implementation

implementation cost of training employee	
hours of training required	2
opportunity cost of labour ($/hr)	20
per person implementation cost	40

Staff to Train Relative to site size			implementation	implementation
		vineyard	No of personnel	cost
size	tonnes	size (ha)	to be trained	$
very small	<100	<15	1	$ 40
small	100-499	15-70	3	$ 120
medium	500-2,499	71-360	6	$ 240
large	2,500-9,999	361-1430	10	$ 400
very large	>10,000	>1430	10	$ 400

Yield Monitoring

OWN	Cost of Yield Monitor (new)	
	machine cost per year	hourly rate to run
	660	0
RENT	Cost to Rent Yield Monitor	
	fixed cost	$ per Ha
	50	4

Data Processing		
$/hr	hr/ha	$ per Ha
20	0.25	5

Yield Monitoring cost of implementation

implementation cost of training employee	
hours of training required	2
opportunity cost of labour ($/hr)	20
per person implementation cost	40

Staff to Train Relative to site size			implementation	implementation
		vineyard	No of personnel	cost
size	tonnes	size (ha)	to be trained	$
very small	<100	<15	1	$ 40
small	100-499	15-70	3	$ 120
medium	500-2,499	71-360	6	$ 240
large	2,500-9,999	361-1430	10	$ 400
very large	>10,000	>1430	10	$ 400

PV Capital Expenses

PV Machinery and Equipment

Machinery and Equipment	Included Y/N	New Value	Disposal Value %	Useful Life Yrs	Salvage value	Depreciation per year	Cost per year	Cost per Ha per year
iPad	Y	$ 700	67%	3	$ 469	$ 77	$ 77	$ 1
GPS (standard)	Y	$ 100	40%	5	$ 40	$ 12	$ 12	$ 0
GPS Smartantenna	Y	$ 1,350	40%	5	$ 540	$ 162	$ 162	$ 2
DGPS	Y	$ 3,500	40%	5	$ 1,400	$ 420	$ 420	$ 4
Yield Monitor	Y	$ 8,250	20%	10	$ 1,650	$ 660	$ 660	$ 7
Recycle Sprayer	N	$ 2,000	20%	10	$ 400	$ 160	$ -	$ -
total depreciation PV equipment per year							$ 1,331	$ 13

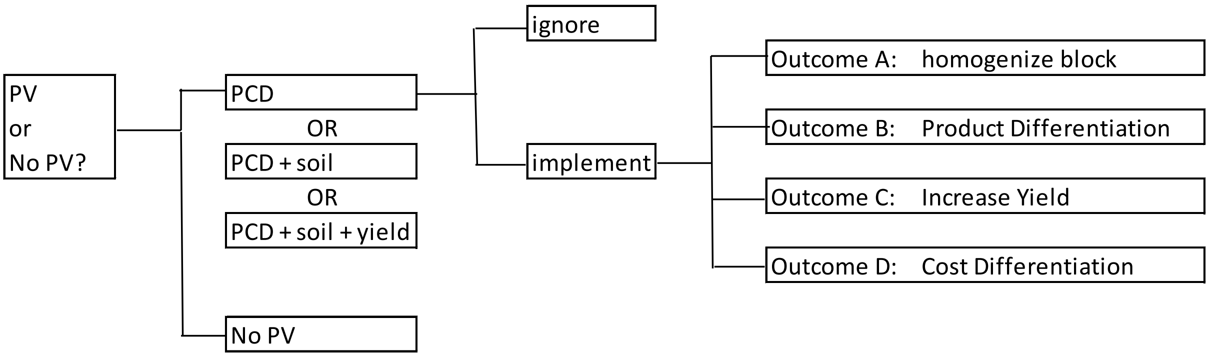
PV Response Functions (as determined by comprehensive literature review, case studies from this thesis, and input from subject matter experts)

increase revenue (fruit price and yield)			
vigour variability	PCD	soil sensing	yield increase
very low	0%	0%	0%
low	10%	10-15%	5%
medium	20%	10-15%	10%
high	30%	10-15%	15%

decrease cost			
vigour variability	PCD	soil sensing	yield monitoring
very low	0%	0%	0%
low	5%	10%	0%
medium	10%	15%	5%
high	15%	20%	10%

size	vineyard size (ha)	potential for variability
very small	<15	very low
small	15-70	low-medium
medium	71-360	medium-high
large	361-1430	high-very high
very large	>1430	high-very high

PV Response Probabilities



Outcome A/B		Overall Price Increase (%)				
	size/vigour	**0**	**10**	**20**	**30**	**40**
Probability associated (%)	very low	100	0	0	0	0
PCD	low	10	80	10	0	0
	medium	5	20	60	15	5
	high	0	10	20	60	10
Probability associated (%)	very low	95	5	0	0	0
PCD + soil sensing	low	5	40	50	5	0
	medium	0	10	40	50	10
	high	0	5	15	30	50

Outcome C		Overall Yield Increase (%)			
	size/vigour	**0**	**5**	**10**	**15**
Probability associated (%)	very low	100	0	0	0
PCD + soil sensing + yield monitoring	low	20	75	5	0
	medium	5	15	75	5
*NB: Results lagged one year	high	0	10	15	75

Outcome D		Overall OPEX Cost Decrease (%)				
	size/vigour	**0**	**10**	**20**	**30**	**40**
Probability associated (%)	very low	100	0	0	0	0
PCD	low	90	10	0	0	0
	medium	15	80	5	0	0
	high	0	90	10	0	0
Probability associated (%)	very low	95	5	0	0	0
PCD + soil sensing	low	5	90	5	0	0
	medium	0	10	80	10	0
	high	0	5	20	70	5

PV Weighted Averages as determined by probability of vigour variability increasing as a function of size

size	tonnes	vineyard size (ha)	potential for variability
very small	<100	<15	very low
small	100-499	15-70	low-medium
medium	500-2,499	71-360	medium-high
large	2,500-9,999	361-1430	high
very large	>10,000	>1430	high

Outcome A/B		**Overall Price Increase (%)**					**weighted average**	**wtd average**
	size/vigour	**0**	**10**	**20**	**30**	**40**	**price increase**	**as %**
Probability associated (%)	very low	100%	0%	0%	0%	0%	0	0%
PCD	low	10%	80%	10%	0%	0%	10	10%
	medium	5%	20%	60%	15%	5%	21	21%
	high	0%	10%	20%	60%	10%	27	27%
Probability associated (%)	very low	95%	5%	0%	0%	0%	0.5	1%
PCD + soil sensing	low	5%	40%	50%	5%	0%	15.5	16%
	medium	0%	10%	40%	50%	10%	28	28%
	high	0%	5%	15%	30%	50%	33	33%

Outcome C		**Overall Yield Increase (%)**					**weighted average**	**wtd average**
	size/vigour	**0**	**5**	**10**	**15**		**yield increase**	**as %**
Probability associated (%)	very low	100%	0%	0%	0%		0	0%
PCD + soil sensing + yield monitoring	low	20%	75%	5%	0%		4.25	4%
	medium	5%	15%	75%	5%		9	9%
*NB: Results lagged one year	high	0%	10%	15%	75%		13.25	13%

Outcome D		**Overall OPEX Cost Decrease (%)**					**weighted average**	**wtd average**
	size/vigour	**0**	**10**	**20**	**30**	**40**	**cost decrease**	**as %**
Probability associated (%)	very low	100%	0%	0%	0%	0%	0	0%
PCD	low	90%	10%	0%	0%	0%	1	1%
	medium	15%	80%	5%	0%	0%	9	9%
	high	0%	90%	10%	0%	0%	11	11%
Probability associated (%)	very low	95%	5%	0%	0%	0%	0.5	1%
PCD + soil sensing	low	5%	90%	5%	0%	0%	10	10%
	medium	0%	10%	80%	10%	0%	20	20%
	high	0%	5%	20%	70%	5%	27.5	28%

PV Model Summary Flowchart

To Develop Levelised (break-even) cost per ton of fruit incorporating costs and benefits of PV as step-wise adoption process

Develop 3 steps to PV adoptions

1. PCD
2. PCD + soil sensing
3. PCD + soil sensing + yield monitoring

Account for any costs incurred through PV:

1. data acquisition
2. ground truthing
3. implementation
4. capital costs

Add extra costs associated with PV step-wise into Levelised Cost (Uniform) model

Project all costs forward (accounting for depreciation of capital assets, replacement costs, etc.)

Using info from SME and data from case studies develop PV response functions as a function of vigour

potential for variability increase with size

maximum of 3 potential management strategies (low, medium, high)

Response functions are a percentage potential change in cost, price, or yield

create probability table of achieving benefits of PV-- the more technologies used the greater the odds of achieving maximum potential benefit

create weighted average of receiving full benefits for each step of PV and attribute % benefit to each size category of vineyard (very small, small, medium, large, very large)

install learning lag of 4 years to achieve full benefits

for each step (addition of new technology) multiply the % expected change in Opex

Add total Opex (uniform + PV), overheads, and total Capex (uniform + PV)
Subtract the Expected Savings Opex value incurred through PV
Multiply by Profit Margin
Divide by Production tonnes
This is the Minimum Price per ton of fruit for PV

Multiply the Minimum Price per ton of fruit for PV by the % expected change in fruit price (do this separately for the three steps)
This is the fruit price benefit received from PV

Sum the Expected Benefits in Cost and Price

Take NPV of Total Opex, Capex, and PV Benefits

Sum Opex + Capex and then Subtract the PV Benefits

Divide by Discounted Yield
This is Levelised Cost (break-even $/ton)

Add a profit margin to arrive at economic value of fruit

To incoporate yield, incorporate an extra year into the lag as yield benefits are acquired the following vintage

Multiply Expected yield increase by Total Production Tonnes

Discount the Yield

Using the same Cost values (Opex, Capex, Overheads - PV Benefits) from Step 2
1 Divide by Discounted PV Yield instead of Discounted Yield with no PV

2

3

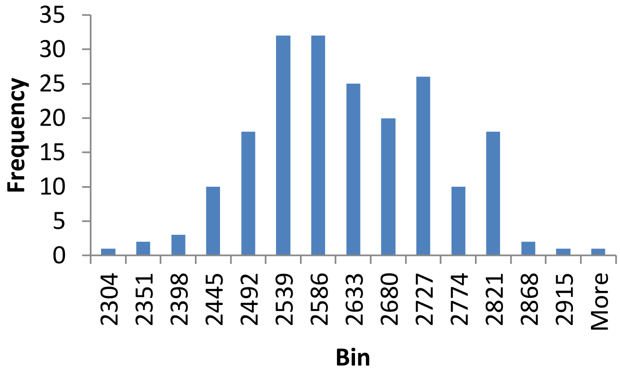
4

Appendix 8

Sensitivity analysis on the random yield array used in the model run at **5% discount rate**. Histograms, descriptive statistics, and levelised cost value from chosen yield array are included by size.

Very small (10 ha)

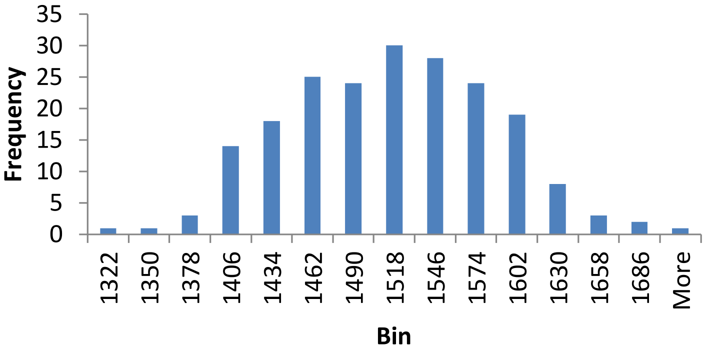
Price generated from random yield array **$2,616**



Descriptive Statistics	
Mean	2605
Standard Error	8.529005
Median	2588
Mode	2538
Standard Deviation	120.9195
Sample Variance	14621.53
Kurtosis	-0.38656
Skewness	0.129115
Range	658
Minimum	2304
Maximum	2962
Sum	523562
Count	201
Confidence Level (95.0%)	16.81831

Small (50 ha)

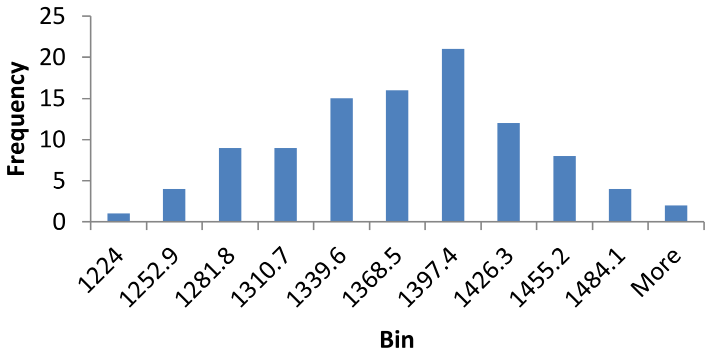
Price generated from random yield array **$1506**



Descriptive Statistics	
Mean	1503
Standard Error	5.03515782
Median	1505
Mode	1514
Standard Deviation	71.3856825
Sample Variance	5095.91567
Kurtosis	-0.316606
Skewness	0.10777785
Range	392
Minimum	1322
Maximum	1714
Sum	302079
Count	201
Confidence Level (95.0%)	9.92880869

Medium (100 ha)

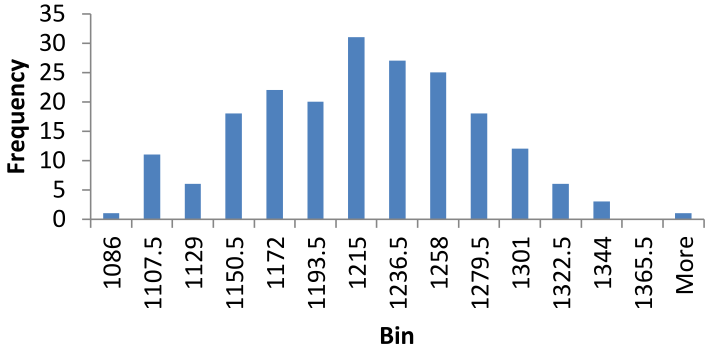
Price generated from random yield array **$1366**



Descriptive Statistics	
Mean	1364
Standard Error	4.462647909
Median	1365
Mode	1358
Standard Deviation	63.26895366
Sample Variance	4002.960498
Kurtosis	-0.242183289
Skewness	0.15918731
Range	313
Minimum	1218
Maximum	1531
Sum	274192
Count	201
Confidence Level (95.0%)	8.799878558

Large (500 ha)

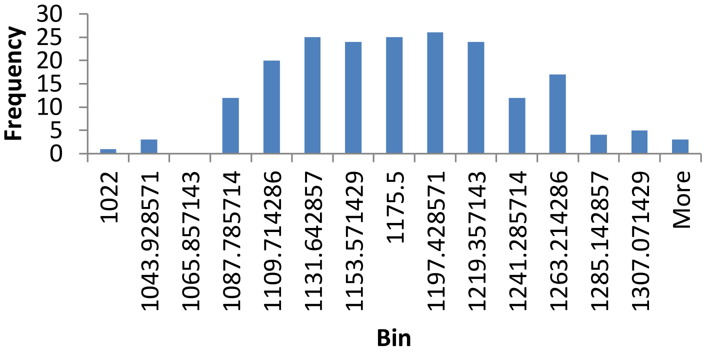
Price generated from random yield array **$1205**



Descriptive Statistics	
Mean	1208
Standard Error	4.087758
Median	1209
Mode	1205
Standard Deviation	57.95397
Sample Variance	3358.663
Kurtosis	-0.2917
Skewness	0.048551
Range	301
Minimum	1086
Maximum	1387
Sum	242767
Count	201
Confidence Level (95.0%)	8.060635

Very large

Price generated from random yield array **$1168**



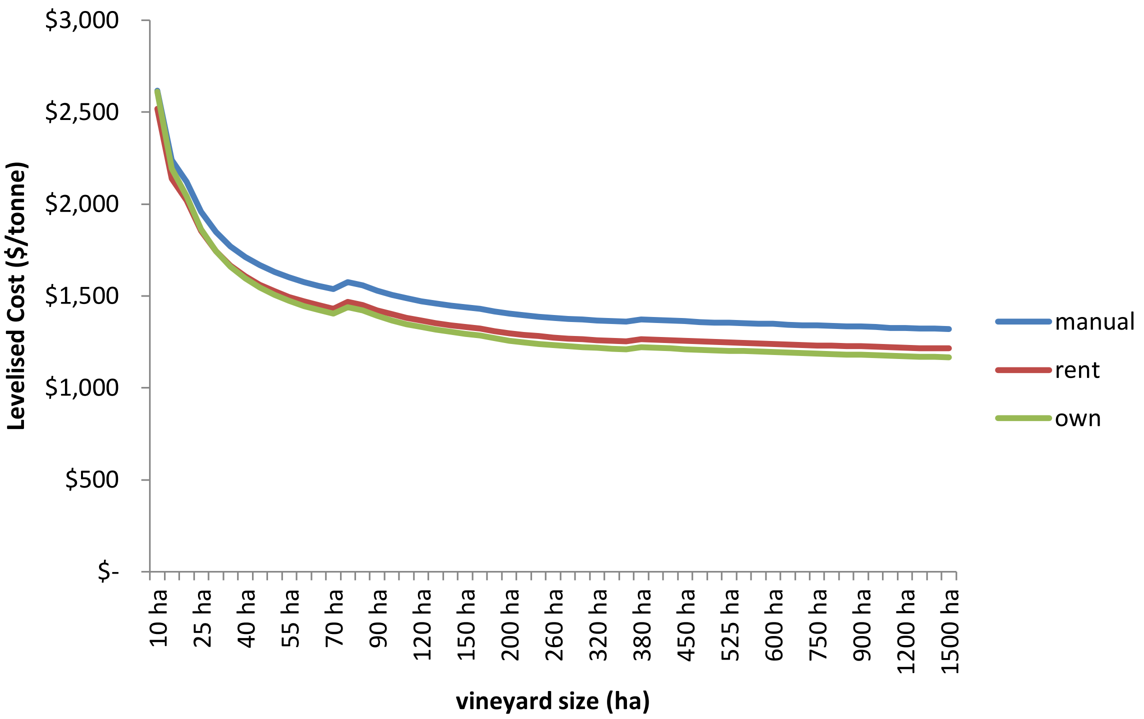
Descriptive Statistics	
Mean	1169
Standard Error	4.366224
Median	1168
Mode	1110
Standard Deviation	61.9019
Sample Variance	3831.846
Kurtosis	-0.44366
Skewness	0.201196
Range	307
Minimum	1022
Maximum	1329

Sum	234945
Count	201
Confidence Level (95.0%)	8.60974

Appendix 9

Results from the model run at 5% discount rate. This rate is most appropriate for very small to small producers, however, medium to very large producers are less sensitive to discount rate than are the smaller producers, so results from these sizes at this discount rate still provide valuable insight.

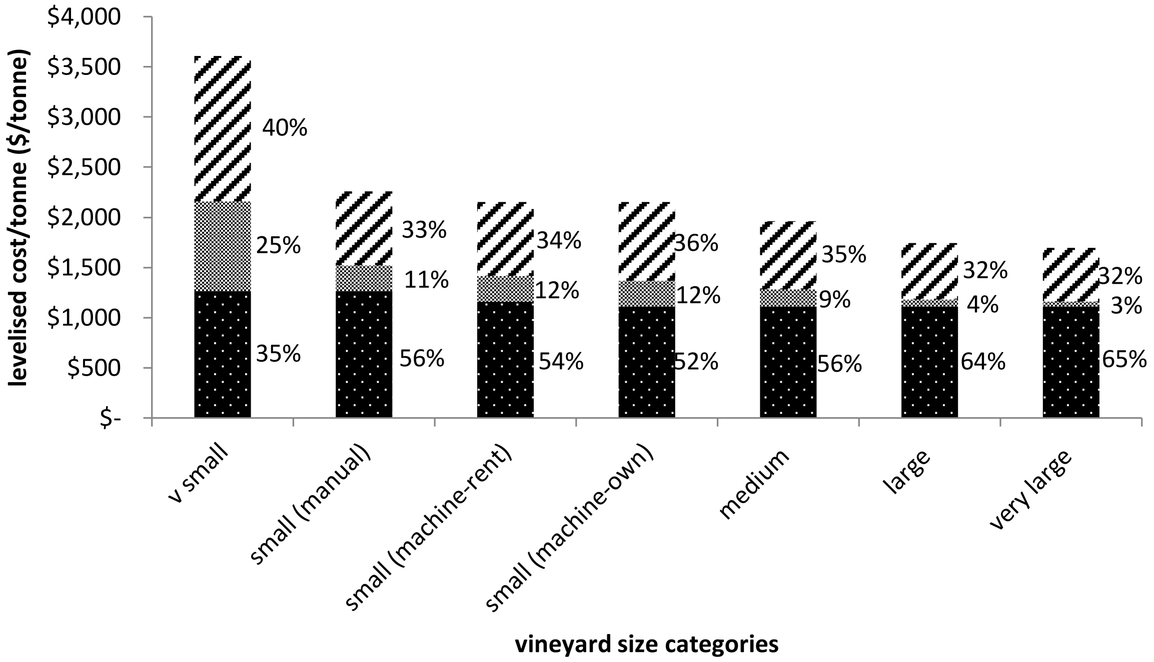
Levelised Cost/tonne as it changes with producer size and harvesting method. Around 35 ha there is a change and it becomes more economically viable to own a mechanical harvester. However, small producers may receive a premium for hand-harvested fruit in which case renting may be the most efficient.



Levelised Cost/tonne ($/tonne) including initial capital and land purchase and accounting for different harvesting methods.

Vineyard size	Vineyard size (ha)	Harvest method	Break-even Cost/tonne ($/tonne)
Very small	<15	manual	$ 3,609
Small	15-70	manual	$ 2,262
Small	15-70	mechanical (rent)	$ 2,156
Small	15-70	mechanical (own)	$ 2,154
Medium	71-360	mechanical (own)	$ 1,963
Large	361-1430	mechanical (own)	$ 1,747
Very large	>1430	mechanical (own)	$ 1,699

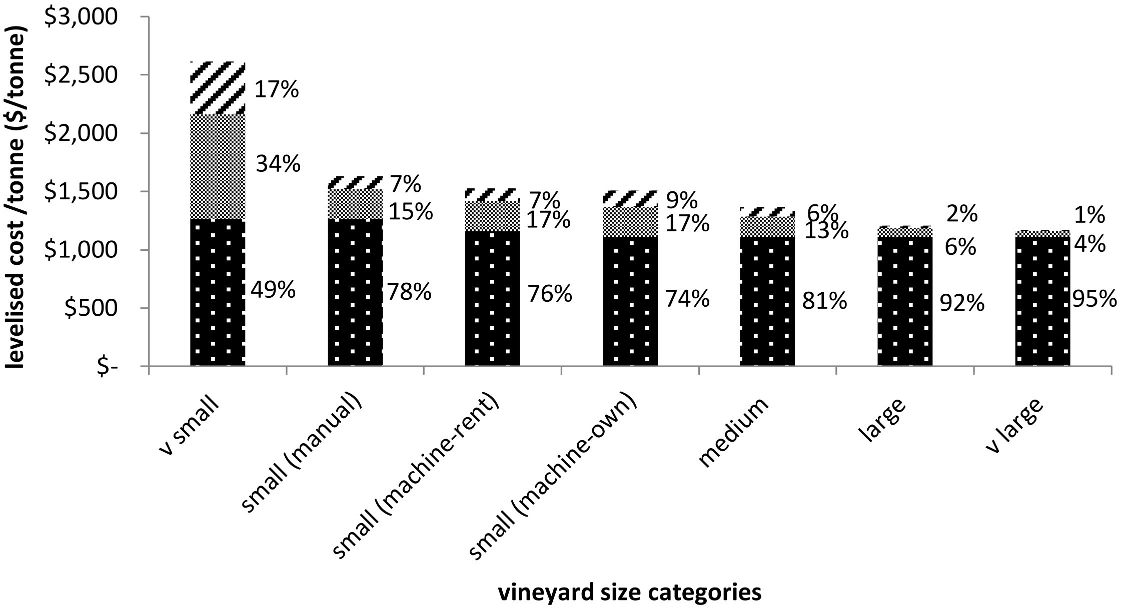
Levelised cost/tonne including initial capital. Capital expenses are incurred at the beginning of the project and therefore weigh heavily on ultimate levelised cost/tonne. Capital expenses are coloured with black and white diagonal lines, overheads are in grey, and operating expenses are black with white dots.



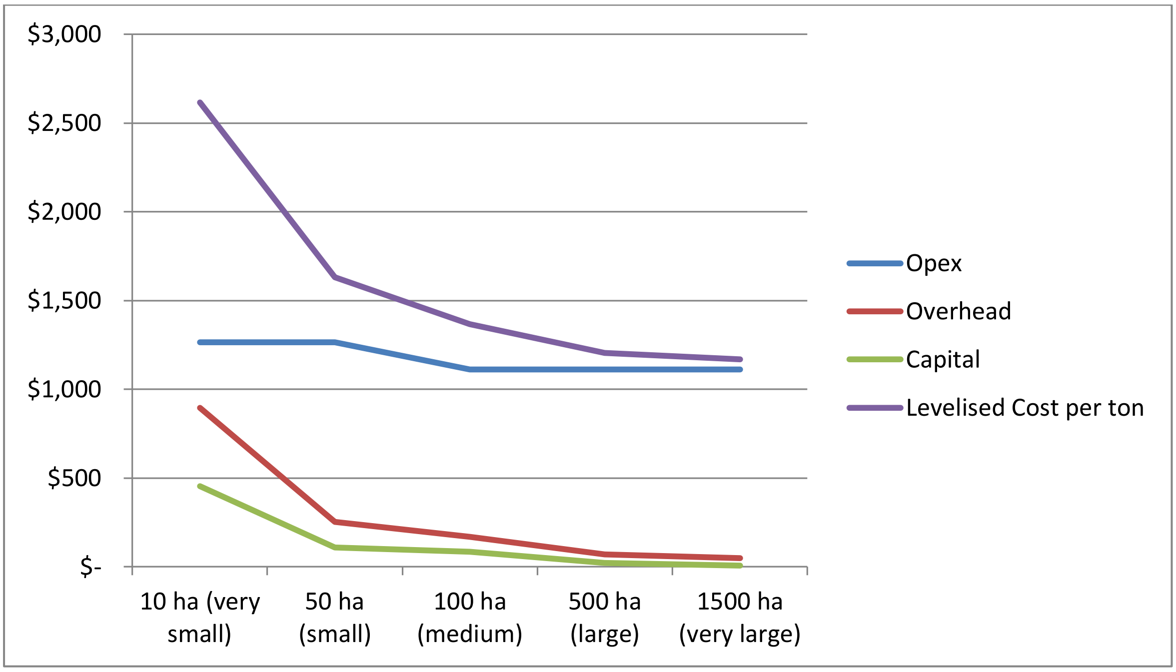
Levelised Cost per tonne ($/ton) NOT including initial capital and land purchase and accounting for different harvesting methods.

Vineyard size	Vineyard size (ha)	Harvest method	Break-even Cost per tonne ($/ton)
Very small	<15	manual	$ 2,616
Small	15-70	manual	$ 1,630
Small	15-70	mechanical (rent)	$ 1,525
Small	15-70	mechanical (own)	$ 1,506
Medium	71-360	mechanical (own)	$ 1,366
Large	361-1430	mechanical (own)	$ 1,205
Very large	>1430	mechanical (own)	$ 1,168

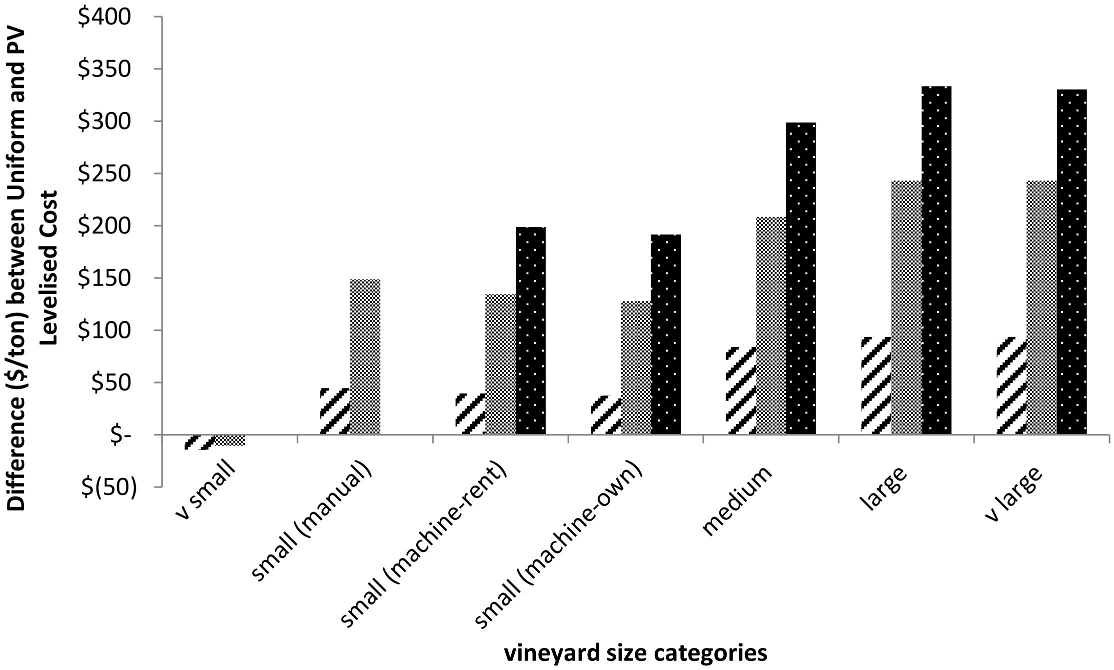
Levelised Cost per tonne not including initial capital. Breakdown by cost category: capex costs are shaded with black and white diagonal lines, overheads in grey, and operating expenses are coloured black with white dots.



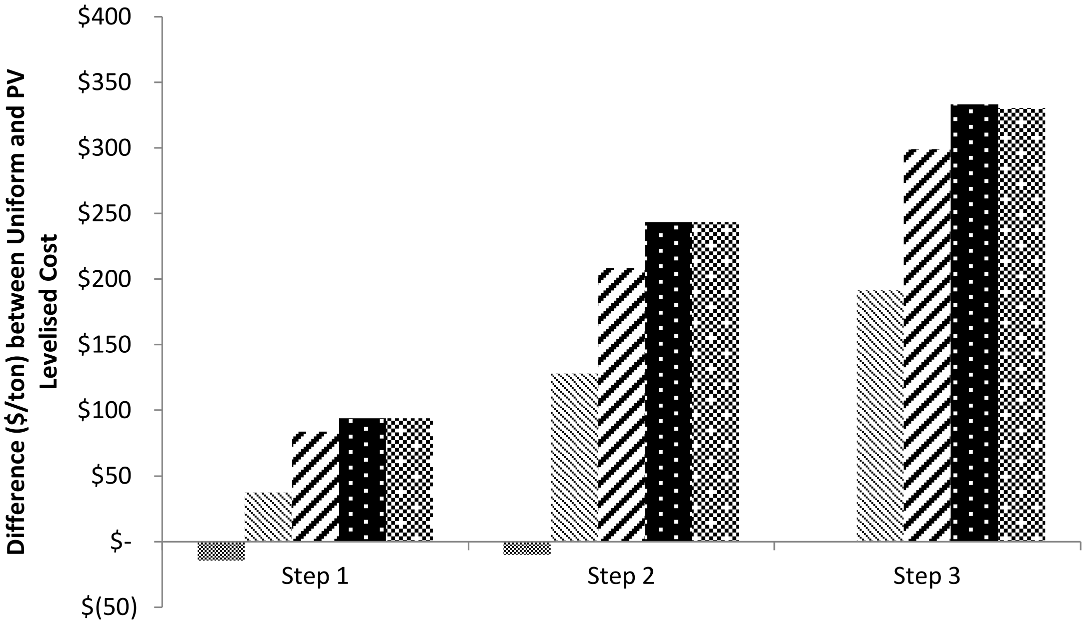
Levelised cost per tonne as it breaks down into sub categories of cost. Notice that overheads remain fairly constant across producer sizes however capital expenses and overheads decrease with increasing size.



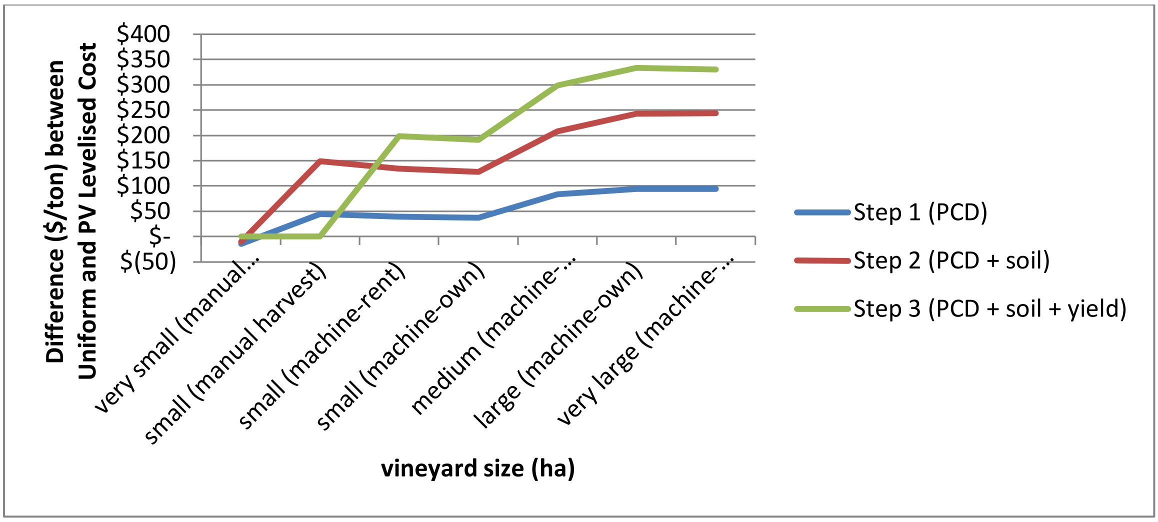
Bar chart of the benefits of PV (Step 1, Step 2, Step 3) in terms of the difference ($/ton) between levelised cost under uniform management and under PV management for each producer size. Step 1 is coloured with black and white diagonal lines, Step 2 is grey, and Step 3 is black with white dots. Very small producers achieve no benefit to any PV adoption, however, full adoption is recommended for all other size producers.



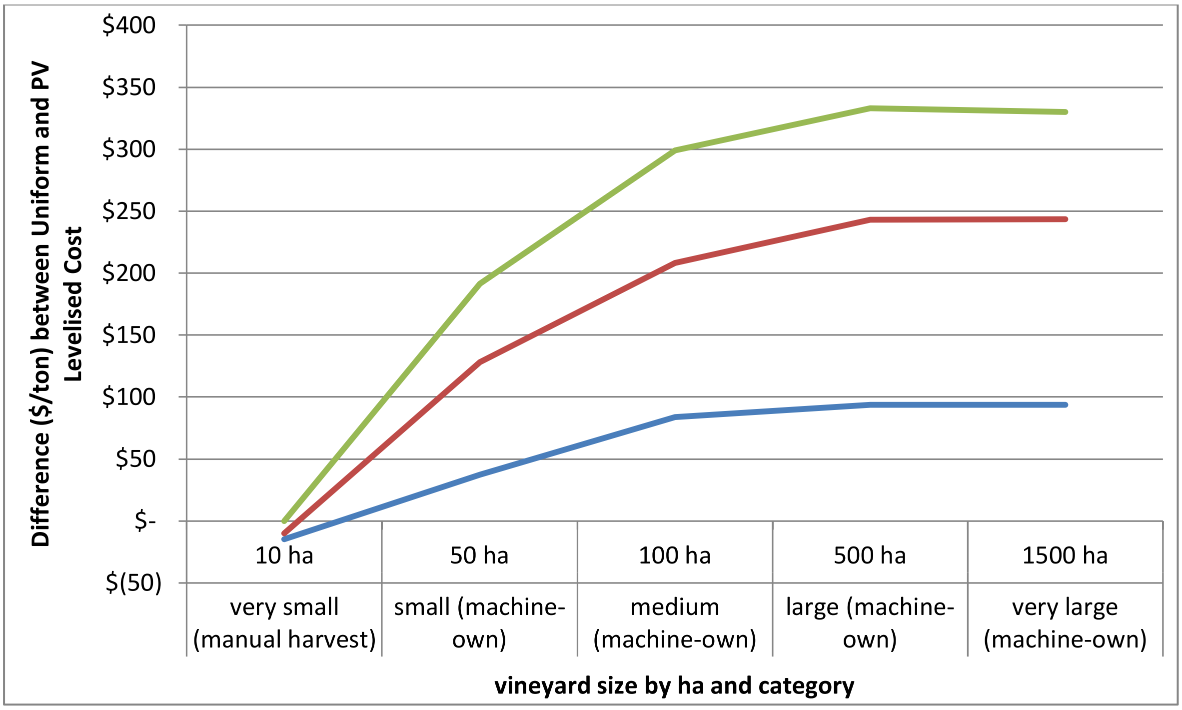
Bar chart of PV benefits for each producer across each of the 3 steps of PV. Very small producers are shaded in dark grey, small producers (own mechanical harvester) are a lighter grey, medium size producers are black and white diagonal lines, large producers are black with white dots, and very large producers are grey with white dots.



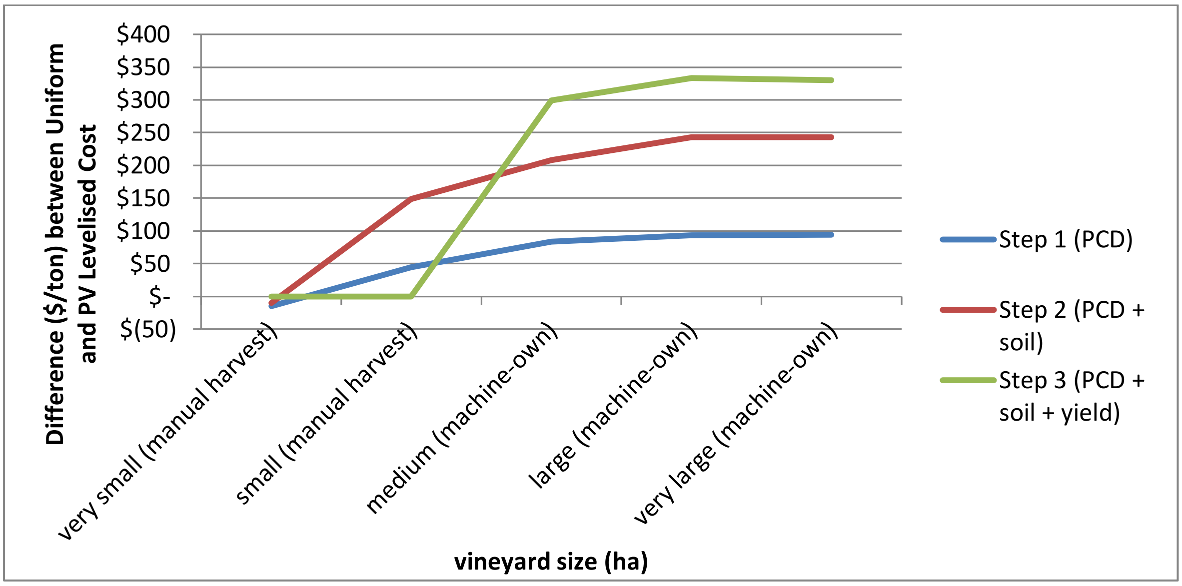
Line graph which shows clear benefits to different size producers for each of the 3 steps to PV adoption. Marginal PV benefit is maxed at Step 2 across producers, however, benefit is still realized for small to very large producers who incorporate Step 3.



Shows the overall benefits or otherwise achieved through stepwise adoption of PV. Very small producers achieve no benefit, whereas small-very large producers achieve increased benefits with size. Step 1 (imagery) is in blue. Step 2 (imagery + soil) is in red. Step 3 (imagery + soil + yield) is in green.



Again shows the overall benefits or otherwise achieved through stepwise adoption of PV, however, in this case the small producer is manually harvesting. This indicates the need to own a mechanical harvester to realize full benefits from Step 3 of PV which incorporates a yield monitor and enhanced decision making through information generated from this instrument.



Shows a strong visualization of the benefits generated from PV for each size category of producer. Very small producers do not break even and should not incorporate PV into their management plan.

However, even small producers (15-70 ha) gain a benefit through PV adoption. Depending on harvesting methods producers of this size may choose to stop at Step 2 or if a mechanical harvester is owned then incorporate all three steps. Benefits generated from PV increase with size until flattening off between large and very large producers.