Using GPS, GIS & Remote Sensing to Understand Niagara Terroir: Pinot noir in the Four Mile Creek & St. David's Bench Sub-appellations

by

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Abstract

The relationships between vine water status, soil texture, and vine size were observed in four Niagara, Ontario Pinot noir vineyards in 2008 and 2009. The vineyards were divided into water status zones using geographic information systems (GIS) software to map the seasonal mean midday leaf water potential (Ψ), and dormant pruning shoot weights following the 2008 season. Fruit was harvested from all sentinel vines, bulked by water status zones and made into wine. Sensory analysis included a multidimensional sorting (MDS) task and descriptive analysis (DA) of the 2008 wines. Airborne multispectral images, with a spatial resolution of 38 cm, were captured four times in 2008 and three times in 2009, with the final flights around veraison. A semi-automatic process was developed to extract NDVI from the images, and a masking procedure was identified to create a vine-only NDVI image. 2008 and 2009 were cooler and wetter than mean years, and the range of water status zones was narrow. Yield per vine, vine size, anthocyanins and phenols were the least consistent variables. Divided by water status or vine size, there were no variables with differences between zones in all four vineyards in either year. Wines were not different between water status zones in any chemical analysis, and HPLC revealed that there were no differences in individual anthocyanins or phenolic compounds between water status zones within the vineyard sites. There were some notable correlations between vineyard and grape composition variables, and spatial trends were observed to be qualitatively related for many of the variables. The MDS task revealed that wines from each vineyard were more affected by random fermentation effects than water status effects. This was confirmed by the DA; there were no differences between wines from the water status zones within vineyard sites for any attribute. Remotely sensed NDVI (normalized difference vegetation index) correlated reasonably well with a number of grape composition variables, as well as soil type. Re-sampling to a lower spatial resolution did not appreciably affect the strength of correlations, and corresponded to the information contained in the masked images, while maintaining the range of values of NDVI. This study showed that in cool climates, there is the potential for using precision viticulture techniques to understand the variability in vineyards, but the variable weather presents a challenge for understanding the driving forces of that variability.

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Symbols & Abbreviations

ANOVA	Analysis of variance
AVHRR	Advanced very high resolution radiometer
AVIRIS	Airborne visible/infrared imaging spectrometer
CCOVI	Cool Climate Oenology & Viticulture Institute
CIR	False-colour near-infrared
CV	Coefficient of variation
DA	Descriptive analysis
DN	Digital number
GCP	Ground control point
GIS	Geographic information system
GPS	Global positioning system
HPLC	High pressure liquid chromatography
IDW	Inverse distance weighting
LAI	Leaf area index
LSD	Least significant difference
MDS	Multidimensional sorting
NDVI	Normalized difference vegetation index
NIR	Near-infrared
PA	Precision agriculture
PCA	Principal component analysis
PV	Precision viticulture
RGB	Red-green-blue
RMSE	Root mean square error
ROI	Region of interest
RSQ	Overall squared correlation index
RST	Rotation stretch translation
TA	Titratable acidity
TDR	Time domain reflectometry
UTM	Universal transverse mercator
VI	Vegetation index
Ψ	Leaf water potential

1.0 Introduction

1.1 Terroir

In Old World winegrowing regions, the effects responsible for differences between vineyards have been collectively referred to as *terroir* (Van Leeuwen & Seguin 2006). This idea can be applied to any product with characteristics that are unique to its region of origin, but is perhaps most renowned for its long history associated with wine appellations of origin.

There are many factors accepted to be part of terroir, and these have been subject to research around the winegrowing world. The regional climate, and the site-specific microclimate, the soil pedology or texture, soil nutrient content and uptake by the vine, and the underlying geology of a region all play a role in defining terroir (Van Leeuwen & Seguin 2006; Andres-de Prado et al. 2007).

The human component of grape growing is also a factor in terroir. The traditional viticultural and winemaking practices of a region, the characteristics of sites devoted to grape growing, the crops sharing the land, and the varieties of grapes planted are influenced by tradition as well as emerging technologies (Van Leeuwen & Seguin 2006).

In the New World, especially in younger regions such as the Niagara Peninsula in Ontario, there is not the history and tradition to direct the grading of wines grown from specific sites. Thus in the open market, growers are left to find and adapt new tools for understanding their vineyards.

1.2 Vine Water Status

As living plants, grapevines require water, which they draw primarily from the soil. The available water is controlled by climate, irrigation, solar radiation and the water-holding capacity of the soil. These factors have been shown to impact the vegetative growth of grapevines, as well as the composition of the fruit and the organoleptic character of the wine (Koundouras et al. 2006).

The increasing use of irrigation in many New World vineyards necessitates the need to understand how the application of water, or withholding water from vines, will change the growth habits of the vine and the composition of the fruit. Conversely, where irrigation is not used, the water status of the vines may be manipulated through other cultural practices, but will ultimately be affected by variations in the soil with consequences for the composition of the fruit (Acevedo-Opazo 2008). Variable water status within a vineyard is itself a component of the terroir of that site.

1.3 Precision Viticulture

The basic premise of precision agriculture (PA) is that inputs to farming practices are in response to information gathered with the intent of affecting outputs through an information feedback-loop system (Bramley et al. 2001). On a commercial scale, PA involves the collection of data on any number of specific metrics of interest, as well as ancillary data, the interpretation and analysis of those data in order to identify trends, the implementation of a management plan to accommodate or change those trends, and the collection of data to observe those results leading to a new cycle (Bramley et al. 2001). When applied to viticulture, there is a focus on understanding the spatial and temporal variability in the production of winegrapes (Hall et al. 2003). Grapegrowers have traditionally accepted the variability within vineyards as inherent to the underlying qualities of the site itself, the terroir. With many years of experience, vineyard areas have been subdivided into individually rated vineyards of higher or lower quality.

The emergence of geomatics software has allowed grape growers to geographically link information from their vineyards into the PA feedback loop, and target inputs to specific regions of their vineyards. Remote sensing and geomatics tools have been used successfully in grape production in New World regions including California (Johnson et al. 2001), Australia (Hall et al. 2003; Lamb et al. 2004), and Chile (Acevedo-Opazo 2008) as well as Old World regions including Spain (Zarco-Tejada et al. 2001).

1.4 Hypotheses & Objectives

This study aimed to investigate the use of precision viticulture in building understanding terroir in a New World growing region. Four individual commercial vineyards planted to *Vitis vinifera* L. cv. Pinot noir in the Four Mile Creek and St. David's Bench sub-appellations, Niagara Region, Canada were the study locations.

Geomatics tools can be used to understand some of the aspects of New World terroir in terms of spatial variability of soil composition and vineyard moisture status. These tools were to be tested for use in the cool climate Niagara Region.

It was hypothesized that vine water status will be related to yield components and berry composition. In particular, soluble solids, pH, titratable acidity (TA), total anthocyanins, total phenolic compounds, colour intensity and hue will be affected by the water status of the vine. These effects will also be apparent in the must and wine chemical composition, and in the sensory attributes of the wines made from fruit in delineated water status zones.

Additionally, it was hypothesized that information extracted from multispectral remotely sensed images can be used to identify variations in vineyard metrics and berry composition.

2.0 Literature Review

2.1 *Terroir*

2.1.1 Terroir & Soil

The combined effects that create innate differences between vineyards have been collectively referred to as *terroir* (Van Leeuwen & Seguin 2006).

As a principal driver of terroir, and the primary growth media for grapevines around the world, the soil is an important component of grape growing. Seguin (1986) made a thorough investigation into the soils of the Bordeaux region in France, finding that the complex interactions of the vine with the soil and the climate produce very difficult to predict results. There is no single ideal soil type for grape production: schist, granite, gravel, clay, marl, sandstone and sand are all associated with premium wine regions around the world (Seguin 1986; Andres-de Prado et al. 2007). The soil type, along with climatic and viticultural factors including soil tillage and rootstock selection, will affect the vine's ability to use available soil nutrients and moisture, affecting vine health and even influencing the incidence of root rot (Seguin 1986).

Implicit in the discussion of terroir is that the grapes from different regions, even if vinified in the same way by the same winemaker, will create wines that are different as a reflection of where they were grown.

Guinard & Cliff (1987) used descriptive analysis to derive a sensory profile of Pinot noir wines from the Carneros region in California that was different from the wines of the Napa Valley and the larger Sonoma regions. However, the wines evaluated by Guinard & Cliff (1987) were commercially crafted wines from a number of wineries, and they may have been describing winemaking influences rather than terroir differences.

The human component of grape growing is also part of terroir. The traditional viticultural practices of a region, the type of sites devoted to grape growing, and the varieties of grapes planted are influenced by tradition as well as emerging technologies (Van Leeuwen & Seguin 2006). By some definitions, the viticulturist and the winemaker themselves may be a part of terroir.

The depth and distribution of the roots is influenced by soil texture (Seguin 1986) as well as inter-row management (Morlat & Jacquet 2003). Nutrient content was found to be greater with the presence of inter-row vegetation; however, when this vegetation was permanent, the vine root systems did not spread into this space as they did without the presence of vegetation. Consequently, the vines may not have been able to uptake their nutrient requirements, and musts were found to have lower concentrations of yeast-assimilable nitrogen compounds. Similarly, soil under permanent cover had higher moisture holding capacity and a higher soil nitrogen content, but the vines were unable to use this moisture or nitrogen because of reduced root growth (Morlat & Jacquet 2003). In New York State, alternative ground covers were investigated in a Pinot noir vineyard by Hostetler et al. (2007). They found that geotextile mulches reduced weed growth, but had no positive influence on available soil moisture, vine size, yield or grape composition. Viticultural practices are a component of terroir; this may be especially true in regions where traditions, rather than innovation, govern activities in the vineyard.

In the New World, especially in younger regions such as the Niagara Peninsula in Ontario, consumers are left to be the judge of a wine's value. The degree of variation within New World regions cannot be over-estimated; there is a wide range of soil parent material, slope & aspect, distance from the moderating influence of Lake Ontario and associated mesoclimate conditions in the Niagara Peninsula (Shaw 2005). The soils are predominantly Halton clay over Queenston shale and lacustrine sandy loam, with high water holding capacity. The Niagara Escarpment, the most prominent geological feature in the area, has exposed dolomite limestone cliffs with gentler slopes covered with silty and clay loams. These areas experience far better drainage, and are almost entirely north-facing (Shaw 2005). This variation, the relatively young age of the grape-growing industry, and the lack of a strict appellation of origin system means that growers and wineries are left to find and adapt new tools for understanding their vineyards.

Reynolds et al. (2007b) used geomatics tools to map variability in elevation, soil type, yield, and grape composition as a means of understanding how these factors of terroir express themselves in Niagara-grown Riesling. They found that both vine vigour and soil texture influenced berry composition, but expression of yield components and some grape composition was not stable over time, suggesting the presence of other physical factors, in addition to underlying vine balance issues.

2.1.2 Water Status

The effect of water stress on grapevine and fruit development has been extensively documented. The physiological impact of water stress on grapevines is largely agreed upon, but the mechanisms and effect on grape composition is not.

Generally, when water loss from transpiration exceeds the available water, governed by solar radiation, temperature and relative humidity, physiological stress occurs (Hardie & Considine 1976). Water stress may result in reduced fruit set (Hardie & Considine 1976), reduced yield (Hardie & Considine 1976), increased sugar accumulation and break-down of malic acid (Koundouras et al. 2006), increased concentrations of anthocyanins and total grape phenolics (Koundouras et al. 2006; Sivilotti et al. 2005), and generally desirable grape composition and wine sensory attributes (Reynolds et al. 2007b; Matthews et al. 1990).

Stomatal openings regulate the rate of photosynthetic activity. As leaf water potential (Ψ) approaches -5 bar, the openings begin to narrow, and at -12 bar they close entirely (Kriedemann & Smart 1971). The timing of the water stress has been shown to affect the vine in different ways. Extreme water stress after veraison has a negative impact on the vine's ability to produce sugars, and the concentration of soluble solids in the grapes will be negatively affected (Hardie & Considine 1976). Around the period of bloom, severe water stress causes a reduction in yield by impacting fruit set (Hardie & Considine 1976). Sivilotti et al. (2005) found that moderate water stress after veraison did not impact that soluble solids, pH or TA of the berries, but increased the concentration of polymerized phenolic compounds as well as berry anthocyanins in Merlot. They attributed the discrepancies in the effect of water stress on soluble solids and TA to the different environmental conditions of research sites (Sivilotti et al. 2005). They also observed that soil moisture was inconsistent with irrigation regimes, and not clearly related to wine water status. It was postulated that temperature affected transpiration, and that after a vintage of stress the vine would respond with reduced water uptake and a more negative Ψ (Sivilotti et al. 2005).

It was observed in an Oregon Pinot noir vineyard that the presence of inter-row cover crop decreased soil moisture, but did not affect vine water status. Where there was lower soil moisture observed between vintages, there was a corresponding increase in water stress (Sweet & Schreiner, 2010). While in general, soil moisture and vine water status are intuitively related, the specifics of current and previous vineyard conditions may change this relationship.

Choné et al. (2001) found that the method of measuring water potential, as well as soil type, impacted the ability to detect water stress. Dawn leaf water potential and stem water potential as well as midday stem water potential were much more responsive to water stress than was midday leaf water potential, and would indicate water stress first (Choné et al. 2001).

In Cabernet Sauvignon grapes in Washington state, Keller et al. (2008) found that increasing the degree of water stress through deficit irrigation did not impact vine vegetative growth, or berry composition except when the water stress was applied before fruit set.

Additional contradictions were observed by Koundouras et al. (2006), who found that yield and berry size were not affected by water stress, while vegetative growth and soluble solids were affected. The timing, rather the intensity, of the water stress had the most significant impact on grape phenolics, whereas the timing of the water stress was more important for soluble solids.

Skin flavonoid concentrations were increased under a deficit irrigation regime by Kennedy et al. (2002). These differences were on a by-weight basis, but not on a per-berry basis. They found that there was little change in the concentration of berry anthocyanins late in ripening under water stress, but that an increase in pigmented polymers may have led others to the conclusion that anthocyanin concentrations were increasing (Kennedy et al. 2002). The physiological processes of ripening berries while subjected to water stress are not entirely understood.

In terms of sensory attributes, there is a relationship between the presence of moderate water stress and hedonic liking of wines made from the Agiorgitiko grape (Koundouras et al. 2006). Conversely, Reynolds et al. (2007a) found that irrigation used to decrease the level of water stress increased the intensity of desirable sensory attributes in Chardonnay.

There is a large degree of disagreement in literature as to the effect of water stress on grapevine physiology and resulting wine characteristics and quality. These disagreements may arise from other factors influencing the vine growth, ultimately included in a broad definition of terroir.

2.1.3 Vine Vigour

There have many numerous studies into the effect of fruit shading and vine vigour on grape composition and wine attributes. The sunlight exposure of the grapes is directly related to the vigour of the vines, and can be influenced by canopy management that must balance exposure with sufficient leaf area to ripen the fruit. Bergqvist et al. (2001) found that in California-grown Cabernet Sauvignon and Grenache grapes, increased sunlight exposure increased berry soluble solids, decreased the TA, and increased the concentration of phenolic compounds. Different treatments were achieved by leaf thinning, and shoot thinning or positioning as required to gain complete exposure, single or multiple layers of leaf shading, and fully shaded by more than four leaf layers. The change in berry composition was limited; there was an increase in ambient temperature resulting from the increased intensity of solar radiation, and grapes with increased exposure to afternoon sun did not experience the same degree of compositional changes (Bergqvist et al. 2001).

In a more controlled environment, Cortell & Kennedy (2006) placed Oregon Pinot noir clusters in shade boxes to exclude light exposure to specific clusters on the same vine as exposed clusters. They did not find a temperature increase of more than 0.5°C inside the light exclusion boxes. The exposed fruit had higher concentrations of proanthocyanins, as well as the five individual anthocyanins found in Pinot noir grapes. In particular, the relative proportion of the anthocyanin delphinidin-3-O-glucoside was found to be lower in light excluded clusters in both high and low vigour vines, suggesting a direct response to sunlight exposure (Cortell & Kennedy 2006).

The effect of canopy density in British Columbia Pinot noir vines on yield and grape composition was studied by Reynolds et al. (1994). They found that in high vigour zones, a vertically divided canopy could be used to maintain a higher number of shoots/metre of canopy, and consequently increase the total yield. It would also limit fruit shading, and improve fruit composition metrics (Reynolds et al. 1994). The increased canopy area meant that a larger crop could be successfully ripened through the larger photosynthetic active area. Additionally, the divided canopy architecture encouraged light exposure of the fruit.

To separate the effect of sunlight and temperature, Spayd et al. (2002) introduced treatments in combinations of sun-exposure, shading, heating and cooling. The concentration of monomeric anthocyanins increased in exposure to sunlight, regardless of the temperature regime. Excess exposure to sun, resulting in high temperatures in the fruiting zone decreased the total anthocyanin concentrations, and higher temperatures generally resulted in lower concentrations of anthocyanins. Sunlight is required, but excess heat should be avoided for anthocyanin synthesis, especially in warm to hot viticultural regions (Spayd et al. 2002).

The relationship between vigour and anthocyanin concentration in Oregon Pinot noir was studied extensively by Cortell et al. (2007a, 2007b, 2008). Vines were assigned to spatially delineated vigour zones based on shoot length, trunk cross-sectional area and leaf chlorophyll content. The yield was highest in the medium-vigour zone, soluble solids accumulation was lower in the high-vigour zones, and TA was lower in the low vigour zones. In other words, fruit was riper in the lower vigour zones. There was higher anthocyanin accumulation in the lower vigour zones, in particular the concentrations of delphindin-3-O-glucoside and petunidin-3-O-glucoside increased. They concluded that the fruit zone microclimate was ideal in the lower and medium vigour zones, resulting in a balance of sunlight and heat, and favorable vine balance conditions (Cortell et al. 2007a). In the wines made from the fruit in these vigour zones, the high vigour zones had the lowest concentration of anthocyanins, and the medium vigour zone wines had the highest concentrations (Cortell et al. 2007b).

The wines that were made as a part of that study were subjected to sensory analysis by Cortell et al. (2008). The differences between the wines were in astringency, bitterness, sour and sweet tastes, earthy and chemical flavours, and heat. The low vigour zone wines tended to have the highest intensity of perceived astringency, and this was related to the actual tannin concentration in the fruit and skins. In a stepwise regression, the vine vigour was more important than vineyard site to explain the differences in the wines for the significantly different attributes. This was especially true of the differences in astringency, sour, chemical and bitterness (Cortell et al. 2008). There is a relationship between the vigour of the vine, fruit shading and temperature, and the sensory properties of the wine.

2.2 Geomatics

Geographic information systems (GIS) is an increasingly popular means of combining layers of data linked to specific locations. This layering can take many forms, and by processing multiple layers, derived data can be produced to predict, plan or model the system. The use of global positioning systems (GPS) is needed as an ancillary technology in order to locate specific sampling points in two or three dimensions.

Surface maps can be created as a tool to interpolate between sample points. Rather than treating points as individuals in a sample mean, they are treated as distinct points on a surface grid. There are many spatial prediction models, which are appropriate for use with different types of data, and with different outputs. Spatial dependence, or spatial autocorrelation, means that the value of a variable at one point is not independent of the points nearest to it (Whelan et al. 2001; Almeida-Neto & Lewinsohn 2004). The final surface is represented by a two-dimensional XY grid, where each grid node has an associated Z value for a given variable. In assigning the value to each node, global predictors use the entire sample set, whereas local predictors use only the points closest to the node. Exact interpolators assign the actual value to a grid node when a sample point is at that node. Smoothing interpolators reduce the weighting of all nodes, such that the value of the node will not necessarily be the exact measurement value to reduce sudden peaks that may result from measurement anomalies or errors.

There is no single correct gridding method for any data set. The method chosen must represent the extents of the data appropriately, and create maps that are of use for their intended purpose (Whelan et al. 2001). A short description of several common methods follows.

The modified Shepard's method can be used as either a local or global quadratic interpolator. It uses inverse distance weighting; points farther from the grid node are weighted less heavily than those closer to the node. It also uses a local nearest neighbour in order to smooth harsh peaks and valleys that may result from outlying data, giving it an advantage over regular inverse distance weighting (IDW) methods (Renka 1988). In practice, it can be made a smoothing interpolator with the inclusion of a smoothing factor to reduce to effect of small-scale measurement errors.

Kriging is appropriate for large data sets. It can be implemented as global or local Kriging, which use the entire data set and a moving neighbourhood of points, respectively. Computationally, it follows a least squares distance weighted model, using a covariance function to estimate the variogram (Whelan et al. 2001). The variogram is a function that predicts the spatial dependence between points, and is itself a function of the distance between sample points, or lag, the error and the variation in the data set (Almeida-Neto & Lewinson 2004). An advantage to Kriging is that the use of the covariance function allows for a prediction of variance at each grid node, meaning that a map of Kriging variances can be drawn as a measure of confidence in the map of the variable of interest (Whelan et al. 2001).

2.3 Remote Sensing

In broad terms, remote sensing is any form of observation in which there is no contact between the target and the observer. Optical remote sensing is a particular application in which reflected light is collected by a sensor. Different surfaces have unique spectral reflectance patterns; that is, they absorb, reflect or transmit light at different proportions of incident light in the ultraviolet, visible, and infrared spectra in a predictable way (Lillesand & Kiefer 2000).

The spectral resolution of an imaging system refers to the number of wavebands that can be simultaneously recorded for an area (Hall et al. 2002). Multispectral imaging typically involves a small number of wavebands, between two and 10, that may cover a large range of wavelengths. Hyperspectral imaging typically involves a large number of wavebands, greater than 10 but potentially many more, with each waveband corresponding to a narrow range of wavelengths (Hall et al. 2002). The type of optical sensor and corresponding spectral resolution is chosen with respect to how the data will be collected, the computing power available, and the type of sensors available for the desired application.

In visualizing remotely sensed images, either a grayscale single band, or a three-band representative image is used. Since the actual wavebands may come from beyond the range of human vision, these three bands are limited to red, green and blue. The bands assigned to the three possible bands may be drawn from any of the available wavebands, and will be displayed in the representative colours. In this way, selecting the red, green and blue wavebands will result in a true-colour red-green-blue (RGB) image. A false-colour near-infrared (NIR) image (CIR) is created by assigning the NIR, red and green bands to red, green and blue, respectively. The more red a pixel appears in a CIR image, the higher the NIR and lower the red reflectance in that pixel. This is typically associated with dense, healthy vegetation (Lillesand & Kiefer 2000).

A spectral index takes the information from more than one waveband, and reduces it to a single value. A large number of these indices have been developed for many different purposes, tied to specific multi- and hyperspectral wavebands. They may include compensation for atmospheric and soil affects, depending on the source of the radiometric data (Jackson & Huete 1991; Zarco-Tejada et al. 2005). Vegetation indices (VI) make particular use of the large differences between red, green and NIR wavebands that occur in plants (Hall et al. 2002). The classic VI is the Normalized Difference Vegetation Index (NDVI), defined as the difference between the red and NIR wavebands, divided by their sum, shown in Equation 2.1.

$$NDVI = \frac{\text{NIR-RED}}{\text{NIR+RED}} \qquad \text{Equation 2.1}$$

NDVI was first proposed by Rouse et al. (1973) for monitoring pastureland vegetation on the American Plains. This VI gives a value between -1 and +1, and is a common indicator of plant vigour, biomass or health, where values approaching +1 are indicative of a large volume of vegetation, and 0 typically represents a lack of vegetation. Negative values are not expected for natural surfaces, but may occur for man-made objects (Hall et al. 2002). Gitelson et al. (1996) proposed using the green waveband to monitor vegetative growth, and found the NDVI-green to be more sensitive to chlorophyll content of leaves. This index is identical to the standard NDVI, but the red waveband is replaced by the green.

Spatial resolution depends on the sensitivity of the detector as well as the distance between the detector and the surface of interest. These two factors will contribute to the total area (or footprint) of the image, and the size of individual pixels. There are a number of commonly used satellite-based and aircraft-mounted imaging systems with a variety of available wavebands and spatial resolutions. IKONOS is a privately-operated multiband satellite imager with a resolution of 4m. Operated by the same corporation, GeoEye-1 is a commercial multiband satellite with a resolution of 1.65m (www.geoeye.com/CorpSite). The AVHRR (Advanced Very High Resolution Radiometer), operated by the American government, is a multiband satellite imager with wavebands operating in the upper range of the visible spectrum, and full-infrared for cloud cover observations (http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html). AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) is an aircraft-mounted Hyperspectral imaging system covering visible and infrared wavebands operated by NASA (http://aviris.jpl.nasa.gov). Landsat was the first space-borne remote sensing system, it is a low resolution satellite-based system operated by NASA with 8 wavebands in the 15-60m spatial resolution range (http://landsat.gsfc.nasa.gov). There are many other aircraft and satellite based systems available, and in addition to these systems specific applications can be custom developed to capture the desired spectral and spatial resolution required.

Remote sensing has been used in both plant and non-plant fields of study. In the case of mineralogical and soil analysis, it has been used in identifying surface mineral deposits (Rast et al. 1991). It has also been used to predict soil albedo, a major factor in global climate models, relating to soil colour and moisture content (Post et al. 2000). It has been used to predict soil water content in prevention of drought stress in golf courses (Dettman-Kruse et al. 2008), and in non-irrigated cotton plantations (Ben-Dor & Levin 2000).

Land-cover classification is commonly achieved using remote sensing data, typically covering a large ground area for planning and land management (Lillesand &

Kiefer 2000). It was this use for remote sensing that prompted the creation of the NDVI by Rouse et al. (1973). In agricultural applications, remote sensing has been used as a tool in mapping weed densities (reviewed by Lamb & Brown 2001). Water use and demand have been measured in areas of high irrigation use through the use of spectral indices and remote thermal sensing (Bastiaanssen et al. 2000). The consensus of these reviews is that remote sensing has been proven in multiple scenarios as a research tool, but is lacking in industrial applications without the high cost of skilled personnel, control of image capture dates and image resolution (Lamb & Brown 2001; Bastiaanssen et al. 2000).

In viticultural applications, remote sensing has been used in modeling vegetative growth, and to infer grape composition from those measurements. Wildman et al. (1983) used colour infrared film to capture aerial images of a California vineyard to monitor the spread of the phylloxera louse. They used a qualitative assessment of pictures to identify changes in canopy density, verified by field scouting. The use of digital, CIR images was introduced by Johnson et al. (1996), who found relationships between the NDVI extracted from the CIR images and the vegetative growth of the vines. In this case, vegetative growth was influenced most by two factors, the incidence of phylloxera, and the moisture holding capacity of the soil (Johnson et al. 1996).

Again in California, Johnson et al. (2001) used remotely sensed spectral data to delineate a vineyard site of Chardonnay into small-lot production zones. Using an aircraft-mounted, multi-band imager, a single airborne image was captured after leaf expansion but before veraison. The NDVI transform of this image was used to divide the site into vigour zones. They found that the vine size was related to the vigour zones, as identified by the airborne image. The vigour zones were also related to vine water status, and grape composition variables. Thus, indirectly, remote sensing was used to predict vineyard status and grape composition, with direct implications for wine quality (Johnson et al. 2001).

The relationship between VI and vegetative growth, measured using dormant pruning weights, was further explored by Dobrowski et al. (2003). Using Cabernet Sauvignon grapes planted in California with five different between-vine spacing treatments, pruning weights were measured per metre of canopy across the treatment vines. Multiband images with 1.0 and 0.5m spatial resolution were captured post-veraison in two years, with ground-cover vegetation senescent or sprayed with herbicide prior to imaging. There was a strong, positive correlation between the extracted VI and the pruning weight in both years. Additionally, the relationship established in the first season was able to predict the pruning weights in the second study vintage (Dobrowski et al. 2003). Within season changes in shoot density and leaf area were compared to the change in NDVI by Johnson (2003). Leaf area index (LAI) was estimated on target vines, and multiband satellite images with 4m pixel size were captured four times through the growing season. There was a strong correlation between the LAI and the NDVI on each imaging date, and for the pooled data (Johnson 2003).

Conversely, Hall et al. (2008) found that NDVI was more closely related to canopy planimetric area, the total two-dimensional area occupied by the vine as viewed from above, than with the LAI. The Australian Cabernet Sauvignon grapevines were unconstrained by training wires and were not hedged mid-season, resulting in a large degree of lateral growth into the inter-row space. There were three multispectral image capture dates during one growing season with a 25cm spatial resolution. They found that using the pooled data of the entire growing season, the planimetric area was more highly correlated to the LAI than was the NDVI. The high resolution (small pixel size) used in this study generated values of NDVI approaching 1, and composed almost entirely of vine area. They attributed this to a saturation of the LAI, which becomes non-linear at high density (Hall et al. 2008).

Extensive use of computer-aided image classification for monitoring vineyard performance was first introduced by Hall et al. (2001; 2003). Using image processing software, the vineyard was masked to eliminate non-vine pixels. This step was possible by the pre-imaging application of herbicide to the inter-row groundcover, creating a distinct bimodal distribution of vine and non-vine pixels. They created the "Vinecrawler" algorithm, which automatically extracted NDVI values from all pixels, and mapped them in vectors according to the position of the vines in UTM (Universal Transverse Mercator) and vine-row spacing co-ordinates (Hall et al. 2001; 2003). The high spatial resolution, 25cm, and the clearing of inter-row vegetation made their algorithm possible for the extraction of extremely detailed information about canopy architecture and biomass density.

The ability of remote sensing to be used to directly predict grape composition variables was explored by Lamb et al. (2004). This Australian study focused on the colour and total phenolics in Cabernet Sauvignon grapes in an irrigated, clean cultivated vineyard. Multispectral images were captured using an aircraft mounted imager with 60cm pixel size, three times through the growing season in each of two vintages. They found that re-sampling the image to a final pixel size approximately the same as the distance between rows to integrate vine size and density information into a single pixel resulted in the strongest correlations to total phenolics and colour. They also reported that the strongest correlations (most negative) between NDVI and total phenolics or colour occurred around the time of veraison (Lamb et al. 2004).

In the Languedoc region of France, Acevedo-Opazo et al. (2008) performed a study on remotely sensed VI, vine water status, and grape composition on a number of winegrape varieties in non-irrigated vineyards. Three multispectral images were captured with a 1m spatial resolution. They found temporally stable relationships between zones delineated based on NDVI and vegetative growth, vine water status, and yield. These zones were also consistent with soil type. However, the zones based on NDVI were not different for most grape composition metrics. They concluded that a combination of remotely sensed data with intimate vineyard knowledge, especially of the soil, is needed to predict grape composition and ultimately wine quality (Acevedo-Opazo et al. 2008).

The use of NDVI has been researched from ground-based imaging systems. Still technically remote sensing, as there is no contact between the sensor and the vines, a vehicle-mounted sensor is driven up and down the rows of the target vineyard. GPS is used to track the location of NDVI measurements, and maps can be created of the vineyard. Drissi et al. (2009) evaluated one such system, the GreenSeeker, in Merlot vineyards in the Bordeaux region of France. They found correlations between the NDVI measured by a ground sensor and the LAI, and relations to the vine vegetative growth; however, areas of very high vigour saturated both the LAI and the NDVI, and differentiation was not possible (Drissi et al. 2009).

Overall, remote sensing has been proven as a tool for monitoring vineyard vegetative growth, and for making inferences into grape composition from the spectral measurements.

2.4 Precision Agriculture

The basis of precision agriculture (PA) is that inputs to farming practices are tied to specific outputs through a feedback-loop based system (Bramley et al. 2001). On a commercial scale PA involves the collection of data on any number of specific metrics of interest, as well as ancillary data. Then the interpretation and analysis of those data in order to identify trends, and implementation of a management plan to accommodate or change those trends. Finally, this is repeated with collection of data to observe the effect of management changes (Bramley et al. 2001). Targeting agricultural inputs will, ideally, optimize production to goals of yield or quality, while reducing operational costs and waste. Functionally, precision viticulture (PV) has the same goals and feedback-loop structure with the specific application to grapevines.

Grapegrowers have traditionally accepted the variability within vineyards as inherent to the underlying qualities of the site itself, the terroir. With many years of experience, vineyard areas have been subdivided into individually rated vineyards of higher or lower quality, the Burgundy region of France is considered by some to be the pinnacle of this process. In New World wine regions, there have not been generations of trial and error that led to vineyard designations, and for some growers, volume of grapes rather than quality may be the motivating factor for growing. This idea may be unromantic, but has its place in the economy of grape and wine production. A low-cost bulk grape should be fairly uniform, with minimal input costs.

The emergence of geomatics software has allowed grape growers to geographically link information from their vineyards into the PV feedback loop, and target inputs to specific regions of their vineyards. Remote sensing and geomatics tools have been used successfully in grape production in New World regions including California (Johnson et al. 2001), Australia (Hall et al. 2003; Lamb et al. 2004), and Chile (Acevedo-Opazo 2008) as well as Old World regions such as Spain (Zarco-Tejada et al. 2001).

A spatial database of a vineyard may include natural factors such as soil type, topography or climate trends, as well as horticultural factors such as clone, rootstock and planting information, in addition to cultural practices including fertilizers, irrigation, pesticide spray scheduling and canopy management (Smith & Whigham 1999). The geocoding of these layers of information allows a single query to provide information about location over time or at a particular moment, as well as the spatial distributions of patterns in a vineyard. The level of detail in these databases is necessarily a trade-off between the time required to take samples, and the feasibility of adjusting the required inputs (Smith & Whigham 1999). For example, it is possible to record information about every vine, but it would require extensive data collection, and it is not currently feasible to adjust a sprayer to apply the desired treatment to each vine. Spatial trends are a far more reasonable approach to observing vineyards and creating layers of information (Smith & Whigham 1999), which can be combined with aerial images, and linked to wine composition (Bramley et al. 2001).

Understanding and taking advantage of the variability in vineyard soils is a key stage in using technology to help the New World understand its terroir. Nutrient application can have a high input cost and high environmental impact. Mapping the variability in soil nutrient content and vine uptake is a direct application of PV. Davenport & Bramley (2007) measured soil nutrients and collected petiole samples in Australian Cabernet Sauvignon and Ruby Cabernet vineyards. Petiole samples were collected at flowering and at veraison in two vintages. The soil nutrients nitrogen, phosphorus, potassium, sulfur, manganese and zinc varied significantly within vineyard sites, and between sampling dates. Analysis by k-means clustering revealed that these nutrients showed trends in terms of both spatial and temporal variability; that is, the zones with higher concentrations of these nutrients tended to remain high over time, and areas of low concentration tended to remain low through the season and between vintages (Davenport & Bramley 2007). By creating maps of these zones, a vineyard manager would be able to apply nutrients only in areas of the vineyard where they are needed.

In order to take full advantage of targeted inputs, it must be understood if there is spatial and temporal stability in the target variable output. Bramley & Hamilton (2004) found that there was a 10-fold range of yields in Australian Cabernet Sauvignon, Merlot and Ruby Cabernet vineyards in a single year. This range of yields was found over several vintages, while the relative values were different between years, the range was consistently large. The yield values, recorded with a yield monitor integrated into a mechanical harvester, were normalized and plotted using a Kriging technique. The maps from all vintages were then subjected to a k-means clustering, and zones of stable yield were identified. The zones were harvested into segregated bins by the mechanical harvester, and vinified separately. There was no clear relation between the yield zone and the chemical attributes of the wines in either year (Bramley & Hamilton 2004).

Bramley (2005) investigated these same vineyard sites in terms of the variability in fruit composition. He found that some attributes, in particular the anthocyanins and phenolics, were highly variable within vineyards. Other metrics such as soluble solids and pH were far less variable, although the range of values did suggest implications for the composition of the fruit from the entire site if bulked together. The spatial distribution of the grape composition variations were roughly similar from year to year, and zones were discernable using a k-means clustering of the interpolated surfaces. For the study of variability in grape composition, fruit was sampled manually, as there was no commercial on-the-go sensor available at the time. The general spatial trends in grape composition were noted to be similar to those of the yield in the same vineyards, and Bramley (2005) suggested that until a sensor exists for rapid sampling in the vineyard, yield alone may be a viable, if not ideal, method for fruit segregation.

Using remote sensing as a tool for PV creates an additional layer of information which can be gathered quickly and across the entire vineyard. Canopy area and density were described using 25cm spatial resolution images of Australian Cabernet Sauvignon in two years (Hall et al. 2010). The strength of the correlation to total anthocyanins, phenolics, and yield increased through the growing season, even after veraison. Soluble solids, on the other hand, did not correlate well to the canopy architecture descriptors. Sampling was performed on a subset of vines at the site, both from the aerial images and for berry composition analysis (Hall et al. 2010). Aerial imaging may be a possible solution to the lack of on-the-go sensor for grape composition; identifying zones of potential grape quality may reduce in-field sampling, and allow for differential harvesting.

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3.0 Spatial Variability in Vineyards: The Use of Geomatics and Implications for Precision Viticulture

3.1 Introduction

In Old World winegrowing regions, the effects that create differences between vineyards have been collectively referred to as *terroir* (Van Leeuwen & Seguin 2006). This idea can be applied to any product with characteristics that are unique to its region of origin, but is perhaps most renowned for its long history associated with wine appellations of origin.

There are many factors understood to be part of terroir, and these have been subject to research around the winegrowing world. The regional climate, and the site-specific microclimate, the soil pedology or texture, soil nutrient content and uptake by the vine, and the underlying geology of a region all play a role in defining terroir (Van Leeuwen & Seguin 2006; Andres-de Prado et al. 2007).

In the New World, especially in younger regions such as the Niagara Peninsula in Ontario, consumers are left to be the judge of a wine's value. The degree of variation within New World regions cannot be over-estimated. In Niagara, Ontario there is a wide range of soil parent material, slope & aspect, distance from the moderating influence of Lake Ontario and associated mesoclimate conditions (Shaw 2005). The soils are predominantly Halton clay over Queenston shale and lacustrine sandy loam, with high water holding capacity. The Niagara Escarpment, the most prominent geological feature in the area, has exposed dolomite limestone cliffs with gentler slopes covered with silty and clay loams. These areas experience far better drainage, and are almost entirely north-facing (Shaw 2005). This variation, the relatively young age of the grape-growing industry, and the lack of a strict appellation of origin system means that growers and wineries are left to find and adapt new tools for understanding and managing their vineyards.

As living plants, grapevines require water, which they draw primarily from the soil. Generally, when water loss from transpiration exceeds the available water, governed by solar radiation, temperature and relative humidity, physiological stress occurs (Hardie & Considine 1976). Water stress may result in reduced fruit set (Hardie & Considine

1976), reduced yield (Hardie & Considine 1976), increased sugar accumulation and break-down of malic acid (Koundouras et al. 2006), increased concentrations of anthocyanins and total grape phenolics (Koundouras et al. 2006; Sivilotti et al. 2005), and generally desirable grape composition and wine sensory attributes (Reynolds et al. 2007b; Matthews et al. 1990).

The increasing use of irrigation in many New World vineyards necessitates the need to understand how the application of water, or withholding water from vines, will change the growth habits of the vine and the composition of the fruit. Conversely, where irrigation is not used, the water status of the vines may be manipulated through other cultural practices, but will ultimately be affected by variations in the soil with consequences for the composition of the fruit (Acevdeo-Opazo et al. 2008). Variable water status within a vineyard is itself a component of the terroir of that site. There is ongoing disagreement in literature as to the effect of water stress on grapevine physiology and resulting wine characteristics and quality. These disagreements may arise from other factors influencing the vine growth, ultimately included in a broad definition of terroir.

The basic premise of precision agriculture (PA) is that inputs to farming practices are in response to information gathered with the intent of affecting outputs through an information feedback-loop system (Bramley et al. 2001). When applied as precision viticulture (PV), there is a focus on understanding the spatial and temporal variability in the production of winegrapes (Hall et al. 2003). Grapegrowers have traditionally accepted the variability within vineyards as inherent to the underlying qualities of the site itself, the terroir. With many years of experience, vineyard areas have been subdivided into individually rated vineyards of higher or lower quality.

The emergence of geomatics software has allowed grape growers to geographically link information from their vineyards into the PA feedback loop, and target inputs to specific regions of their vineyards. PV has been used successfully for grape production in New World regions including California (Johnson et al. 2001), Australia (Hall et al. 2003; Lamb et al. 2004), and Chile (Acevedo-Opazo 2008) as well as Old World regions such as Spain (Zarco-Tejada et al. 2001).

One purpose of this study was to validate the use of PV in building understanding terroir in a New World growing region. Four individual commercial vineyards planted to

Vitis vinifera L. cv. Pinot noir in the Four Mile Creek and St. David's Bench sub-appellations, Niagara Region, Canada were the study locations.

It was hypothesized that vine water status would be related to yield components and berry composition. In particular, soluble solids, pH, titratable acidity, total anthocyanins, total phenolic compounds, colour intensity and hue would be affected by the water status of the vine. These effects will also be apparent in the must and wine chemical composition of the wines made from fruit in delineated water status zones.

3.2 Materials & Methods

3.2.1 Vineyard Sites & Sentinel Vines

Four commercial vineyard sites planted to *Vitis vinifera* L. cv. Pinot noir were identified for inclusion in this study in 2008. These sites were at Coyote's Run Estate Winery and Five Rows Craft Wine of Lowrey Vineyards, in the St. David's, Ontario area. Two of the sites were in the "Red Paw Vineyard," and one in the "Black Paw Vineyard" at Coyote's Run in the Four Mile Creek sub-appellation. The fourth site was at Five Rows Craft Wine of Lowrey Vineyards, in the St. David's Bench sub-appellation. For the purpose of this study, the vineyard sites were named "Red Paw 1," "Red Paw 2," "Black Paw," and "Lowrey's."

Red Paw 1 was 0.66 ha (1.62 acres), planted in 1997/1998 with Dijon clones 115, 777 and an unknown third clone on SO4 rootstock with rows oriented east-west. Vine spacing was 1.2 m and rows were spaced 2.4 m. Red Paw 2 was 0.79 ha (1.95 acres), planted in 1997/1998 with Dijon clone 115 on SO4 rootstock with rows oriented north-south. Vine spacing was the same as Red Paw 1. Both of the Red Paw Vineyard blocks had tile under-drainage in every other row. Black Paw was 0.41 ha (1.02 acres), planted in 1998 with Dijon clone 115 and two additional unknown clones on SO4 rootstock with rows oriented north-south. Vine spacing was the same as Red Paw blocks. Drainage tile was installed in every other row in spring of 2009 to the Black Paw Vineyard. Red and Black Paw Vineyards were managed uniformly by a third party service hired by the winery, and were not irrigated. Protective bird netting was installed in both 2008 and 2009 after veraison. Lowrey's was 2.45 acres (0.99 ha), planted in 1987 (the five easternmost rows), 1992 (the next seven rows), and 1997 (the eight western rows), Dijon clone 115 on SO4 rootstock with rows oriented north-south. Vine spacing was 1.2 m and rows were spaced 2.4 m. Under-drainage tile was in every other row, and permanent bird netting was in place, bunched at the top wire of the trellis with shoots positioned through the netting in both 2008 and 2009. All vines were cane-pruned, and trained using vertical shoot positioning.

At each vineyard site, sentinel vines were identified evenly distributed throughout the vineyard. The panel at either end of the row, and rows at the edge of vineyard were not used for sentinel vines. A single sentinel vine was in every other panel in every other row, except at Lowrey's where sentinel vines were in every third row. There were 84 sentinel vines in Red Paw 1 (52 per acre), 90 sentinel vines in Red Paw 2 (46 per acre), 52 sentinel vines in Black Paw (51 per acre), and 91 sentinel vines in Lowrey's (37 per acre). Of these, one in five sentinel vines were marked as a water status vine such that this sub-set of vines was distributed throughout the vineyard block. These vines were subsequently monitored for Ψ. There were 18 in Red Paw 1 (11 per acre), 18 in Red Paw 2 (nine per acre), 11 in Black Paw (11 per acre) and 19 in Lowrey's (eight per acre). In total, there were 317 sentinel vines and 66 water status vines. Sampling strategy maps can be seen overlaid onto images of the vineyards in Figure 3-1 for the Red Paw vineyards, Figure 3-2a for the Black Paw vineyard and Figure 3-2b for Lowrey's vineyard.

With the exception of harvest and pruning, all regular operations were carried out on the sentinel vines by the vineyard crews. This included but was not limited to pesticide applications, mid-season hedging and leaf-pulling, soil tilling, mowing and cluster-thinning as deemed necessary by the vineyard managers. In general, clusters were thinned to one cluster per shoot at veraison, and extensive leaf removal in the fruiting zone was performed just before or after veraison.

Sentinel vines were geolocated on 29 & 30 May 2008 using a Trimble GeoXT Handheld GPS, running Trimble TerraSync software (Version 2.53; Trimble Navigation Ltd., Sunnyvale, CA), with approximately 8.6m accuracy. Post-collection differential correction was performed using GPS Pathfinder Office (Version 3.10; Trimble Navigation Ltd., Sunnyvale, CA) to sub-metre accuracy using the Port Weller, Ontario base station correction. Final accuracy was in the range of 30-50cm. The map projection used was in Universal Transverse Mercator (UTM) coordinates, Zone 17N with the 1927 North America Datum.

3.2.2 Soil Sampling

Soil samples were collected at each water status vine on 22-26 May 2008. Samples were taken to the north of the trunk of the vine (west in the case of Red Paw 1). The ground was first leveled to roughly the same height as the inter-row space, with loose surface soil removed. A single gauge auger (Eijkelkamp Agrisearch Equipment BV, Giesbeek, NL) was vertically driven to a final depth of 75 cm, the entire core was homogenized and shipped to Agri-Food Labs (Guelph, ON) for analysis of soil pH, buffer pH (when pH<6.8), organic matter (OM, %), phosphorus (ppm), potassium (ppm), magnesium (ppm), calcium (ppm), cation exchange capacity (CEC, meq/100g), and texture (% silt, sand, clay) using standard procedures.

3.2.3 Soil Moisture

Vineyard soil moisture was measured by time domain reflectometry (TDR) using the Field Scout TDR 300 Soil Moisture Meter (Spectrum Technologies, Plainfield, IL). The volumetric water content mode was used, with the high clay setting for soils with more than 40% clay content. A pair of 20-cm stainless steel probes was installed for measurements at all sentinel vines. Measurements were made bi-weekly in both 2008 and 2009. In 2008, seven sets of measurements were collected on 19 June, 2 July, 14 July, 31 July, 12 August, 27 August and 8 September. In 2009, six sets of measurements were collected on 8 July, 20 July, 5 August, 19 August, 3 September and 17 September. In each case, where possible there were at least 24 hours between the last rainfall event and data collection.

Before inserting the probes, the surface soil around the base of the sentinel vine was brushed away to be level with the inter-row space. The probes were inserted vertically into the soil with care to keep the probes parallel. The first two measurements were taken on opposite sides of the trunk, within 30 cm of the vine. If the two measurements were different by more than 10% of the reading, then a third measurement was taken at roughly the midpoint between the first two measurements. The two or three measurements were averaged for a single value at each vine for that date.

3.2.4 Vine Water Status

Vine water status was measured using midday Ψ by the pressure chamber, or pressure bomb, technique (Soil Moisture Equipment Corp., Santa Barbara, CA) of Turner (1988). Measurements were made only at the water status vines, on the same days as the soil moisture measurements (see section 3.2.3 above). Measurements were taken between the hours of 1000hr and 1400hr, roughly centred on solar noon under full sun. To minimize the time between removal of a leaf from the vine and measurement, the pressure bomb and gas cylinder were carried to each vine.

A fully expanded leaf from a primary shoot that was fully exposed to the sun was removed from the vine. The petiole was immediately sliced with a razor blade transverse to the length of the petiole, and inserted through the lid of the pressure bomb with the cut end exposed. Nitrogen gas was used to slowly pressurize the chamber at a constant rate until sap began to flow out of the cut end of the petiole. The pressure in the canister at this moment was recorded. A second leaf, from another part of the canopy was treated in the same way. If the two pressures were more than 1.5 bar apart (approximately 15% of the reading), then a third leaf was sampled.

Vine water status zones were delineated based on the seasonal mean of all pressure bomb measurements. Using the mapping techniques described in section 3.2.10 (Spatial Mapping), the maps of Ψ were created for each block, and divided into zones. In 2008, the Red Paw and Black Paw vineyards were divided into high and low water status, and Lowrey's was divided into high, medium and low water status. In 2009, all four vineyards were divided into high and low water status. Since the range of values was not the same in each vineyard, a different threshold value was used to divide each of the sites. The threshold value was arbitrarily chosen near the middle of the range, without respect to actual vine water stress response at that value such that the number of vines in each zone was roughly equal. These divisions can be seen in Figure 3-3, Figure 3-4, Figure 3-5 and Figure 3-6 for Red Paw 1 & 2, Black Paw, and Lowrey's Vineyards, respectively. The consequence of the division and range of water status values observed is discussed below.

3.2.5 Vine Size

Vine size was measured using dormant pruning weights. Timing of pruning, and number of buds per cane was determined by the winery/grower. In the 2008 season, Lowrey's vineyard was pruned on 14 December 2008 and the Red Paw & Black Paw vineyards were pruned on 17 February 2009. In the 2009 season, Lowrey's vineyard was pruned on 15 December 2009. The Red Paw and Black Paw vineyards were pruned by the winery's commercial crew in early February 2010, before the sentinel vines could be pruned.

In both years, Lowrey's vineyard was pruned to two canes, 10 to 12 buds each. In the 2008 season, the Red Paw and Black Paw vineyard blocks were pruned to 3 canes, 10-12 buds each. The current season's growth was bundled and weighed in-situ using a Rapala scale (Model RSDS-50; Rapala). Attempting to replace the weight of cane pruning measurement at Coyote's Run in the 2009 season, a pair of alternate metrics was evaluated. The mean internode length on the remaining canes was measured using the length of the cane from the first to last node, and the diameter of the canes between the first and second bud was measured using digital calipers. To validate this method, measurements were taken at Lowrey's vineyard in April 2010. A standard least squares regression was performed, using both cane diameter and internode length as model effects. There was not a strong correlation between internode length and cane diameter against pruning shoot weight. The resulting model can be seen in the supplemental materials in Figure 7-1, the r^2 was 0.28, and these alternate measurements were not accepted as a replacement for weight of cane pruning as a measure of vine size or vigour. Consequently, vine size was not evaluated for the three Coyote's Run vineyard sites for 2009.

3.2.6 Harvest

Harvest dates were at the discretion of the vineyard managers or winemakers. In 2008, Lowrey's vineyard was harvested on 16 September, Red Paw 1 & 2 on 29 September, and Black Paw on 30 September. In 2009, Red Paw 1 was harvested first on 1 October, Lowrey's on 5 October, and Red Paw 2 & Black Paw on 6 October. All of the fruit from the sentinel vines was collected, the number of clusters per vine counted, and the fruit from each vine weighed using a portable field scale. Mean cluster weight was calculated from this data. Fruit to be kept for winemaking was bulked by water status zone as described above.

In 2008, the severe incidence of rot in the fruit necessitated extensive sorting of the fruit to reject excessive break-down. The fruit from the Black Paw vineyard was so severely affected by rot that sorting was not possible, and all fruit was accepted. In 2009, the disease pressure was much lower, and fruit sorting was not necessary for any of the vineyards.

3.2.7 Winemaking

Fruit from all of the sentinel vines in each water status zone was crushed and destemmed in the teaching & research winery at the Cool Climate Oenology & Viticulture Institute (CCOVI) at Brock University into a large plastic bin. The must was mixed thoroughly, and distributed into four 20-L plastic buckets so that they contained 16kg each. 50 mg/L SO_2 in the form of potassium metabisulfite (KMS) was added with mixing. The musts were left at 4°C for approximately 40 hours, before being allowed to warm to room temperature. Must samples of 250 mL were taken just before inoculation. The musts were inoculated with *Saccharomyces cerevisiae* strain RC212 (Lallemand Inc., Montreal, QC) at 0.30 g/L (30 g/hL), and moved into a temperature controlled room set at 25°C. Caps were punched down two or three times a day, as time permitted, and fermentations were monitored daily by measuring temperature and soluble solids by Brix hydrometry. In 2008, the Black Paw vineyard fermentations were inoculated immediately after crushing and destemming, because of the severely rotten state of the fruit. Otherwise all fermentations were handled identically in both 2008 and 2009.

After each of the fermentations had reached dryness, the maceration period was extended by two days, with gentle mixing of the skins. The wines were pressed from the skins into 12L glass carboys using a water bladder press, up to a pressure of two bar for five minutes, with the addition of 25 mg/L of SO_2. The wines were settled for four days, and then racked into clean carboys. To initiate malo-lactic fermentation (MLF), the lactic acid bacteria *Oenococcus oeni* VP41 (Lallemand Inc., Montreal, QC), was added at 0.01g/L. The wines were left at 23°C for two weeks, with regular protection under CO_2

gas, and evaluations by smell and taste. Completion of MLF was verified by thin layer chromatography following the protocols of Iland et al. (2004). Wines were racked, with the addition of 50 mg/L SO_2, and moved to a -2°C freezer for cold stabilization. After five weeks, wines were racked from the precipitated tartaric acid with another addition of 20 mg/L SO_2. Wine samples were taken after cold stabilization. The fourth fermentation replicate from each group was used as a top-up wine for the other three fermentations, resulting in three fermentation replicates for each water status zone. In 2008, there was only a single fermentation for each of the water status zones in the Black Paw vineyard.

Copper fining trials were conducted as per Iland et al. (2004) to reduce the presence of reductive aromas in the wines, and 0.5mg/L Cu^{2+} was added to the wines. They were racked a final time at bottling with the addition of SO_2 to bring each batch of wine to 45 mg/L free SO_2. In 2008, wines were filtered through a 0.25-1.0 μm pre-filter and a 0.45 μm final filter (Pall Corp., Port Washington, NY), bottled under nitrogen gas, and closed with natural cork. 2008 wines were filtered and bottled in June 2009. They were then moved to the wine cellar at CCOVI for storage. The 2009 wines were pre-filtered through three 0.5-μm pad filters in March 2010 with the addition of 30 mg/L SO_2. Red Paw 1 and Black Paw wines were filtered through a 0.45-μm membrane filter (Pall Corp., Port Washington, NY) and bottled, until the filter cartridge became clogged and lost integrity. The remaining wines were filtered a second time through three 0.5-μm pad filters and bottled. All wines were bottled under nitrogen gas, and closed with natural cork. They were then moved for storage in the wine cellar at CCOVI.

3.2.8 Weather Data

Weather data for both growing seasons was provided by Weather INovations Incorporated. In 2008 the nearest weather station was in Virgil, Ontario, and St. David's, Ontario in 2009. This station was installed in spring of 2009 and was the closest station to the sample vineyards at roughly 1.5km. Daily precipitation, maximum and minimum temperatures, relative humidity, leaf wetness, solar radiation, and wind speed and direction are recorded by the stations. Weather INovations Incorporated then compiled an annual report of the growing season describing general trends.

3.2.9 Berry, Must & Wine Composition

3.2.9.1 Sample Preparation

At harvest, a randomly distributed 100-berry sample was taken from each sentinel vine, placed in labelled sample bags, and frozen at -25°C until further analysis. The berry sample was weighed to determine the mean berry weight, and then placed in a 250mL beaker in a water bath at 80°C for one hour to dissolve all precipitated tartaric acid. The samples were allowed to cool, and then homogenized in a commercial juicer (Model 500; Omega Products, Harrisburg, PA). After settling, juice was decanted from the top layer of foam. Must and wine samples were treated in the same way as the berry samples after juicing. This included all centrifuging, freezing and thawing leading to measurements of soluble solids, pH, TA, colour/hue, total phenolic compounds and total anthocyanins.

3.2.9.2 Soluble Solids, pH, Titratable Acidity

Soluble solids were measured in Brix using an Abbe benchtop refractometer (Model 10450; American Optical, Buffalo, NY). Berry pH was measured using an Accumet pH/ion meter and VWR SympHony electrode.

Juice samples (≈ 35mL) were clarified by centrifugation at 4500g for 10 minutes to remove large particles using an IEC Centra CL2 benchtop centrifuge (International Equipment Co., Needham Heights, MA). The remainder of the juice (≈ 20mL) was placed in plastic snap-top vials and returned to the -25°C freezer for colour analysis at a later date. Titratable acidity (TA) was measured on 5.0mL of the centrifuged juice, titrated to an endpoint of pH 8.2 with 0.1N NaOH using a PC-Titrate autotitrator (Model PC-1300-475; Man-Tech Associates, Guelph, ON).

3.2.9.3 Colour/Hue, Total Anthocyanins, Total Phenolic Compounds

The re-frozen samples were heated at 80°C for 30 minutes, centrifuged at 10,000g at 4°C in an IEC refrigerated centrifuge (Model B-20; International Equipment Co., Needham Heights, MA) and then re-frozen. Samples were heated at 80°C for 30 minutes a final time before analysis of colour/hue, total phenolic compounds and total anthocyanins.

Colour and hue were measured using a modification of the method reported by Mazza et al. (1999). In 2008, samples were loaded directly into a 1mm pathlength quartz cuvette. Samples were darker in 2009, and so they were diluted 1:10 in 9mL of pH 3.5 buffer (0.1M citric acid and 0.2M Na_2HPO_4), and mixed by vortexing. They were allowed to sit in the dark for one hour to equilibrate, and poured into a 10mm pathlength plastic cuvette. In both years, absorbance at 420nm and 520nm was measured using a UV-VIS spectrophotometer (Model Ultrospec 2100 pro; GE Healthcare Life Sciences, Fairfield, CT). Colour intensity was calculated as $A_{420}+A_{520}$, and hue (tint) as A_{420}/A_{520}.

Total anthocyanins were quantified using the pH shift method of Fuleki & Francis (1968). Samples were diluted 1:10 in 9mL of pH 1.0 buffer (0.2M KCl and 0.2M HCl) and pH 4.5 buffer (1M NaOH and 1M HCl), and mixed by vortexing. The samples were allowed to sit in the dark for one hour to equilibrate. In a 10mm pathlength plastic cuvette, absorbance at 520nm was measured using a UV-VIS spectrophotometer. A standard curve was generated using six concentrations of malvidin-3-o-glucoside. Total anthocyanins were given by $(A_{520,\ pH1.0}-A_{520,\ pH4.5})/0.0042$, in mg/L malvidin equivalents.

Total phenolic compounds were quantified using the Folin-Ciocalteu method (Slinkard & Singleton, 1977). Waterhouse (2001) developed a method with scaled-down volumes, reducing the volume of reagents required and the volume of waste produced. A calibration curve was created with each set of samples evaluated. The calibration curve was made with a stock solution of gallic acid (0.5g gallic acid in 10mL of ethanol, brought to a volume of 100mL with water for a final concentration of 5000mg/L). The gallic acid concentrations in the standard curve were 0, 50, 100, 150, 250 and 500mg/L. Samples were diluted 1:10 in 9mL of distilled water in test tubes, and mixed by vortexing. 20μL of each sample or standard was pipetted into a 10mm pathlength plastic cuvette, to which 1.58mL of water was added. 100μL of the Folin-Ciocalteu reagent (VWR Scientific) was added to each cuvette, followed by mixing. After 30 seconds but no longer than 8 minutes, 300μL of 20% sodium carbonate (anhydrous $NaCO_3$) was added to the cuvettes with mixing. Solutions were left in the dark for 2 hours at room temperature. Absorbance at 765nm was measured using the UV-VIS spectrophotometer. Total phenolic compounds were determined from the standard curve, corrected for the dilution in water, and expressed in mg/L gallic acid equivalents (GAE).

3.2.9.4 Ethanol

Ethanol content of the wines was measured using gas chromatography (GC). Wines samples were diluted, 50µl of wine in 1.95mL 1% 1-butanol. A standard curve was prepared using eight standards (1%, 5%, 10%, 12%, 14%, 16%, 18%, 20% ethanol). All standards and samples were prepared in duplicate, and 1.0µL was injected twice by an Agilent autosampler. The GC unit used was an Agilent 6890 series running ChemStation software with Agilent J&W 122-1032 column (Agilent, Santa Clara, CA) of dimensions 30.0m x 250µm interior diameter x 0.25µm film thickness. Auto-integration of peaks of minimum width 0.040 was used to find the ethanol to internal standard ratio, and ethanol content was determined from the standard curve.

The carrier gas was helium, with total flow 242.7mL/min and the split flow 237.5mL/min at a carrier gas pressure of 24.40 psi. Inlet and detector temperatures were 225°C, initial oven temperature was 60°C at time zero. Initial time was 0.00, equilibration time 0.50 minutes, post temperature was 60°C, post time was 0.50 minutes, and run time was 5.07 minutes. Temperature profile was as follows:

Ramp	Rate (°C/min)	Final Temperature (°C)	Final Time
1	15.00	95	0.00
2	75.00	225	1.00
3	0.0 (off)		

3.2.9.5 Reverse-phase HPLC Quantification of Phenolic Compounds

Reverse-phase HPLC was used to quantify individual anthocyanins and other phenolic compounds in the wines using the method of Ibern-Gomez et al. (2002) with flow rate modified to 1.0mL/min and a maximum pressure of 300 bar. Wines were filtered through 0.22µm Millipore membrane filters (Millipore Corp., Billerica, MA) before injection. A Hewlett-Packard model 1100 HPLC (Palo Alto, CA) equipped with autosampler, diode array detector and Zorbax SB-C18 column, 4.6x50mm, 3.5µm particle size (Agilent, Santa Clara, CA) at 30°C. Detector wavelengths were 280nm for quantification of flavanol-3 polyphenolics (catechin, epicatechin) and gallic acid, 320nm for cinnamic acids (caffeic acid, p-coumaric acid) and trans-resveratrol, 365nm for flavonols (quercetin), and 525 nm for anthocyanins.

Mobile phase solvents were all HPLC grade: Mobile A was 0.2% trifluoroacetic acid (TFA) in MilliQ water, and Mobile B was 0.2% TFA in acetonitrile (Caledon, Georgetown, ON). Gradient elution profile was as follows, with a linear gradient between timepoints: initial 5% B to 35% B at minute 15, 100% B at minute 16, 100% B maintained to minute 25, and 5% B at minute 26 with 10 minutes post-run at 5% B. Sample injections were 10μL with needle wash between samples. A computer running ChemStation (Version A.07.01; HP/Agilent) software was used for chromatographic analysis.

3.2.10 Spatial Mapping

All field and berry sample measurements were tied to specific vines, and so geographic information systems (GIS) software was used to map the variables onto a two-dimensional surface. Parameters were mapped using Surfer (Version 8.05, Golden Software Inc., Golden, CO). Data were gridded using the modified Shepard's method. The modified Shepard's method was made a smoothing interpolator with the inclusion of a 0.2 smoothing factor. Variation was assumed to be isotropic, and a round search radius was used for gridding.

The grid line geometry was determined independently for each site. X and Y direction maximum and minimum values were extended by several metres to create a rectangular frame around the vineyard block without any sentinel vine touching the edge of the grid. The larger direction was assigned 100 lines by default, and in the other direction the number of lines was assigned to keep the grid blocks as close to square as possible. The sizes of the grids were (X and Y, in metres): Red Paw 1, 1.82x1.96; Red Paw 2, 1.31x1.43; Black Paw, 2.20x2.01; and Lowrey's, 1.74x1.85.

Since grid node values were determined by the surrounding nodes, those at the extents of the maps were often assigned unreasonable values. A blanking file was created for each vineyard to isolate the actual sentinel vines within the larger vineyard map and eliminate the extreme values. Where unreasonable values occurred inside the vineyard block (such as a negative value for the yield), grid math was used to replace these values (in the case of yield, negative nodes were replaced with zeros). The extents of the colour scale were adjusted for each map, and this must be considered when comparing maps of the same variable between vineyards or across vintages.

3.2.11 Data Analysis

Gross variation of yield components, grape composition and vineyard variables was described using the methods of Bramley (2005). The median and coefficient of variation (CV) were calculated to express the distribution of the data points. Within a single vintage, the range (maximum and minimum values) can be used to express the variation of a variable within a vineyard. Bramley (2005) proposed the variable spread as a normalized value that can be used to compare variation across variables and vintages. The spread is defined as the range divided by the median, expressed as a percent, and acts as an indicator of the degree of variation in the parameter in a way that is potentially more valuable to a winery.

Analysis of variance (ANOVA) was performed on the data collected at each vineyard site individually, for each vintage. Sentinel vines were grouped first by water status zone, and then by vigour status zone. Data were submitted to the PROC GLM in SAS (Version 9.1.3; SAS Institute, Cary, NC), with means separation by the LSD (α=0.1). Pearson's correlation matrices were generated between all variables using PROC CORR for each vineyard individually as well as for all sentinel vines. Principal component analysis (PCA) was performed on the mean values grouped by water status zone for all vineyard sites using JMP (Version 8.0.1; SAS Institute, Cary, NC).

Monthly rainfall data was compared to the long-term monthly mean from 1971 to 2000 collected by Environment Canada at the St. Catharines Airport weather station. The daily rainfall events were plotted for 2008 and 2009 along with dates of data collection for visual comparison of rainfall events and intensity in both years, and to compare phenological development between years.

3.3 Results & Discussion

3.3.1 Vineyard Variability

3.3.1.1 Within Vineyard Differences

The within-vineyard gross variability of yield components, berry composition, and vineyard soil variables including soil moisture and Ψ are given in supplemental materials, Table 7-1, Table 7-2, Table 7-3, and Table 7-4 for Red Paw 1, Red Paw 2, Black Paw, and Lowrey's vineyards, respectively. In all four vineyards, in both years, the berry pH had the smallest coefficient of variation and spread followed by hue and soluble solids. These three berry composition measurements had the least gross variability within each vineyard site. The crop load, vine size and total yield per vine had the highest degree of gross variation within each vineyard site. Total anthocyanins and total phenols had high coefficients of variation and spread, although not the highest. It is notable that for these two berry composition metrics, there was more variability in 2008 than in 2009 at all four vineyards. In terms of soil variables, while the texture of the soil at each site is dominantly clay, it is the sand component that is the most variable. With the exception of Red Paw 1, where the clay content had the lowest coefficient of variation and spread, the other three sites were least variable in soil pH.

There was a great deal of variation in most grape composition and vine growth metrics in both vintages at all four vineyards. In grape composition, total anthocyanins, phenols and colour intensity were the most variable within each of the four vineyard sites within each vintage. Bramley (2005) found similar results, with anthocyanins and phenols being the most variable of grape composition metrics, anthocyanins having CV values from 11.7-21.6%. In this study the CV for anthocyanins ranged from 10.4-19.2%. In order to attempt to normalize the degree of variability for each metric, Bramley (2005) developed the "spread," as described above. This parameter conveys more information to a winemaker, as it indicates the magnitude of variability that can be compared across metrics, or vintages. Variables with the highest CV were also the variables with the highest spread, the advantage being that the variability is normalized for ease of comparison.

A winemaker would most likely desire the fruit being delivered to their winery to be of a consistent, and high, quality, and the spread is a potential tool to convey how successfully a vineyard site has achieved this (Bramley 2005).

In yield components, the total yield per vine was the most variable, while berry size was the least variable. Yield per vine varied by five-fold at the lowest in Black Paw in 2009 (Table 7-3), to over 20-fold in Lowrey's vineyard in 2008 (Table 7-4). Bramley & Hamilton (2004) also found a great deal of variation in yield, up to 10-fold variation in a single vineyard.

ANOVA and means separation were performed on the water status zones within each block. These tests were performed separately for each site, such that the means of the same variable were not compared between vineyard sites. With sentinel vines grouped by water status zone, tables of means of yield components for all four sites in both years are shown in Table 3-1; means of soil moisture, Ψ and shoot weight are shown in Table 3-2; berry composition means are shown in Table 3-3 and Table 3-4; soil analysis variables are shown in Table 3-5. With sentinel vines grouped by vigour zone, tables of means of yield components for all four sites in both years are shown in Table 7-5; means of soil moisture, Ψ and vine size Table 7-6; berry composition means are shown in Table 7-7 and Table 7-8; soil analysis variables are shown in Table 7-9. As the 2009 data was incomplete, and as wine was made from water status zonings but not vine size, these tables were included in the supplemental materials.

Mean separation was performed using the least significant difference (LSD) test. The alpha value was increased from the typical 0.05 to 0.1 in order to identify trends after it was noted that there were no differences where $p \leq 0.05$. Note that in the tables, a single asterisk denotes $p \leq 0.1$.

The division by water status zone was verified by the means of Ψ for each site, with $p \leq 0.0001$ in both years (Table 3-2). There were no other variables for which there were differences between water status zones at all four sites, in either vintage. In 2008 cluster size, berry TA and colour intensity were different between water status zones in three of the four vineyards; however, for each of these metrics, the direction of the trend was not the same for all three vineyards. The low water status zone has the higher TA in the Black Paw vineyard, but it was the high water status zone with the higher TA in Red

Paw 2 and Lowrey's vineyards (Table 3-3). In 2009, there were never more than two of the four vineyards with differences between water status zones.

The division by vigour status zone was verified by the means of dormant pruning weight for each site, with $p \leq 0.0001$ for all sites in 2008 and at Lowrey's in 2009 (Table 7-6). There were no other variables for which there were differences between vigour zones at all four sites in 2008. Berry size and percent sand were different between vigour status zones in three of the four vineyards (Table 7-5 and Table 7-9). In berry size, the trend was the same in each of those three vineyards, with the high vigour status zone having the larger berries. In 2008, vines with higher vigour resulted in larger berries, but the same was not true in 2009. The trend was not consistent for all three vineyards in terms of sand. In 2009 vigour zones, there were differences for all yield components, berry TA, colour intensity, soil clay and sand, and organic matter, but this was only observed at Lowrey's vineyard.

3.3.2 Must &Wine Analysis

Wines were made by water status zone in both years. The means of wine chemical attributes from all four vineyard sites in both years are shown in Table 3-6 and Table 3-7. Means of must composition chemical attributes are shown in Table 3-8 and Table 3-9. Means of individual anthocyanin concentrations for wines from all four vineyard sites in both years are shown in Table 3-10. Means of concentrations of individual flavonol-3 phenolic compounds for wines from all four vineyard sites in both years are shown in Table 3-11, and means of concentrations of non-flavonoid phenolic compounds and stilbene (trans-resveratrol) for wines from all four vineyard sites in both years are shown in Table 3-12.

There were no chemical attributes in the musts or the wines, in either vintage, with differences between the water status zones for all four vineyards. In fact there were never more than two of the vineyards with differences between water status zones for any attribute. The same was true for individual anthocyanins and other phenolic compounds.

Differences between the must soluble solids in Red Paw 1 and Lowrey's vineyards did not translate to differences in wine ethanol content, although in general, the water status group with the higher soluble solids concentration became the wine with the higher ethanol content, as would be expected (Table 3-8 and Table 3-6). Also as expected, the concentration of anthocyanins and phenols was much higher in the wines than in the musts, as these compounds were extracted over time with increased temperatures and increasing ethanol content during fermentations (Cortell et al. 2007b). The lack of differences between the chemical attributes of the musts and wines emphasizes that there was not a great difference between water status zones in the vineyard.

Reverse-phase HPLC was used to quantify the concentration of individual anthocyanins, flavonol-3 phenolics (catechin, epicatechin, quercetin) non-flavonoid phenolics (gallic acid, caffeic acid, p-coumaric acid), and trans-resveratrol in the wines. There were no differences in the concentrations of any of the compounds in all four vineyards. There were differences in Red Paw 2 wines for delphinidin and petunidin in both years, and peonidin, malvidin, caffeic acid and trans-resveratrol for 2008 (Table 3-10). Red Paw 1 high and low water status wines were different for catechin and quercetin in 2008 (Table 3-11). Wines from the Lowrey's vineyard were significantly different in delphinidin, peonidin and trans-resveratrol in 2008 (Table 3-10 and Table 3-12). Black Paw wines were significantly different in gallic acid and trans-resveratrol in 2009 (Table 3-12). All differences in individual anthocyanins were oriented intuitively, with the low water status wines having the higher concentration of the anthocyanins as was found by Koundouras et al. (2006). This same trend was not present in wines from all vineyard sites, and conclusions cannot be drawn about the influence of water status on the concentration of individual phenolic compounds.

Typical for *V. vinifera*, malvidin represented the largest proportion of anthocyanins, followed by peonidin, petunidin, delphinidin and cyanidin (Fong et al. 1971). In general, the concentrations of all anthocyanins were higher in 2009 than in 2008. Trans-resveratrol concentrations were higher in 2009 than in 2008, in some cases by more than double, with the exception of Red Paw 2 wines where the low water status wines were higher in 2008. Goldberg et al. (1995) found relatively high concentrations of trans-resveratrol in Pinot noir wines, regardless of their region of origin. They concluded that generally, cool and humid climates tend to produce wines with higher trans-resveratrol concentrations. In Ontario wines, they found a mean of 3.16±1.34 mg/L

(Goldberg et al. 1995), the mean concentration of trans-resveratrol in wines for this study was 2.29mg/L, within one standard deviation of the mean observed by Goldberg et al.

3.3.2.1 Correlations between Variables

Pearson's correlation coefficients between yield components, berry composition, vine size, and soil metrics for the pooled data from all vineyards are shown in the supplemental materials in Table 7-10 for 2008 and Table 7-11 for 2009. These tables have been colour-coded, such that cells highlighted in yellow, blue and red represent a p-value $\leq$ 0.0001, 0.01, and 0.05 respectively. In large spatial datasets, it is not uncommon to consider correlation coefficients as low as 0.5 or 0.4 to be of note so long as the p-value is small enough to give confidence in the correlation (Reynolds et al. 2007b). These correlations are not referred to as strong, but are worth noting.

There were strong correlations between yield components; yield against number of clusters (2008: r=0.89, 2009: r=0.88; p$\leq$0.0001 in both years) and moderate correlations to cluster size (2008: r=0.65, 2009; 0.57; p$\leq$0.0001, both years). In 2008, yield was also marginally correlated with anthocyanins (r=-0.49; p$\leq$0.0001) and colour (r=-0.51; p$\leq$0.0001). Increasing yield had the effect of decreased ripening in the grapes.

In 2008, berry size was best correlated with berry pH (r=0.39; p$\leq$0.0001), berry TA (r=0.31; p$\leq$0.0001), and mean soil moisture (r=-0.47; p$\leq$0.0001). In 2009, berry size was best correlated with colour and hue (r=-0.30; p$\leq$0.0001, and r=0.35; p$\leq$0.0001 respectively), soil clay content and silt content (r=-0.43; p$\leq$0.01, and r=0.37; p$\leq$0.01 respectively).

Weight of cane prunings was best correlated with berry pH (r=-0.30, p$\leq$0.0001), total anthocyanins (r=-0.34; p$\leq$0.0001), and mean Ψ (r=0.46; p$\leq$0.01) in 2008. Cane pruning weight was measured only at the Lowrey's vineyard site in 2009, and was not included in the analysis. In 2008, mean Ψ was correlated with berry pH (r=-0.48; p$\leq$0.0001), soluble solids (r=-0.43; p$\leq$0.01), weight of cane prunings, total berry anthocyanins (r=-0.65; p$\leq$0.0001), colour (r=-0.58; p$\leq$0.0001), soil clay content (r=-0.43; p$\leq$0.01), and sand content (r=0.47; p$\leq$0.0001). In 2009, mean Ψ was marginally correlated with hue (r=0.32; p$\leq$0.01), soil clay content (r=-0.47; p$\leq$0.0001), and sand content (r=0.52; p$\leq$0.0001). There was a relationship between the vine water status and the ripening of the grapes; as Ψ became more negative, the grapes accumulated more sugars and anthocyanins, as was seen by Sivilotti et al., (2005) for anthocyanins but not soluble solids. This occurred in soils with more clay and less sand.

Mean soil moisture in 2008 was correlated with berry size ($r=-0.47$; $p\leq0.0001$), colour ($r=0.44$; $p\leq0.0001$), total berry phenols ($r=0.41$; $p\leq0.0001$), soil clay content ($r=0.67$; $p\leq0.0001$), silt content ($r=-0.79$; $p\leq0.0001$), soil CEC ($r=0.82$; $p\leq0.0001$), and soil pH ($r=0.64$; $p\leq0.0001$). In 2009, mean soil moisture was moderately correlated with total berry anthocyanins ($r=-0.51$; $p\leq0.0001$), soil clay content ($r=0.69$; $p\leq0.0001$), silt content ($r=-0.81$; $p\leq0.0001$), soil CEC ($r=0.81$; $p\leq0.0001$), and soil pH ($r=0.64$; $p\leq0.0001$).

These correlations to mean soil moisture are not intuitive, one would not expect an increase in soil moisture to result in a decrease in berry size and increase in grape ripening, and anthocyanin concentration; however, it has been noted that not all vines will respond to excess or deficit irrigation in the same way, and past research has found conflicting results (Koundouras et al. 2006). The soil moisture content was measured using soil bulk conductivity, and the presence of water did not necessarily translate to water that is available for the vines. The higher clay soils may have had higher volumetric water content, but the vines were not accessing it, and the higher sand soils were likely better drained, with less available water. Shoot weight was not highly correlated to any other variable, in disagreement with the findings of Cortell et al. (2008).

3.3.2.2 Principal Component Analysis

PCA of yield components, grape composition and vineyard variables when grouped by water status zone as well as observation loadings are shown in Figure 3-7 for 2008 and Figure 3-8 for 2009 from all vineyard sites. All four vineyard sites from both vintages are shown in Figure 3-9.

In Figure 3-7, the first two principal components explained 86.46% of the variation in the 2008 data. With the exception of TA, all variables were heavily loaded on these components. TA was not heavily loaded on either of the first two components, but was explained by PC3, with an eigenvalue of -0.74 on that component. Vine vigour and mean Ψ were highly correlated with the sand content, and were inversely correlated with berry soluble solids, TA, total anthocyanins, and berry pH. Yield was inversely correlated with clay, as well as total phenols and colour. The vineyard sites clustered in the observations plot with some difference between the water status zones, but the larger differences were between vineyards.

Black Paw vineyard was heavily loaded with soil clay content and organic matter, and was the most different from the other three sites. Red Paw 1 and Red Paw 2 were similar to one another, without clear separation of the water status zones within the vineyards. The Lowrey's vineyard was loaded with mean Ψ, sand content and shoot weight. The mean Ψ was negatively correlated with soluble solids, berry pH and total anthocyanins.

For 2009, Figure 3-8 shows the first two principal components explained 70.34% of the variation in the data. There were more variables which were not heavily loaded on PC1 or PC2 compared to 2008, with eigenvalues in the range of 0.2 to 0.5. Yield and cluster size were inversely correlated to total anthocyanins, hue and soluble solids. Clay content and mean soil moisture were inversely correlated with mean Ψ, berry size and silt. In 2009, all four vineyard sites separated in the observation loadings plot. Black Paw was loaded with clay, CEC, and soil moisture. Red Paw 2 was loaded with total anthocyanins, hue and berry size. Red Paw 1 was loaded with sand, total phenols and TA. Lowrey's was not distinctly loaded with any variables, but was most closely loaded with yield and colour intensity.

In 2009, there were far fewer strong correlations between variables overall. In both years it was the soil type, especially the clay content that was a major factor in the soil moisture. Mean Ψ was moderately correlated with the soil clay content ($r=-0.47$; $p<0.0001$), and sand content ($r=0.52$; $p<0.0001$). Again, the soil type was a driver of the water status, and of the terroir, in agreement with Seguin (1986). The clay content was also marginally correlated with berry size ($r=-0.43$; $p<0.01$), and silt was correlated with total anthocyanins ($r=0.45$; $p<0.01$). Soil texture and water status were both observed to be factors in the variability in grape composition.

As in 2008, Black Paw was very different from the other sites, and heavily loaded with soil clay content. In 2009, the two Red Paw vineyards were more distinct from one another, with Red Paw 2 being more heavily loaded with berry soluble solids, total anthocyanins and hue. Red Paw 1 was loaded with total phenols and berry TA. The fruit from Red Paw 1 was harvested earlier than the other vineyards, as the winery harvested this block early as a part of a new sparkling wine program. The extra ripening time was the likely cause of this difference.

Considering both vintages, the output of the PCA is seen in Figure 3-9. Grape composition variables (soluble solids, berry pH, total anthocyanins and phenols) were generally highly correlated to one another, and negatively correlated with yield and cluster size, mean Ψ, and soil sand content. The first two principal components explained 61.3% of the variation in the data. Total anthocyanins, phenols, soluble solids and berry pH were all well correlated. All of these metrics were roughly inversely correlated with yield, cluster size, Ψ, and sand. Clay content and soil moisture were not well correlated with yield or berry composition metrics except for berry size, TA and colour.

In both years, but especially true in 2008, it was a combination of vine water status and soil type that were driving the composition of the grapes at harvest. Soil moisture was not a strong indicator of vine water status, and vigour did not play a significant role in driving vineyard variability.

3.3.3 Weather

It is important to note that the two years for this study were abnormal in several ways. Both years were cooler than average, and wetter than average. In contrast, 2007 was much hotter and drier than average, and vine water stress experienced in 2007 may have laid the foundation for vine performance in 2008 with more of an influence than the excess moisture in the following years. Figure 7-2 in the supplemental materials shows the incidence and intensity of rainfall events in relation to data collection dates for 2008 and 2009.

Rainfall events were more frequent in 2008, but the overall precipitation was higher in 2009. Daily maximum temperatures were slightly above the long-term mean in 2008, but minimum temperatures were below average, with a net effect of lower average temperatures. The monthly rainfall in 2008 and 2009 at the St. Davids, Ontario weather station were compared to the Environment Canada long-term average (1971 to 2000) at the nearby St Catharines airport, as seen in Table 7-12 in the supplemental materials. The monthly rainfall in June, July and August in 2008 and May, June, July, August and October in 2009 were higher than average. Additionally, there was an increase in disease pressure because of the elevated daily maximum temperatures combined with high precipitation. In particular, downy mildew and bunch rot were of great concern in 2008. Maximum and minimum daily temperatures were well below average in 2009. The lower frequency of rainfall events, and the lower temperatures mediated disease pressure, and in general it was observed that disease was less severe in 2009 as reported in the Weather INnovations Inc. growing season reports for 2008 and 2009 (www.weatherinnovations.com).

The effect of the wet weather was apparent in the Ψ measurements made in this study. In 2008 the most severe mean Ψ (most negative) value was -9.4 bar in the Black Paw vineyard, and in 2009 it was -9.5 bar in both Red Paw 1 and Lowrey's vineyards. The minimum mean Ψ (least negative) was -6.0 bar in 2008, and -5.9 bar in 2009, both in Lowrey's vineyard. Stomatal openings and consequently grapevine photosynthesis are generally not affected by water stress until the midday Ψ is less (more negative) than -5 bar (Hardie & Considine 1976). Even at their most negative values, the vines in this study were not subjected to more than mild water stress.

3.3.4 Geomatics

Spatial analysis of vineyard variability was done with the aid of maps. Red Paw 1 2008 yield components and grape composition (yield per vine, cluster size, berry size, soluble solids, pH, TA) are shown in Figure 7-3. Grape composition (total anthocyanins, colour intensity, hue and total phenolic compounds), vine size, and soil moisture are shown in Figure 7-4. Red Paw 1 Ψ and water status zone delineation for both vintages are shown in Figure 3-3 as discussed. Soil texture (clay, silt, sand), and soil composition (pH, organic matter, CEC) are shown in Figure 7-5. Similarly, Red Paw 1 2009 maps of yield components, grape composition, vine size and soil moisture are shown in Figure 7-6**Error! Reference source not found.** and Figure 7-7. Ordered in the same way, Figure 7-8 through Figure 7-12 show Red Paw 2 maps from both vintages; Figure 7-13 through Figure 7-17 show Black Paw maps from both vintages; and Figure 7-18 through Figure 7-22 show Lowrey's vineyard maps from both vintages.

At all four vineyards, in both years, maps of yield and cluster size were similar. Across vintages, there were some trends that are present in both years and others that switched between higher and lower values. The yield per vine map of Red Paw 1 in 2008 (Figure 7-3) had a distinct band of higher yield, running north-east through the eastern half of the vineyard. This region was still there in 2009 (Figure 7-6), although the actual yields were lower overall.

Within the same vintage, maps of berry composition variables were qualitatively similar. Berry soluble solids, pH and TA are intimately related in the ripening of grapes (Coombe 1992), and in Red Paw 2, seen in Figure 7-9-d, -e and -f, there were clear patterns of higher soluble solids corresponding with higher pH and lower TA respectively. Comparing the same variables in 2009, in Figure 7-12-d, -e and –f, there was some similarity between years, but also some differences. In pH, there was a region of higher pH in the eastern half of the site in both years. The western half of the vineyard had a lower concentration of soluble solids in 2008, but this was reversed in 2009, where the concentration was higher.

Maps of total anthocyanins, colour, hue and phenols were very similar to one another within vineyard sites, within vintage. Figure 7-19 shows this for Lowrey's vineyard in 2008 and Figure 7-22 for 2009. Since colour is related to the concentration of anthocyanins, which are phenolic compounds, this relationship is to be expected. Between years, these spatial trends also appeared fairly stable; the western half of the vineyard, lower in anthocyanins in 2008 (Figure 7-19) and was lower again in 2009 (Figure 7-22). This spatial similarity in phenolics was not as obvious at the other vineyards.

In general, the Black Paw maps were difficult to interpret as a result of the site geometry. It was very narrow compared to the length, complicating the surface interpolation process.

Spatial variation in water status zones, the basis for site divisions in this study, was somewhat stable between vintages. Red Paw 1 had the most negative values in the western half of the site in both years, the branch extending east and north in 2009 (Figure

3-3b) cut through the same region as the low water status zone in 2008 (Figure 3-3a). In Red Paw 2, **Error! Reference source not found.**there was a zone of lower water status through the middle of the vineyard in both years, and these two maps were very similar (Figure 3-4). The Black Paw water status zones were roughly similar with the high water status zone running through the middle of vineyard from north to south (Figure 3-5). Lowrey's vineyard seemed as though it was the exception, but in 2008 there were three water status zones, whereas in 2009 there were only two. Ignoring the dividing line between zones, the lower water status zones were focused in the north end of the vineyard in each year (Figure 3-6).

The soil texture of the vineyard, one of the other drivers of variability, also matched spatially with other variables. Figure 7-5a is a map of the clay content in Red Paw 1, and the same patterns of high and low were present in the vine water status (Figure 3-3), yield components (Figure 7-3 and Figure 7-6**Error! Reference source not found.**), and to some extent, grape composition (Figure 7-4 and Figure 7-7). The band of approximately 40% clay running north-east through the vineyard is similar to the yield and berry size, total anthocyanins and soil moisture maps, although not a perfect overlay. This same general relationship between clay content and other variables was present in the other vineyards as well.

Vine size, measured by weight of cane prunings, showed spatial distribution similar to other variables in Red Paw 2, even though there were not strong correlations between these variables. In Figure 7-9e, the map of 2008 vine size measurements in 2008 had a region of higher shoot weight in the eastern half of the vineyard, where there was also higher soil moisture (Figure 7-9**Error! Reference source not found.**f), lower total anthocyanins (Figure 7-9a), and higher soluble solids (Figure 7-8d). This trend did not appear in the other vineyards.

Figure 7-19e shows the pruning weights from 2008 at the Lowrey's vineyard, with almost no similarity to the trends in the soil moisture (Figure 7-19f), and poor similarity to maps of total anthocyanins (Figure 7-19a) and soluble solids (Figure 7-18e). In 2009, this was the only vineyard with shoot weight measurements, mapped in Figure 7-22e, and again there was not a strong similarity to the maps of soil moisture (Figure 7-22f), total anthocyanins (Figure 7-22a) or any other grape composition metric. Cortell et al. (2006) mapped vigour zones in Pinot noir vineyards, and anthocyanin distribution in those same vineyards (Cortell et al. 2007a), but did not compare these maps directly. They found a strong relationship between vine vigour and anthocyanin composition, and when comparing the two publications, there was a clear spatial relationship between the vigour zones and the production of anthocyanins that was not found in this study.

Bramley (2005) found that there were stable and clear patterns in the zones of berry composition. These zones were related to the ones he identified in yield (Bramley & Hamilton 2004), but in contrast to this study, he found a particular similarity of the spatial variation in berry weight to the grape composition variables. Reynolds et al. (2007) found that there were not distinct year-to-year patterns in grape composition or vine performance. The similarity of the weather in 2008 and 2009, while a complicating factor for observing the effect of water status, may have been at least partially responsible for the stability in these trends. The correlations described in Section 3.3.2.1 were generally not very strong, with r values greater than 0.4 discussed as a marginal or moderate correlations. This relatively low cut-off and the subjective nature of qualitatively describing spatial variation in maps mean that the spatial trends may not be as strong as suggested. Further years of study are recommended to gain a better appreciation of trends in spatial variation over time.

3.4 Conclusions

All of the vineyard sites were observed to be highly variable, with anthocyanins and phenols being the most variable grape composition variables. Yield and weight of cane prunings were the two most variable attributes in all four vineyards.

Using water status as the basis for within-vineyard division into production lots, this study did not find differences between the water status zones in terms of vigour, berry composition, or soil properties. Similarly, dividing the vineyards by vigour did not reveal differences in berry composition or soil properties. The wines made from the fruit in the water status zones were not significantly different in chemical attributes. In analysis using HPLC, individual anthocyanins and phenolic compounds were not significantly different between wines from the high and low water status zones.

The weather in 2008 and 2009 complicated this study; both years were wetter and cooler than average. This may have helped to stabilize some of the spatial trends in vineyard performance, but was also likely the principal factor in muting any effect of water status on the vines.

There was some correlation between Ψ and berry composition, but was not proven to be a driving factor in the spatial distribution of variability. The wetter than average years meant that the range of water status values observed were very narrow, with very little difference between high and low water status zones. Vine vigour was also not seen to be a primary factor in driving vineyard variability, in the one year that data was collected at all sites, pruning weights did not correlate well to most other variables. Maps of shoot weights bore some similarity to other variables, but not always.

Spatial trends of variability in grape composition, soil moisture and vine water status were observed to be generally stable from year to year. In addition, correlations between variables were confirmed in spatial distribution by qualitative comparison of maps, but these trends were not clear enough to draw any concrete conclusions.

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Table 3-1: Means of yield components grouped by water status zone within each site at four Pinot noir vineyards, St. Davids, ON, 2008-2009.

Water Status Category	Yield (kg)		No. of clusters		Cluster weight (g)		Berry weight (g)	
Red Paw 1	2008	2009	2008	2009	2008	2009	2008	2009
Low	3.08a	2.74a	27.2	26.4a	112.5a	102.7	1.68	1.55
High	2.65b	2.22b	25.5	22.1b	102.3b	99.8	1.66	1.51
Significance[a]	*	***	ns	**	**	ns	ns	ns
Red Paw 2								
Low	2.53	2.19	26.8	20.8	91.9b	104.8	1.62	1.69a
High	2.69	2.43	27.3	22.3	98.3a	107.4	1.62	1.63b
Significance	ns	ns	ns	ns	*	ns	ns	**
Black Paw								
Low	1.27	2.57	17.7	25.3	70.7	103.2	1.52	1.38
High	1.54	2.56	19.1	25.7	76.3	99.1	1.44	1.40
Significance	ns	ns	ns	ns	ns	ns	ns	ns
Lowrey's								
Low	2.74	2.81	21.1	26.3	129.2a	106.4a	1.46	1.73
Medium	2.39	-[b]	21.6	-	105.2b	-	1.45	-
High	2.69	2.52	24.4	26.3	108.0b	94.4b	1.45	1.73
Significance	ns	ns	ns	ns	***	****	ns	ns

[a]Mean separation at $\alpha=0.1$ using the LSD test *, **, ***, ****, ns: Significant at $p\leq0.1$, 0.05, 0.01, 0.001, not significant, respectively

[b]In 2009, Lowrey's vineyard was divided into two water status zones.

Table 3-2: Means of vineyard water status and vine size grouped by water status zone within each site at four Pinot noir vineyards, St. Davids, ON, 2008-2009.

Water Status Category	Soil moisture (%)		Ψ (bar)		Weight of cane prunings (kg)	
Red Paw 1	2008	2009	2008	2009	2008	2009[c]
Low	13.1	10.2b	-8.3b	-8.7b	0.40	-
High	13.3	10.8a	-7.5a	-7.6a	0.39	-
Significance[a]	ns	*	****	****	ns	-
Red Paw 2						
Low	12.7	10.6	-8.4b	-8.2b	0.32	-
High	12.7	10.6	-7.9a	-7.3a	0.30	-
Significance	ns	ns	****	****	ns	-
Black Paw						
Low	27.4	25.0	-8.9b	-9.1b	0.33	-
High	29.8	25.9	-7.9a	-8.4a	0.32	-
Significance	ns	ns	****	****	ns	-
Lowrey's						
Low	24.0a	19.6	-7.9c	-8.0b	0.57	0.63b
Medium	23.6a	-[b]	-7.3b	-	0.59	-
High	21.7b	19.5	-6.4a	-7.0a	0.69	0.76a
Significance	**	ns	****	****	ns	**

[a]Mean separation at $\alpha=0.1$ using the LSD test *, **, ***, ****, ns: Significant at $p\leq 0.1, 0.05, 0.01, 0.001$, not significant, respectively
[b]In 2009, Lowrey's vineyard was divided into two water status zones.
[c]In 2009, Lowrey's vineyard was the only site where pruning shoot weights were measured.

Table 3-3: Means of berry composition (soluble solids, TA, and pH) grouped by water status zone within each site at four Pinot noir vineyards, St. Davids, ON, 2008-2009.

Water Status Category	Berry Brix		Berry TA (g/L)		Berry pH	
Red Paw 1	2008	2009	2008	2009	2008	2009
Low	20.8	22.3	9.1	10.1a	3.58	3.52
High	21.0	22.6	9.1	9.8b	3.58	3.53
Significance[a]	ns	ns	ns	*	ns	ns
Red Paw 2						
Low	21.7	24.0	7.8b	8.1	3.63	3.61b
High	21.4	23.6	8.0a	8.2	3.62	3.67a
Significance	ns	ns	*	ns	ns	****
Black Paw						
Low	22.5	22.6	8.9a	8.0a	3.59b	3.58
High	22.5	22.6	8.4b	7.5b	3.61a	3.59
Significance	ns	ns	*	*	*	ns
Lowrey's						
Low	20.6	22.2	8.2b	8.4	3.47	3.55
Medium	20.3	-[b]	8.3b	-	3.48	-
High	20.1	22.1	8.5a	8.5	3.46	3.54
Significance	ns	ns	*	ns	ns	ns

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at $p \leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively

[b]In 2009, Lowrey's vineyard was divided into two water status zones.

Table 3-4: Means of berry composition (total anthocyanins, colour intensity, hue, and total phenols) grouped by water status zone within each site at four Pinot noir vineyards, St. Davids, ON, 2008-2009.

Water Status Category	**Total anthocyanins (mg/L)**		**Colour (au)**		**Hue (au)**		**Total phenols (mg/L)**	
Red Paw 1	2008	2009	2008	2009	2008	2009	2008	2009
Low	250.0	350.4	9.1b	10.2	0.6	0.6	1712.9	2457.4
High	272.7	350.2	10.0a	10.0	0.6	0.6	1759.4	2440.0
Significance[a]	ns	ns	*	ns	ns	ns	ns	ns
Red Paw 2								
Low	297.9a	367.5b	10.6a	7.9	0.6	0.7	1550.4	2292.7a
High	272.1b	393.3a	10.0b	7.8	0.7	0.7	1635.5	1990.3b
Significance	**	***	*	ns	ns	ns	ns	****
Black Paw								
Low	359.4	295.4	14.7	7.9	0.6	0.6	2119.1	1985.5
High	349.5	299.4	14.2	8.1	0.6	0.6	2054.8	2029.8
Significance	ns	ns	ns	ns	ns	ns	ns	ns
Lowrey's								
Low	250.5a	287.8	10.2a	6.4	0.6	0.6	1794.9	2221.6
Medium	229.0b	-[b]	9.5b	-	0.7	-	1850.2	-
High	209.0c	290.3	8.7c	6.4	0.7	0.6	1854.3	2230.7
Significance	***	ns	***	ns	ns	ns	ns	ns

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at $p \leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively
[b]In 2009, Lowrey's vineyard was divided into two water status zones.

Table 3-5: Means of soil variables grouped by water status zones from four Pinot noir vineyard sites, St. Davids, ON, 2008-2009.

Water Status Category	Clay (%)		Silt (%)		Sand (%)		OM (%)		CEC (meq/100g)		Soil pH	
Red Paw 1	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
Low	36.1	37.7	56.9	55.5	6.9	6.9	2.2b	2.7	15.9b	17.9	5.5b	5.8
High	38.1	36.4	55.2	56.8	6.8	6.8	2.9a	2.3	19.0a	16.9	6.1a	5.8
Significance[a]	ns	ns	ns	ns	ns	ns	*	ns	*	ns	*	ns
Red Paw 2												
Low	38.0	38.3	54.9	54.4	7.5	7.4	3.8	3.7	17.7	17.7	6.3	6.2b
High	38.8	38.6	53.4	53.8	7.8	7.9	3.9	3.9	20.5	20.5	6.6	6.7a
Significance	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
Black Paw												
Low	64.1	63.4	33.0	33.8	2.9	2.8	4.8	5.5a	40.0	42.8a	7.4	7.4
High	63.7	64.5	33.0	32.3	3.3	3.2	5.2	4.5b	39.7	37.5b	7.4	7.4
Significance	ns	ns	ns	ns	ns	ns	ns	*	ns	*	ns	ns
Lowrey's												
Low	44.2a	43.9a	46.2	47.3	9.7	8.9b	3.4	3.4a	30.0a	28.4a	6.8	6.6
Medium	40.6ab	-[b]	47.6	-	11.8	-	2.9	-	24.9b	-	6.6	-
High	37.1b	38.2b	47.6	47.1	15.3	14.8a	2.8	2.8b	23.5b	24.5b	6.7	6.8
Significance	**	**	ns	ns	ns	**	ns	**	**	*	ns	ns

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at $p \leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively.
[b]In 2009, Lowrey's vineyard was divided into two water status zones.

Table 3-6: Means of wine, grouped by water status zone within each site, chemical attributes; TA, pH, and ethanol (%) at four Pinot noir vineyards, St. Davids, ON, 2008-2009.

Wine	Wine TA (g/L)		Wine pH		Wine ethanol (%)	
Red Paw 1	**2008**	**2009**	**2008**	**2009**	**2008**	**2009**
Low	4.7	4.9	3.90a	3.90	10.19	11.63
High	4.6	4.9	3.88b	3.89	10.37	11.33
Significance[a]	ns	ns	**	ns	ns	ns
Red Paw 2						
Low	4.6	4.6a	3.75	3.88	10.91	12.60
High	4.5	4.7b	3.76	3.92	10.44	12.76
Significance	ns	*	ns	ns	ns	ns
Black Paw						
Low	6.9	5.9b	3.72	3.68	10.62	11.97
High	6.1	5.1a	3.70	3.72	10.03	11.88
Significance	-[c]	**	-	ns	-	ns
Lowrey's						
Low	4.9	5.5	3.53	3.64a	10.77	11.79
Medium	4.6	-[b]	3.61	-	10.32	-
High	4.7	5.2	3.55	3.70b	10.18	11.62
Significance	ns	ns	ns	****	ns	ns

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at $p \leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively

[b]In 2009, Lowrey's vineyard was divided into two water status zones.

[c]Black Paw wines in 2008 were not made in replicate; values shown are for the single fermentation

Table 3-7: Means of wine, grouped by water status zone within each site, chemical attributes; total anthocyanins, colour intensity, hue, and total phenols at four Pinot noir vineyards, St. Davids, ON, 2008-2009.

Wine	Total anthocyanins (mg/L)		Colour (au)		Hue (au)		Total phenols (mg/L)	
Red Paw 1	2008	2009	2008	2009	2008	2009	2008	2009
Low	125.6	161.4	2.3a	0.4a	1.0	0.7	1367.9	1757.0
High	132.1	180.3	2.5b	0.4b	1.0	0.7	1380.0	1790.3
Significance[a]	ns	ns	*	**	ns	ns	ns	ns
Red Paw 2								
Low	172.5	222.2	2.4	0.5a	0.9	0.7	1170.9a	1678.2
High	153.5	217.7	2.5	0.5b	0.9	0.7	955.8b	1708.5
Significance	ns	ns	ns	**	ns	ns	****	ns
Black Paw								
Low	137.1	186.4	4.0	0.4	1.1	0.7	2680.0	2290.3a
High	132.6	185.6	4.2	0.5	0.9	0.7	2389.1	2611.5b
Significance	-[c]	ns	-	ns	-	ns	-	*
Lowrey's								
Low	169.4	177.6	2.5	0.4	0.8b	0.7	1192.1	2226.7
Medium	160.5	-[b]	2.5	-	0.9a	-	1361.8	-
High	159.8	180.2	2.4	0.4	0.8b	0.7	1273.9	2202.4
Significance	ns	ns	ns	ns	*	ns	ns	ns

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at $p \leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively
[b]In 2009, Lowrey's vineyard was divided into two water status zones.
[c]Black Paw wines in 2008 were not made in replicate; values shown are for the single fermentation.

Table 3-8: Means of must, grouped by water status zone within each site, chemical attributes; TA, pH, and soluble solids at four Pinot noir vineyards, St. Davids, ON, 2008-2009.

Must	Must Brix		Must TA (g/L)		Must pH	
Red Paw 1	2008	2009	2008	2009	2008	2009
Low	19.4b	21.0a	9.00	9.54a	3.55	3.43
High	19.8a	20.8b	8.59	8.91b	3.53	3.39
Significance[a]	**	*	ns	*	ns	ns
Red Paw 2						
Low	19.5	22.7	6.87	7.87	3.56	3.61a
High	19.5	22.4	6.50	7.65	3.54	3.53b
Significance	ns	ns	ns	ns	ns	***
Black Paw						
Low	19.1	21.4	10.86	7.96	3.34	3.42
High	20.4	20.9	11.84	7.49	3.34	3.42
Significance	-[c]	ns	-	ns	-	ns
Lowrey's						
Low	19.5a	21.0	6.51ab	8.13	3.45b	3.42
Medium	18.9c	[b]-	6.34b	-	3.49a	-
High	19.0b	20.6	6.74a	7.91	3.45b	3.42
Significance	****	**	*	ns	**	ns

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at $p \leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively

[b]In 2009, Lowrey's vineyard was divided into two water status zones.

[c]Black Paw wines in 2008 were not made in replicate; values shown are for the single fermentation.

Table 3-9: Means of must, grouped by water status zone within each site, chemical attributes; total anthocyanins, colour intensity, hue, and total phenols at four Pinot noir vineyards, St. Davids, ON, 2008-2009.

Must	Total anthocyanins (mg/L)		Colour (au)		Hue (au)		Total phenols (mg/L)	
Red Paw 1	2008	2009	2008	2009	2008	2009	2008	2009
Low	28.3	90.0a	1.4	0.2a	1.2	0.6	366.8	598.6a
High	21.0	68.4b	1.6	0.2b	1.0	0.7	380.5	400.9b
Significance[a]	ns	**	ns	**	ns	ns	ns	**
Red Paw 2								
Low	36.6	53.3	1.6	0.2a	0.9	0.8	382.7	480.5
High	26.9	43.3	1.5	0.2b	1.0	0.9	325.9	455.5
Significance	ns	ns	ns	*	ns	ns	ns	ns
Black Paw								
Low	32.6	60.1	1.2	0.2	0.8	0.8	437.3	535.0
High	36.3	52.5	1.3	0.2	0.8	0.8	587.3	663.0
Significance	-[c]	ns	-	ns	-	ns	-	ns
Lowrey's								
Low	105.6	96.4	3.1	0.2	0.6	0.6	557.7	616.8
Medium	84.7	-[b]	2.7	-	0.7	-	532.7	-
High	85.6	93.5	2.6	0.2	0.6	0.6	446.4	616.8
Significance	ns	ns	ns	ns	ns	ns	ns	ns

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at $p \leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively
[b]In 2009, Lowrey's vineyard was divided into two water status zones.
[c]Black Paw wines in 2008 were not made in replicate; values shown are for the single fermentation.

Table 3-10: Mean of individual anthocyanin concentrations in wines, grouped by water status zone within each site, at four Pinot noir vineyards, St. Davids, ON, 2008-2009.

Wine	Delphinidin[c] (mg/L)		Cyanidin (mg/L)		Petunidin (mg/L)		Peonidin (mg/L)		Malvidin (mg/L)	
Red Paw 1	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
Low	1.92	4.42	0.25	0.36	3.01	6.15	8.68	9.78	56.13	77.46
High	2.13	3.7	0.28	0.49	3.32	5.17	8.07	11.26	58.12	71.59
Significance[a]	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Red Paw 2										
Low	2.90a	4.29a	0.23	0.40	4.61a	6.49a	8.51a	9.82a	88.48a	110.10
High	2.31b	3.81b	0.20	0.48	3.42b	5.82b	7.10b	9.02b	75.87b	106.18
Significance	*	*	ns	ns	**	*	*	ns	*	ns
Black Paw										
Low	3.37	5.55	0.47	0.50	4.22	6.34	9.63	13.63	56.68	83.42
High	3.26	4.98	0.47	0.58	4.04	6.89	9.63	12.24	52.51	82.66
Significance	-[d]	ns	-	ns	-	ns	-	ns	-	ns
Lowrey's										
Low	3.47	4.19	0.48a	0.44	4.68	5.57	12.19a	1.13	81.94	74.35
Medium	3.13	-[b]	0.34b	-	4.36	-	12.29b	-	81.79	-
High	3.18	4.26	0.36b	0.43	4.40	5.62	10.74b	1.07	83.35	75.55
Significance	ns	ns	*	ns	ns	ns	*	ns	ns	ns

[a]Means separation at α=0.05 using the LSD test *, **, ***, ns: Significant at $p \leq 0.05$, 0.01, 0.001, not significant, respectively
[b]In 2009, Lowrey's vineyard was divided into two water status zones.
[c]3-O-Glucosides of individual anthocyanins
[d]Black Paw wines in 2008 were not made in replicate; values shown are for the single fermentation.

Table 3-11: Means of flavonol-3 phenolics concentrations in wines, grouped by water status zone within each site; catechin, epicatechin, quercetin at four Pinot noir vineyards, St. Davids, ON, 2008-2009.

Wine	Catechin (mg/L)		Epicatechin (mg/L)		Quercetin (mg/L)	
Red Paw 1	2008	2009	2008	2009	2008	2009
Low	93.23b	203.48	75.60	119.44	1.46a	3.61
High	104.91a	221.07	79.59	131.42	1.17b	2.99
Significance[a]	*	ns	ns	ns	*	ns
Red Paw 2						
Low	57.72	204.20	43.13	113.12	1.59	2.93
High	59.30	190.31	43.49	104.32	1.53	2.56
Significance	ns	ns	ns	ns	ns	ns
Black Paw						
Low	286.48	198.58	235.74	144.01	2.29	3.28
High	216.98	177.14	159.44	129.15	0.00	3.08
Significance	-[c]	ns	-	ns	-	ns
Lowrey's						
Low	105.30	249.28	56.63	135.26	2.90	3.41
Medium	122.79	-[b]	62.65	-	4.03	-
High	116.3	250.53	59.06	130.16	3.50	3.46
Significance	ns	ns	ns	ns	ns	ns

[a]Mean separation at $\alpha=0.05$ using the LSD test *, **, ***, ns: Significant at $p\leq 0.05$, 0.01, 0.001, not significant, respectively

[b]In 2009, Lowrey's vineyard was divided into two water status zones.

[c]Black Paw wines in 2008 were not made in replicate; values shown are for the single fermentation.

Table 3-12: Means of non-flavonoid phenolics and stilbene concentrations in wines, grouped by water status zone within each site; gallic acid, caffeic acid, p-coumaric acid, and trans-resveratrol at four Pinot noir vineyards, St. Davids, ON, 2008-2009.

Wine	Gallic acid (mg/L)		Caffeic acid (mg/L)		p-Coumaric acid (mg/L)		Trans-resveratrol (mg/L)	
Red Paw 1	2008	2009	2008	2009	2008	2009	2008	2009
Low	15.77	25.47	25.20	23.76	4.72	5.87	2.96	3.19
High	16.24	24.72	26.57	25.75	5.19	6.09	2.73	2.79
Significance[a]	ns	ns	ns	ns	ns	ns	ns	ns
Red Paw 2								
Low	11.53	23.54	25.27a	13.59	5.55	3.40	2.66a	2.41
High	11.25	21.54	23.17b	11.90	5.32	3.83	2.28b	2.49
Significance	ns	ns	*	ns	ns	ns	*	ns
Black Paw								
Low	43.45	42.16a	30.64	19.90	6.55	4.87	1.43	2.97a
High	34.17	34.69b	32.51	13.27	6.68	3.14	1.36	2.52b
Significance	-[c]	*	-	ns	-	ns	-	*
Lowrey's								
Low	12.59	29.05	9.91	7.54	3.59	1.62	1.02b	2.55
Medium	13.37	-[b]	12.40	-	3.09	-	1.30a	-
High	12.83	30.49	11.43	7.82	2.84	1.76	1.36a	2.86
Significance	ns	ns	ns	ns	ns	ns	**	ns

[a]Mean separation at α=0.05 using the LSD test *, **, ***, ns: Significant at $p \leq 0.05$, 0.01, 0.001, not significant, respectively

[b]In 2009, Lowrey's vineyard was divided into two water status zones.

[c]Black Paw wines in 2008 were not made in replicate; values shown are for the single fermentation.

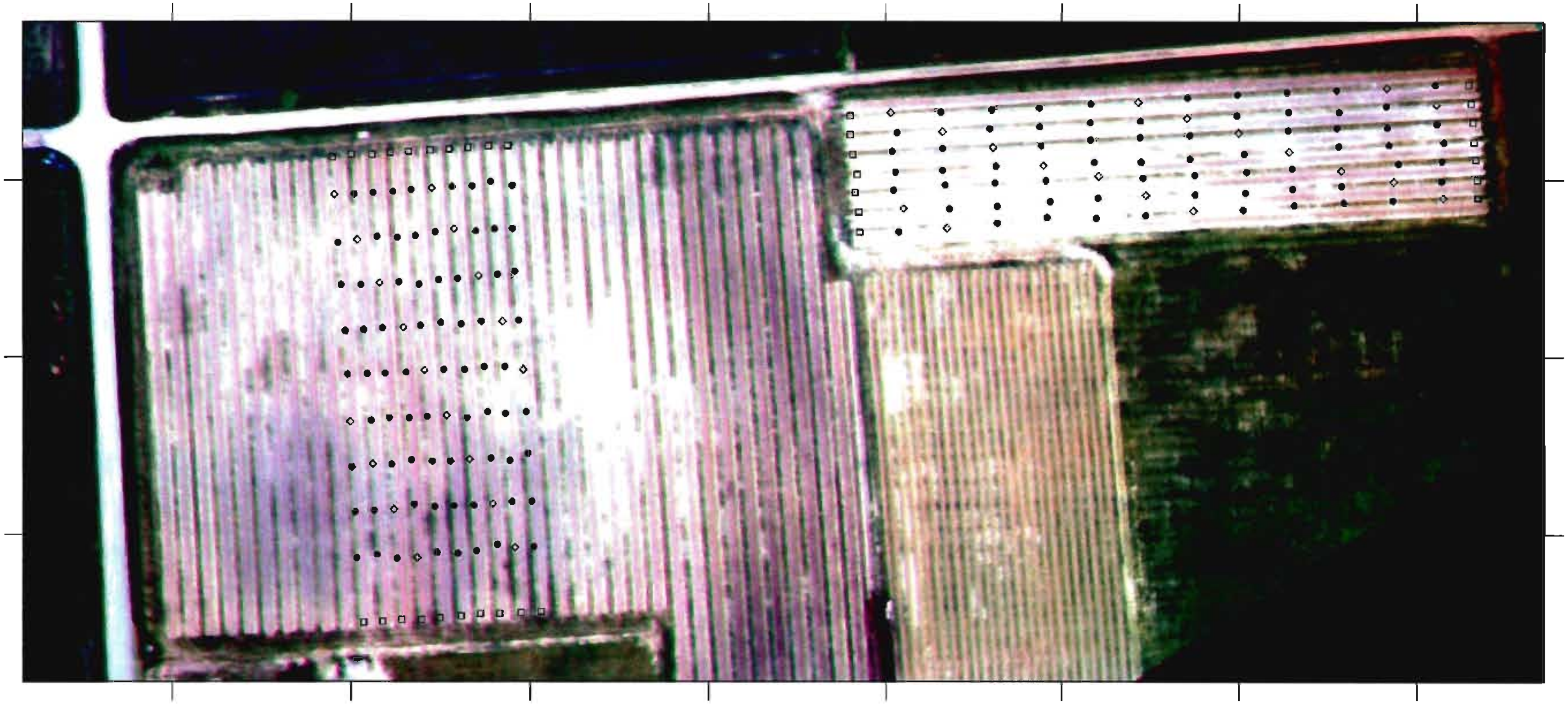


Figure 3-1: Sentinel vines in the Red Paw vineyards, St. Davids, ON overlaid on a true colour (RGB) image from 29 May 2008. Open squares represent end-posts, open diamonds represent water status vines, and solid circles represent other sentinel vines. Red Paw 1 is on the right, with vine rows running east-west; Red Paw 2 is on the left, with vine rows running north-south.

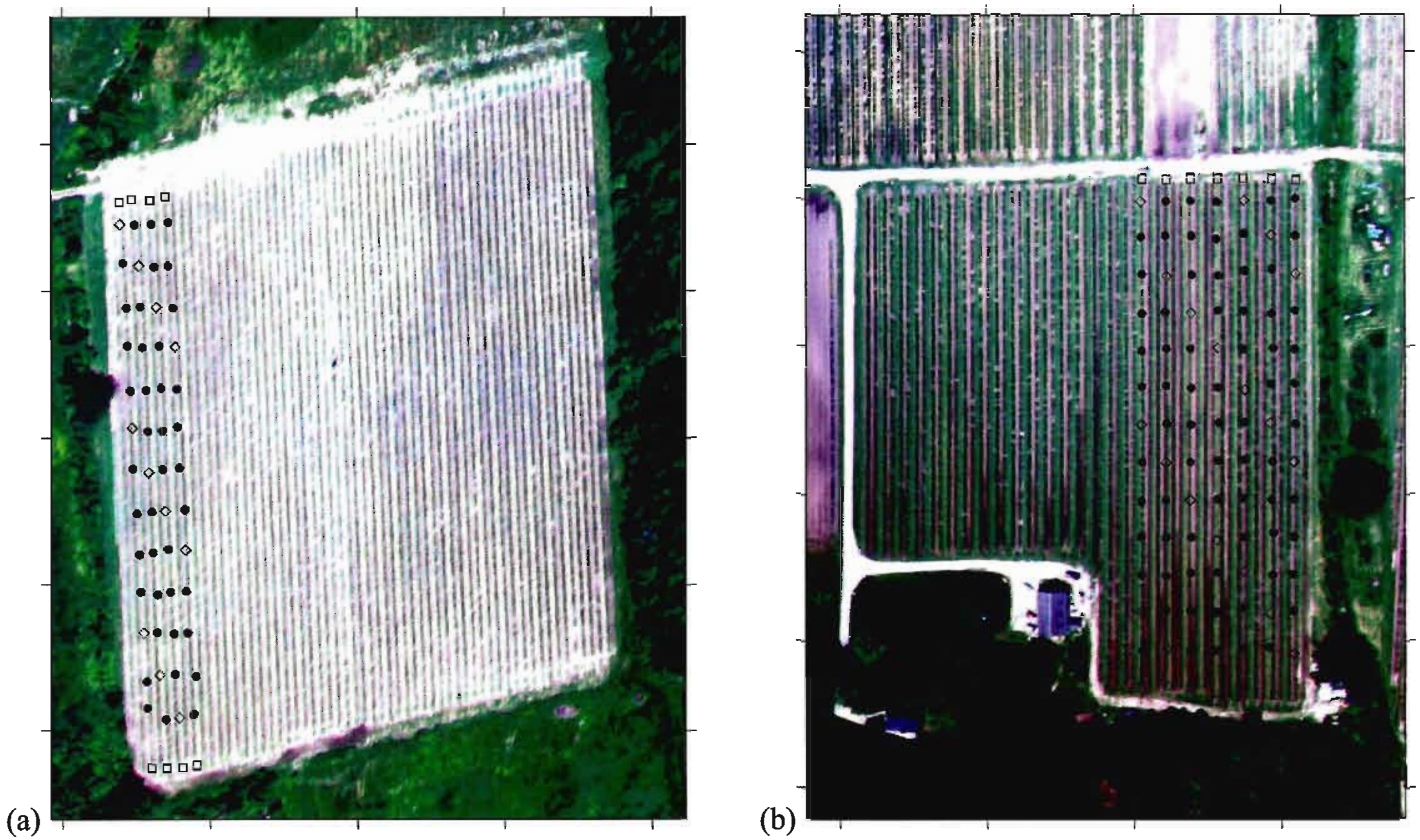
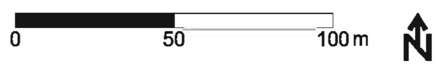


Figure 3-2: Sentinel vines in the (a) Black Paw vineyard and (b) Lowrey's vineyard (Pinot noir, St. Davids, ON) overlaid on true colour (RGB) images from 22 June 2009. Open squares represent end-posts, open diamonds represent water status vines, and solid circles represent other sentinel vines.



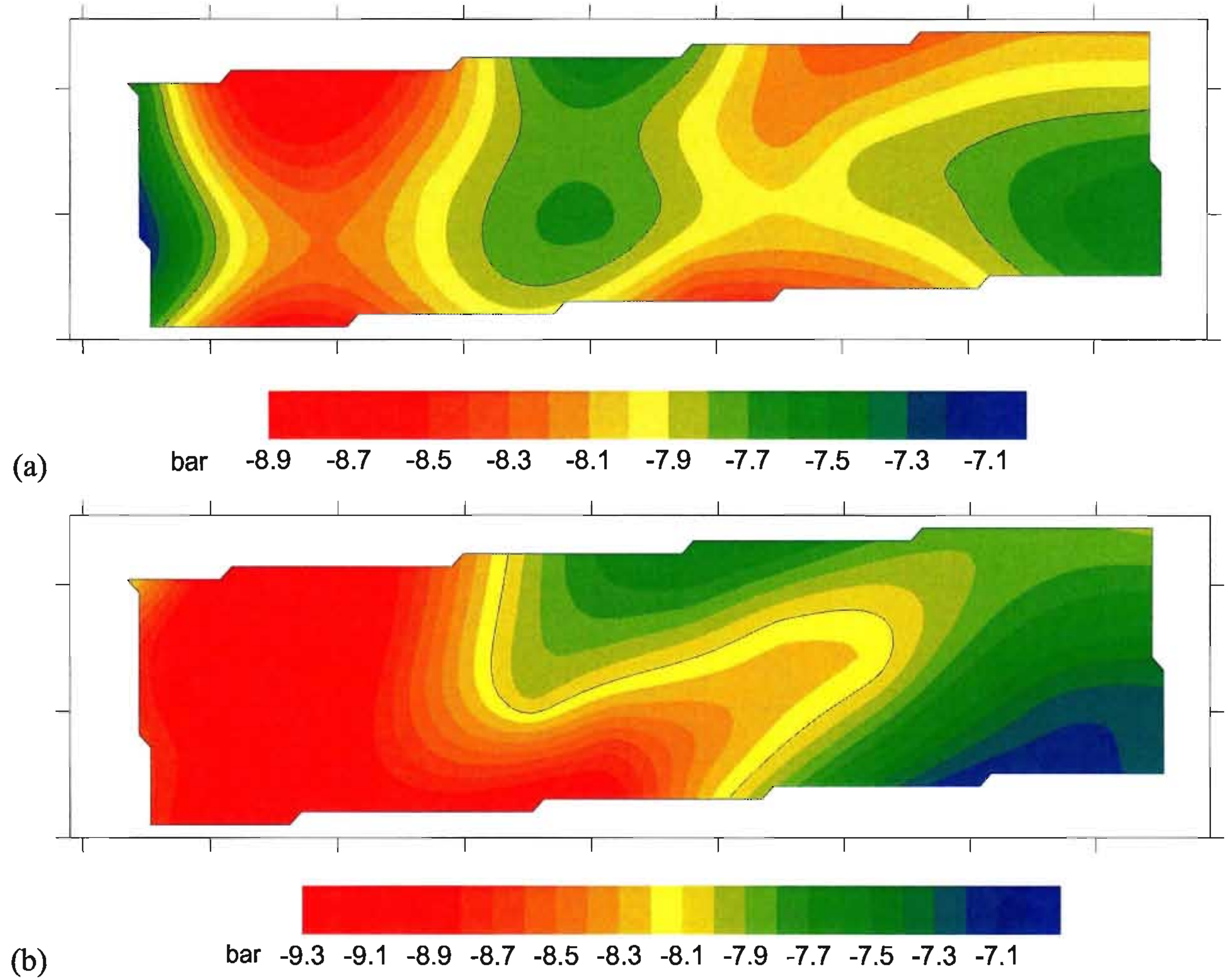
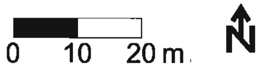


Figure 3-3: Red Paw 1. Mean Ψ (bar); (a) 2008 and (b) 2009 in a Pinot noir vineyard, St. Davids, ON. Note that the range of values was not the same in both years, and a different value scale was used. The dark lines represent the division between high and low water status zones.



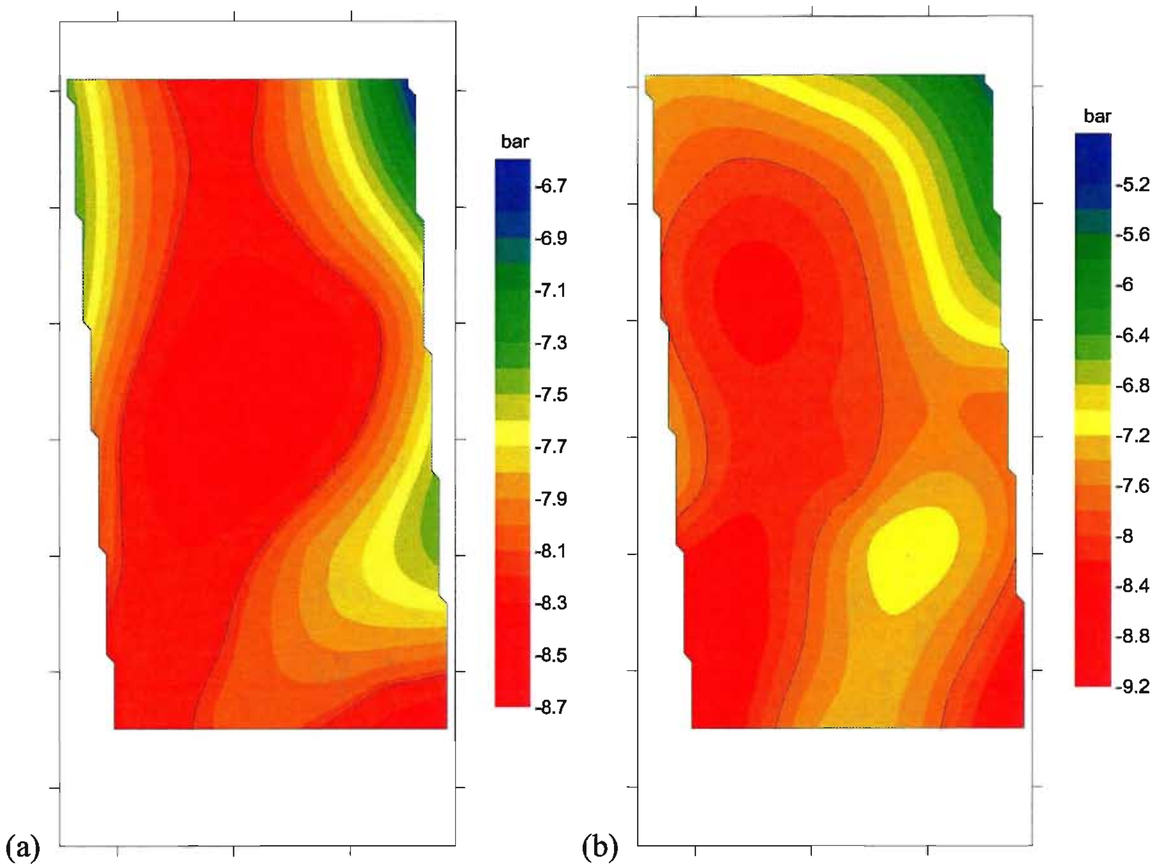
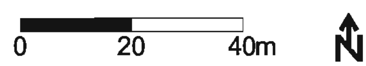


Figure 3-4: Red Paw 2. Mean Ψ (bar); (a) 2008 and (b) 2009 in a Pinot noir vineyard, St. Davids, ON. Note that the range of values was not the same in both years, and a different value scale was used. The dark lines represent the division between high and low water status zones.



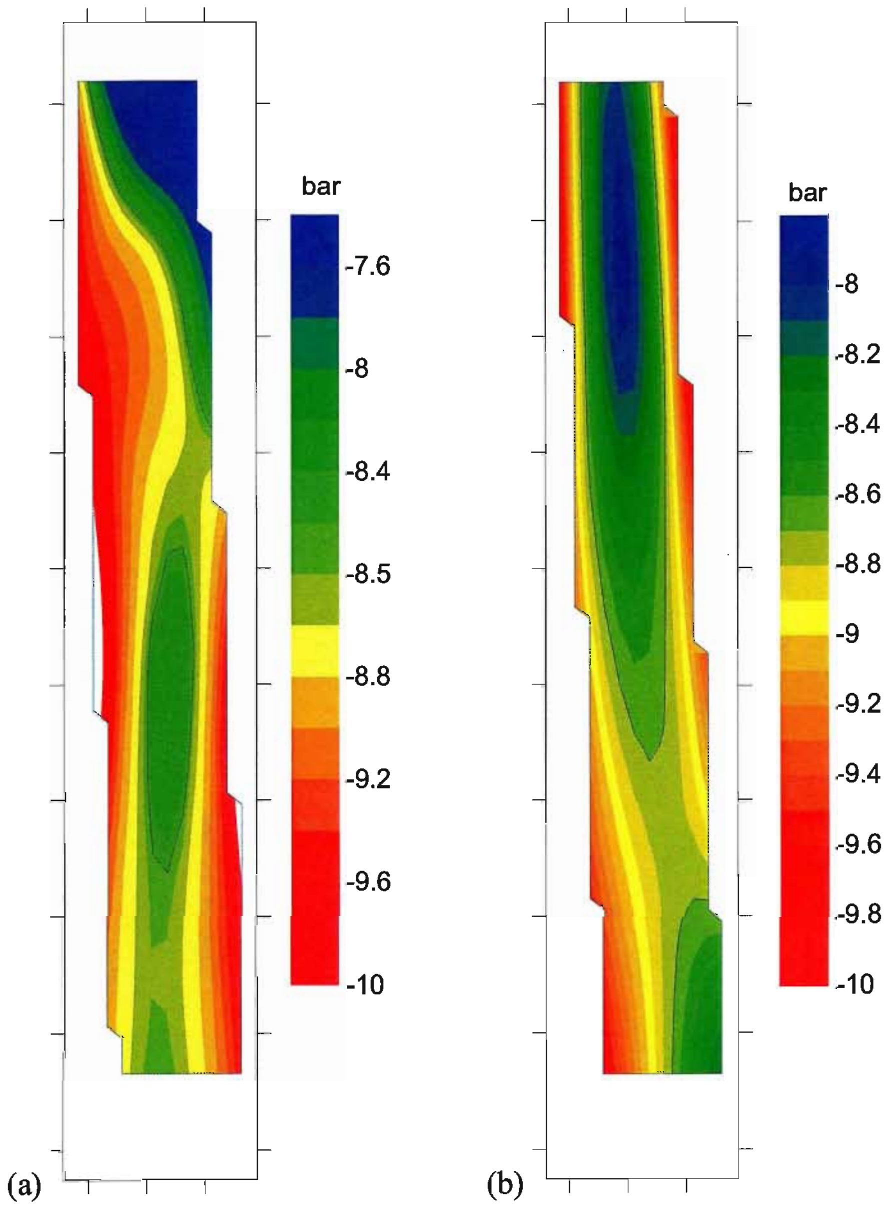
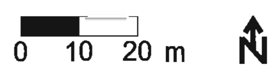


Figure 3-5: Black Paw. Mean Ψ (bar) in a Pinot noir vineyard, St. Davids, ON; (a) 2008 and (b) 2009. Note that the range of values was not the same in both years, and a different value scale was used. The dark lines represent the division between high and low water status zones.



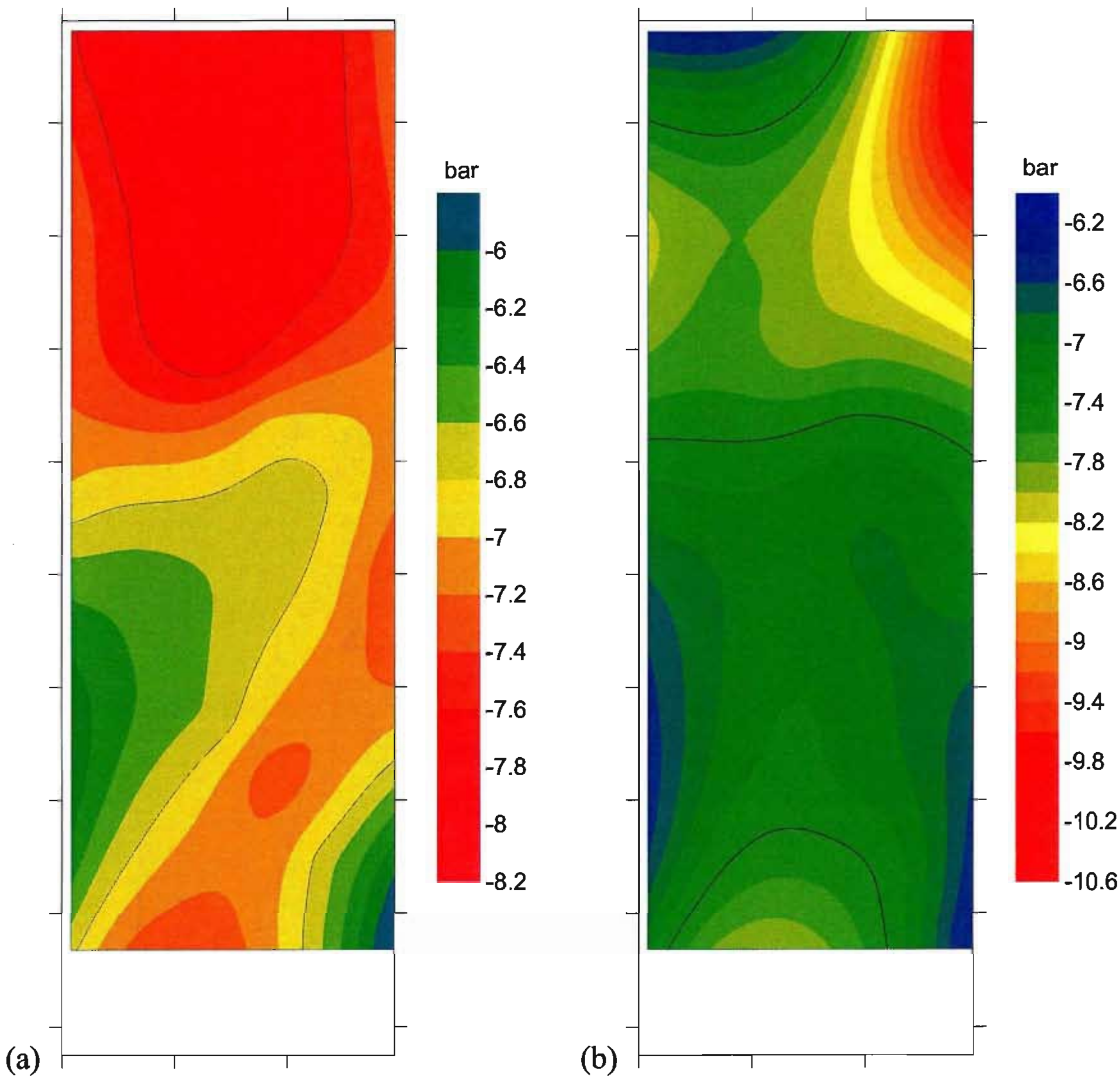


Figure 3-6: Lowrey's. Mean Ψ (bar) in a Pinot noir vineyard, St. Davids, ON; (a) 2008 and (b) 2009. Note that the range of values was not the same in both years, and a different value scale was used. The dark lines represent the division between high, medium & low water status in 2008, & high and low water status zones in 2009.

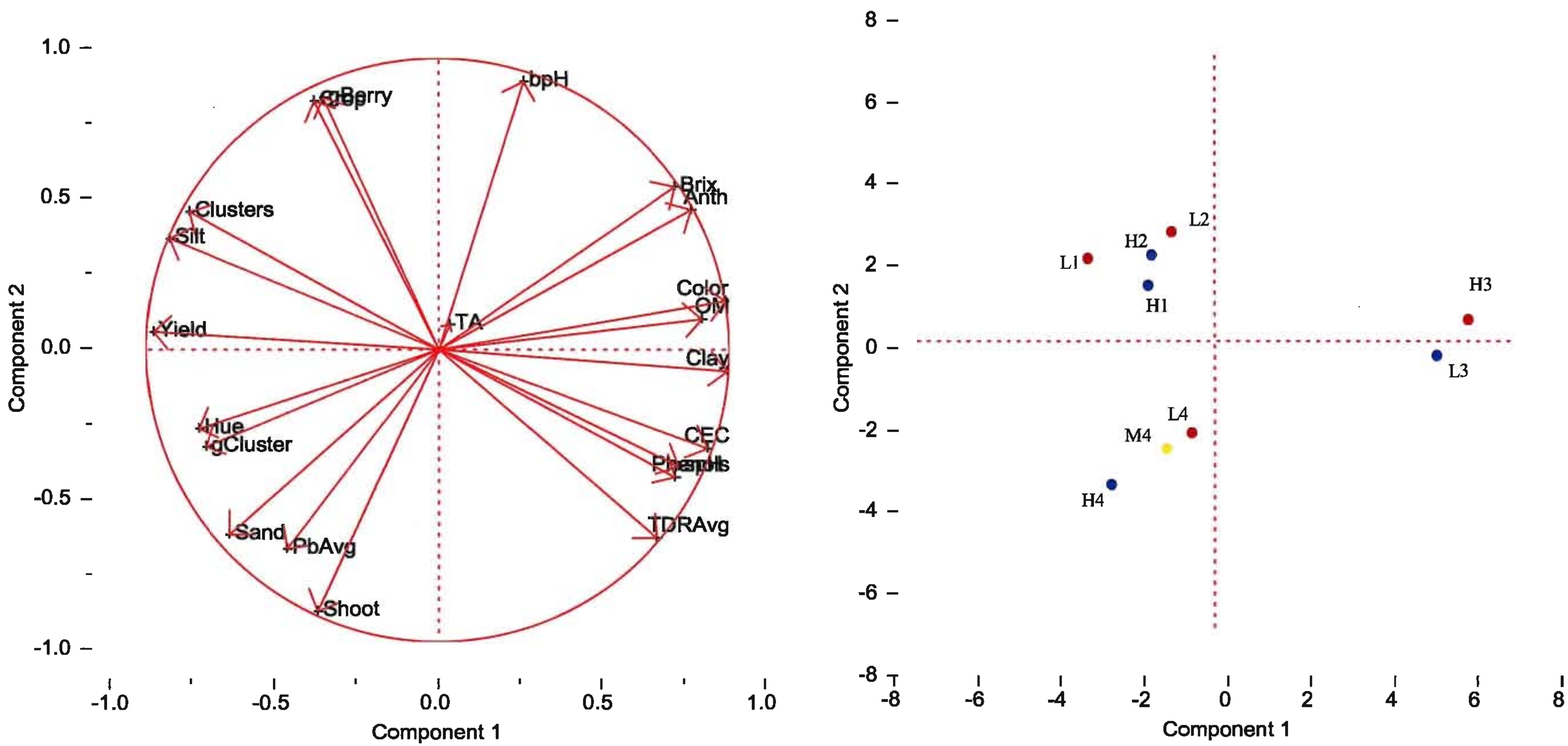


Figure 3-7: PCA of 2008 yield components, grape composition and vineyard variables in four Pinot noir vineyards, St. Davids, ON. Principal component 1 (PC1) (57.86%) and PC2 (28.60%) explain 86.46% of the variation in the data. Left: variable loadings of variables on PC1 & PC2 (Yield – yield per vine (kg), Clusters – number of clusters per vine, gCluster – g/cluster, gBerry – g/berry, bpH – berry pH, Brix – berry Brix, TA – titratable acidity (g/L), Shoot – weight of cane prunings (kg), Crop – crop load, Anth – total anthocyanins (mg/L), Colour (au), Hue (au), Phenols – total phenolics (mg/L), TDRAvg – mean soil moisture (%), PBAvg – mean Ψ (bar), Clay - % clay, Silt - % silt, Sand - % sand, OM - % organic matter, CEC – cation exchange capacity (meq/100g), spH – soil pH). Right: observation loadings (Blue – high water status, Red – low water status, Yellow – medium water status; 1 – Red Paw 1, 2 – Red Paw 2, 3 – Black Paw, 4 – Lowrey's).

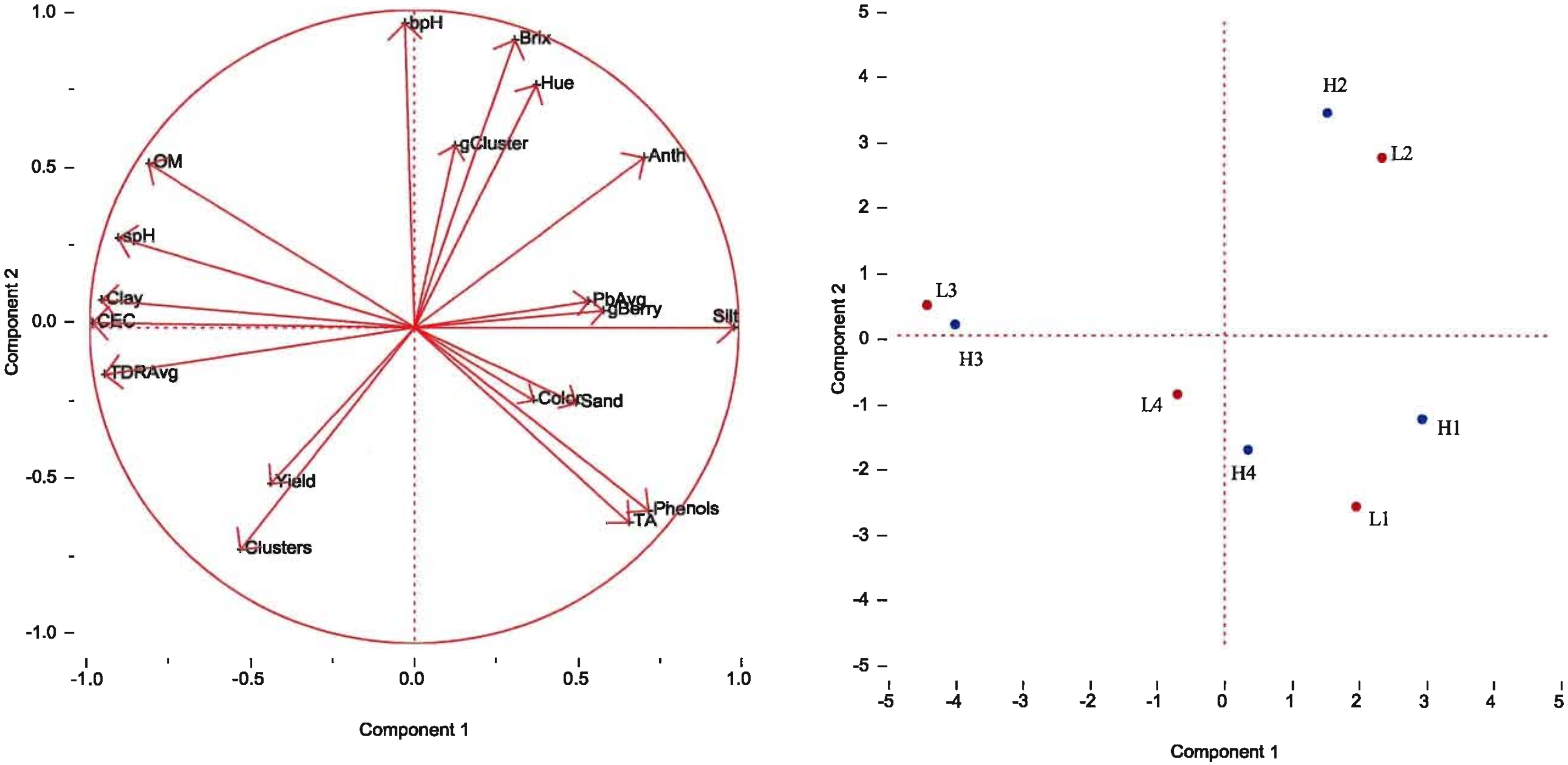


Figure 3-8: PCA of 2009 yield components, grape composition and vineyard variables in four Pinot noir vineyards, St. Davids, ON. Principal component 1 (PC1) (44.68%) and PC2 (25.65%) explain 70.34% of the variation in the data. Left: variable loadings of variables on PC1 & PC2 (Yield – yield per vine (kg), Clusters – number of clusters per vine, gCluster – g/cluster, gBerry – g/berry, bpH – berry pH, Brix – berry Brix, TA – titratable acidity (g/L), Anth – total anthocyanins (mg/L), Colour (au), Hue (au), Phenols – total phenolics (mg/L), TDRAvg – mean soil moisture, PBAvg – mean Ψ (bar), Clay - % clay, Silt - % silt, Sand - % sand, OM - % organic matter, CEC – cation exchange capacity (meq/100g), spH – soil pH). Right: observation loadings (Blue – high water status, Red – low water status; 1 – Red Paw 1, 2 – Red Paw 2, 3 – Black Paw, 4 – Lowrey's).

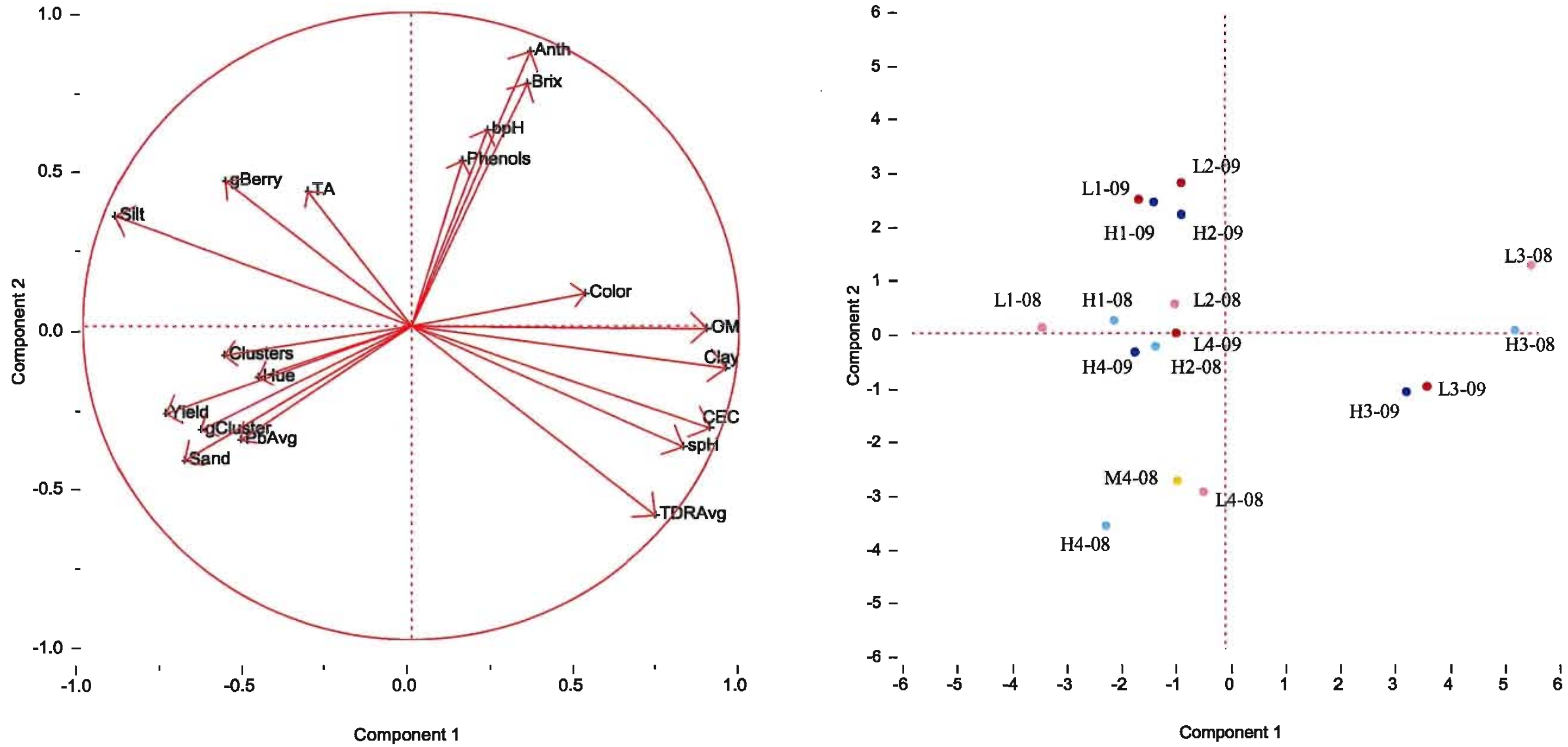


Figure 3-9: PCA of 2008 and 2009 yield components, grape composition and vineyard variables in four Pinot noir vineyards, St. Davids, ON. Principal component 1 (PC1) (41.61%) and PC2 (19.66%) explain 61.27% of the variation in the data. Left: variable loadings of variables on PC1 & PC2 (Yield – yield per vine (kg), Clusters – number of clusters per vine, gCluster – g/cluster, gBerry – g/berry, bpH – berry pH, Brix – berry Brix, TA – titratable acidity, Anth – total anthocyanins (mg/L), Colour (au), Hue (au), Phenols – total phenolics (mg/L), TDRAvg – mean soil moisture (%), PBAvg – mean Ψ (bar), Clay - % clay, Silt - % silt, Sand - % sand, OM - % organic matter, CEC – cation exchange capacity (meq/100g), spH – soil pH). Right: observation loadings (dark blue – high water status 2009; light blue – high water status 2008; dark red – low water status 2009; pink – low water status 2008; yellow – medium water status).

4.0 Influence of Water Status on Sensory Profiles of Niagara, Ontario Pinot noir

4.1 Introduction

The effect of water stress on grapevine and fruit development has been extensively documented. The physiological impact of water stress on grapevines is largely agreed upon, but the mechanisms and effect on grape composition is not.

Generally, when water loss from transpiration exceeds the available water, governed by solar radiation, temperature and relative humidity, physiological stress occurs (Hardie & Considine 1976). Water stress may result in reduced fruit set (Hardie & Considine 1976), reduced yield (Hardie & Considine 1976), increased sugar accumulation and break-down of malic acid (Koundouras et al. 2006), increased concentrations of anthocyanins and total grape phenolics (Koundouras et al. 2006; Sivilotti et al. 2005), and generally desirable grape composition and wine sensory attributes (Reynolds et al. 2007b; Matthews et al. 1990).

In terms of sensory attributes, there is a relationship between the presence of moderate water stress and hedonic liking of wines made from the Agiorgitiko grape (Koundouras et al. 2006). Conversely, Reynolds et al. (2007) found that irrigation used to decrease the level of water stress increased the intensity of desirable sensory attributes in Chardonnay.

Wines that were made as a part of a study on the effect of vine vigour on grape composition were subjected to sensory analysis by Cortell et al. (2008). The differences between the wines were in astringency, bitterness, sour and sweet tastes, earthy and chemical flavours, and heat. The low vigour zone wines tended to have the highest intensity of perceived astringency, and this was related to the actual tannin concentration in the fruit and skins. In a stepwise regression, the vine vigour was more important than vineyard site to explain the differences in the wines for the significantly different attributes, especially astringency, sour, chemical and bitterness (Cortell et al. 2008). There is a relationship between the vigour of the vine, fruit shading and temperature, and the sensory properties of the wine.

Phenolic compounds add to the overall sensory profile of a wine, through direct effects on astringency and bitterness (Noble 1994), and through interactive effects with other basic tastes. Increasing sweetness and polysaccharides has been shown to decrease the perception of astringency caused by grapeseed tannins in solution (Smith et al. 1996). The timing of water stress and vegetative growth has the potential to influence the sensory attributes of a wine through controlled irrigation by affecting the balance of vegetative growth, fruit shading, and accumulation of flavour precursors in the grapes (Reynolds et al. 2007).

This study aimed to investigate the relationship between within vineyard differences in water status and wine sensory attributes. It was hypothesized that there would be a relationship between the sensory attributes of Niagara, Ontario Pinot noir and the water status of the vineyard.

4.2 Materials & Methods

Selection of vineyard sites, sentinel vine sampling strategy, observation of leaf water potential (Ψ), harvest and winemaking were described in detail in an earlier paper in this series (Chapter 3.2).

4.2.1 Multidimensional Sorting Task

A multidimensional sorting (MDS) task was carried out on the 2008 wines as a means of rapidly performing a difference test on all wine samples. This was performed in January of 2009. The Black Paw vines were left out of the task, as there was only a single fermentation from each water status zone, and the wines were faulted such that sensory analysis on them would be unpleasant for panelists.

There were 17 untrained panelists, consisting of volunteers from students and staff of CCOVI (10 male and seven female). Following the procedure of Tang & Heymann (2002), panelists were given no training with the wines. Panelists were presented with three flights of wines in ISO tasting glasses under red ambient lighting to mask colour differences in the wines. Glasses were coded with three digit numbers, and covered with plastic lids to prevent the loss of aromatic intensity. There were two flights of six wines each (Red Paw vineyards), and one flight of nine wines (Lowrey's vineyard). Each flight consisted of all the wines from a single vineyard site. The wines were presented in a randomized incomplete block design.

Panelists were asked to taste the wines, and place them into groups based on basic tastes, flavours and/or mouthfeel. The choice of common or differentiating attributes was entirely up to the individual panelists. They were given the restriction that there must be at least two groups, and each group must contain at least one wine. For each group, they were asked to write the descriptors of the common characteristics of the wines in that group, in order to focus their thoughts. Each flight was separated by a break of at least 15 minutes. Water for rinsing between wines was provided, as well as crackers for clearing the palette between wines and flights.

4.2.2 Descriptive Analysis

A panel of 10 volunteers from staff and students at CCOVI (five male, five female) were gathered in March 2009 to describe the 2008 wines from the Red Paw vineyards and from the Lowrey's vineyard. Black Paw wines were left out of the analysis because they were faulted such that they would be unpleasant for panelists. At the first session panelists were presented with four wines: a Red Paw wine made from excess fruit from sentinel vines in Red Paw 1 and 2 across water status zones, a blended Lowrey's wine made from excess fruit from all three water status zones, and two wines from individual water status zones. They were asked to smell and taste each of the wines, and independently generate descriptors for the wines. Collectively, this list of descriptors was modified over six training sessions during which the panelists were exposed to all of the wines, until all panelists agreed on the descriptors and their definitions.

The final descriptors were: tart fruit aroma (sour cherry, cranberry), sweet fruit aroma (red cherry, strawberry, raspberry), sweet aroma (chocolate/vanilla, butterscotch), pepper spice aroma (black & white pepper), baking spice aroma (clove, anise), tobacco aroma, vegetal aroma (canned beans, asparagus and mushrooms), other aroma (reductive aromas, faults to be identified by written comments), red fruit flavour, spices flavour, vegetal flavour, earthy flavour, acidity, bitterness and astringency.

Aroma standards were made for these descriptors, according to the preparations in Table 4-1. Standards were made using recipes published by Cortell et al. (2008) and Reynolds et al. (1996) as starting point, adjusted with local ingredients and modified for intensity as agreed upon by the panelists during training sessions. These standards were made available for panelists at all training and data collection sessions. The panelists met for a total of six training sessions in which they were exposed to each of the wines at least once. They were trained in the use of line scales for describing the intensity of the attributes relative to the other wines.

Data collection was carried out over five sessions on 15-point unstructured line scales using Compusense software (Version 5.0; Compusense, Guelph, ON). Data collection sessions were carried out in individual booths, with 30mL of the wines presented in ISO glasses under red ambient light to mask colour differences. In each of five sessions, eight wines were evaluated in two flights. The total collection of wines was randomized over the data collection period such that during each session, all panelists were exposed to the same randomly selected eight wines, with the order randomized among panelists. Each wine was presented in two replicates over the course of the data collection period. There was a forced 3 minute break between wines, and a 10 minute break between flights. Water and unsalted crackers were provided for panelists between wines. All wines were expectorated.

4.2.3 Statistical Methods

The results of the sorting task were analyzed using an MDS model. A single similarity matrix for each of the flights of wines was created by summing the number of times each pair of wines was placed into the same group by the 17 panelists. This matrix was submitted to the PROC MDS in SAS using an unweighted Euclidean model (Version 9.1.3; SAS Institute, Cary, NC). The dimensions of interest were chosen using the stress or "badness of fit" and the overall squared correlation (RSQ) indices. These dimensions were submitted to cluster analysis in JMP (Version 8.0.1; SAS Institute, Cary, NC) using centroid hierarchal clustering to identify which wines were more similar to one-another as per the analysis of Tang & Heymann (2002). Cluster analysis takes each point starting as individuals, and through a step-wise process puts neighbouring points into clusters until a set endpoint is reached or until all points are in a single cluster. Where there is a sudden increase in the distance between clusters, a subjective cutting point between clusters can be inserted.

Attribute intensity scores for the wines of each vineyard site were subjected to a three-factor ANOVA using the PROC GLM in SAS. Judge*wine, judge*rep, and wine*rep interaction factors were included to measure panel agreement, judge reliability and presentation errors respectively. Mean separation was performed for attributes that were significantly different between wines using the least significant different (LSD) test with $\alpha=0.05$. A principal component analysis (PCA) was performed on mean attribute intensity scores for all wines using JMP. These methods are common for analysis of DA data as described by Reynolds et al. (1996), Nurgel et al. (2004), Cortell et al. (2008), Guindard & Cliff (1987) and many others.

4.3 Results

4.3.1 Multidimensional Sorting

The fit of the MDS model was evaluated using the optimization of the stress and RSQ. For each flight of wines, three dimensions were chosen to appropriately fit the data with a large RSQ (approaching or equal to 1) and a small stress value. For Red Paw 1, RSQ was 1 and the stress value was $5.93(10^{-10})$; for Red Paw 2, RSQ was 1 and the stress value was $4.01(10^{-7})$; and for Lowrey's, RSQ was 0.98 and the stress value was 0.054 at three dimensions. Increasing the number of dimensions did not appreciably decrease the stress and increase RSQ indices, so three dimensions were chosen as an acceptable representation of the data.

The groupings resulting from the cluster analysis on all three dimensions are shown in Figure 4-1 through Figure 4-3. For Red Paw 1, cluster analysis suggested a four-cluster solution. High water status fermentation replicates two and three, along with low water status replicate two were similar, whereas low water status replicates one and three and high water status replicate one were different from the other wines. For Red Paw 2 a three-cluster solution was appropriate. High water status replicate one and low water status replicate one were different from the other wines; while high water status replicates two and three and low water status replicates two and three were similar. For Lowrey's, a four-cluster solution was appropriate. High water status replicate one was different from the other wines; low water status replicate one and medium water status one were similar, low water status replicate two and medium water status replicate three were similar, and low water status replicate three, medium water status replicate two, and high water status replicates two and three were all similar.

The results of the sorting task demonstrate that there were sensorial differences between fermentation replicates that were too large to separate from differences between water status zones. Fermentation replicates from within water status zones could not be considered to be the same for descriptive analysis, and all fermentation replicates were required to be included as individual samples.

4.3.2 Descriptive Analysis

The F-values resulting from the three-factor ANOVA on results of the DA are seen in the supplemental materials. There was a significant difference between judges for every attribute in each vineyard. Significant differences between wines were seen in sweet aroma and bitterness in Red Paw 1 (Table 7-13), sweet fruit aroma and vegetal aroma in Red Paw 2 (Table 7-14), and sweet aroma, vegetal aroma and spices flavour in Lowrey's wines (Table 7-15). The F-value output from a single-factor ANOVA by water status on each vineyard is shown in Table 7-16. There were no significant differences between water status zones within each vineyard site.

For Red Paw 1 wines, there was a significant judge*wine interaction for sweet fruit aroma, bitterness, and astringency. There was a significant judge*rep interaction for baking spice aroma and astringency (Table 7-13). For Red Paw 2 wines, there was a significant difference in replications for vegetal aroma, a significant judge*rep interaction for baking spice aroma, vegetal aroma, red fruit flavour, and spices flavour (Table 7-14). For Lowrey's wines, there was a significant difference in repetitions for baking spice aroma, vegetal aroma, and acidity. There was a significant judge*wine interaction for sweet fruit aroma, baking spice aroma, vegetal flavour, acidity, and bitterness, and significant judge*rep interaction for vegetal flavour and acidity (Table 7-15).

Means of aroma attribute intensities, and significant differences are shown in Table 7-17 for individual wines from the three vineyards in the supplemental materials. Means of flavour, taste and mouthfeel attribute intensities, and significant differences are shown in Table 7-18 for all wines from the three vineyards. There were wines from each vineyard site with significant differences between individual wines for specific attributes including sweet fruit aroma in Red Paw 2 and Lowrey's vineyards (Table 7-17), but these differences were not consistent with water status within each vineyard.

Means of DA attribute intensities for wines grouped by vineyard site are shown in Table 4-2. There was a difference between sites for pepper spice aroma and vegetal aroma. Means of DA attribute intensities for wines grouped by water status zone within each vineyard are shown in Table 4-3. There was a difference between the water zones for sweet aroma in wines from the Lowrey's vineyard. Pearson correlation coefficients between DA attribute intensities for all wines are shown in supplemental materials (Table 7-23). Cells are colour-coded to indicate significance level such that yellow, blue and red indicate a p-value $\leq$0.0001, 0.01 and 0.05, respectively. Tart fruit and sweet fruit aromas were well correlated with red fruit flavour ($r=0.73$, $r=0.64$; $p\leq0.0001$). Baking spice and pepper spice aroma were well correlated with spices flavour ($r=0.67$, $r=0.68$; $p\leq0.0001$). The strongest correlations were between tart fruit aroma and red fruit flavour, sweet fruit aroma and sweet aroma

($r=0.73$, $p \leq 0.0001$), and between vegetal aroma and vegetal flavour ($r=0.70$; $p \leq 0.0001$). Acidity and astringency had the fewest strong correlations to any other attributes; however, acidity was marginally correlated with bitterness ($r=0.48$; $p \leq 0.0001$) and astringency ($r=0.55$; $p \leq 0.0001$). Bitterness was also marginally correlated with astringency ($r=0.56$; $p \leq 0.0001$).

PCA of all DA attribute intensities for 2008 wines from all three vineyards as well as observation loadings are shown in Figure 4-4. The first two principal components explained 50.73% of the variation in the data. PC1 explains 33.82% and PC2 explains 17.35%, PC3, PC4 and PC5 explain an additional 10.65%, 9.08% and 6.71% respectively, but they were not shown as they do not contribute any visual clarity to the results.

The wines from water status zones within each vineyard tended to cluster together, although not with clear clustering apart from the other wines. From the Lowrey's vineyard, the high and medium water status wines are clustered separately from the low water status wines. The Red Paw 1 high water status wines are reasonably clustered, while the Red Paw 2 wines are not clearly clustered at all.

As was seen in the Pearson correlation coefficients, similarly named aroma and flavour descriptors tend to be highly correlated, and loaded along the same axes. The Lowrey's high and medium water status wines are loaded with vegetal attributes. Red Paw 1, low water status wines are better described by spice attributes.

4.4 Discussion

4.4.1 Multidimensional Sorting

The MDS revealed that the replicate fermentations resulted in unique wines. Some of the wines were more similar based on the groupings created by panelists, but these groupings were not consistent with water status zones. As grapes were bulked by water status zone from across vineyard sites, random fermentation effects were likely responsible for differences between wines greater than any differences that may have been present as a result of water status.

Parr et al. (2007) found that MDS was a strong predictor of varietal typicity in wines. The results of a sorting task of Sauvignon blanc wines from France and New Zealand indicated that the sorting task was a strong predictor of the results of a descriptive task performed later.

In this study, Red Paw 1 wines H2 and H3 from the high water status zone were clustered (Figure 4-1), and in the DA task, these two wines were in the same grouping for sweet aroma (Table 7-17). Similarly in Red Paw 2, wines H2 and H3 were clustered (Figure 4-2), and were not significantly different from one another in sweet fruit and vegetal aromas. The same trend was seen in the Lowrey's wines, where wines that were clustered (Figure 4-3) were not significantly different in mean attribute intensity.

The MDS task was a relatively quick and effective means of performing a difference test, identifying that the differences between water status zones within each vineyard site were not great enough to mask fermentation effects. Small-scale fermentations for research have been criticized for producing faulted wines, and lacking standardized protocols; however, Sampaio et al. (2007) used standardized 4-L fermentation vessels for research-scale fermentation and found that the results were comparable to the commercial scale wines made from grapes from the same vineyard. The winemaking in this study was standardized as much as possible through the bulking of fruit, and consistent handling of the musts, fermenting and final wines through water status zones. It is likely that there were simply not large differences between the water status zones to begin with, and random fermentation effects dominated the differences between wines.

4.4.2 DA Panel Performance

The descriptors used by the DA panelists were similar to those used by other panelists describing Pinot noir (Guinard & Cliff 1987; Reynolds et al. 1996; Cortell et al. 2008). The wines were in general, typical of Pinot noir. The "other" attribute was included as a dumping ground for panelists to describe reductive aromas, or other faults, in the wines. Comments made by panelists who used this descriptor were describing rubber boot, cabbage, or hydrogen sulfide.

In Red Paw 1 wines, Low-3 was identified repeatedly as reductive, and in the MDS task, it did not cluster with any other wine. Similarly, from Red Paw 2, High-1 and Low-1 were repeatedly identified as reductive, and in the sorting task, these two wines did not cluster with the others. From the Lowrey's wines, High-1, High-3, Medium-2 and Medium-3 were described as reductive, but in this case they did not cluster apart from the other wines.

The significant difference between judges for every attribute indicates that the judges were not in agreement in terms of attribute intensity. This is not entirely unexpected, and is a result of panelists using the range of available values on the line scale differently. The judge*wine interaction is an indicator of panel agreement, where the null hypothesis is that the judges tend to score the intensities of the attributes of wines in the same way. This interaction was significant for bitterness in both Red Paw 1 and Lowrey's, astringency in Red Paw 1 wines, and acidity in Lowrey's wines. This indicated that the judges were not in agreement in how to rate these tastes and mouthfeel. It can be difficult to identify these sensations in the complex wine matrix, and differences between individuals, especially in bitterness perception, mean that some panel disagreement is not unusual (King et al. 1995; Pickering et al. 2003).

There were significant judge*rep interactions for baking spice aroma and astringency for Red Paw 1, baking spice aroma, vegetal aroma, red fruit flavour and spices flavour for Red Paw 2, and vegetal flavour and acidity for Lowrey's wines. The null hypothesis of this interaction is that the judges rate the attributes the same way when presented the same wine. The significant interactions listed indicate that the judges were not reliable in rating these attributes. The repeated mention of baking spice and vegetal indicate that further discussion during the training sessions may have been merited in order to increase the judges' familiarity with these descriptors. The overall number of significant interactions was not large, and overall the depth of panel training appears to have been sufficient.

4.4.3 Effect of Water Status & Vineyard Location

There were only two attributes that were significantly different between wines from Red Paw 1, two attributes from Red Paw 2 wines, and three attributes from Lowrey's wines. Averaging all wines from the water status zones in each vineyard, there was a difference between Lowrey's water status zones in sweet aroma; otherwise there were no differences between attribute intensities for any of the vineyard sites (Table 7-16). In the case of Lowrey's, the low water status zone had the highest intensity of sweet aroma, and the high water status zone had the lowest intensity. The medium water status zone was not different from the other two.

Taking the mean of all wines from each vineyard, there were only two attributes that were different between vineyards: pepper spice and vegetal aroma (Table 4-2). These same two attributes were identified as areas where judges did not perform as reliably in rating the intensity. Red Paw 1 had the highest intensity for pepper spice aroma, and Lowrey's had the lowest, while Red Paw 2 was not different from either. Lowrey's wines had the highest vegetal aroma intensity, Red Paw 1 had the lowest, and Red Paw 2 was not different from either. The relationship between the aroma and flavour descriptors of the same name was not surprising. As seen through Pearson's correlation coefficients (Table 7-23), and the PCA (Figure 4-4), these attributes tended to be well correlated. The judges were rating the same attribute in aroma and flavour. Based on observation loadings, the results are similar to those of the sorting task. The wines did not cluster by water status or vineyard, and it is difficult to draw any conclusions as to the effect of water status on the sensory attributes of the wines.

Generally, the Lowrey's vineyard wines were described by vegetal aroma and flavour. Red Paw 1 wines were described by tart fruit aroma, baking spice and pepper spice aroma, and spice flavour. Red Paw 2 wines were the least clustered, and not clearly described by any of the attributes.

Cortell et al. (2008) found that vigour was related to the perceived astringency of Pinot noir wines, and Reynolds et al. (1996) found that canopies with high shoot density resulted in Pinot noir with more vegetal character, and less fruit character. The previously described relationship between water status and vine size (Section 3.3) revealed that there was some relationship between vine size and water status in 2008, but it was not a strong statistical ($r=0.46$; $p\leq 0.01$) or spatial relation in all four vineyard sites. The vine vigour may have been playing a role in the sensory profile of the wines, but was not aligned with the water status zones used to delineate winemaking zones.

4.5 Conclusions

There were random fermentation effects in the winemaking that led to differences between the wines from the water status zones of each vineyard. The multidimensional sorting task revealed that the replicate fermentations resulted in unique wines. The strength of the MDS was verified by the results of the DA task. The winemaking in this study was standardized by bulking the fruit, and consistent handling of the musts, fermenting and final wines through water status zones. There were not large enough differences between the water status zones to begin with so fermentation effects were pronounced.

To understand the true effect of a site's terroir, the unique sensory properties of a wine from that site must be understood. There were only two attributes that were different between all wines from Red Paw 1, two attributes from Red Paw 2 wines, and three attributes from Lowrey's wines. The Lowrey's vineyard was described by vegetal aroma and flavour, the Red Paw 1 vineyard was described by tart fruit, and spice aromas and flavours, and the Red Paw 2 vineyard by a combination of fruit and spice aromas and flavours. Within the sites, there were no differences between the sensory characteristics of wines grouped by water status, and random winemaking effects were responsible for most of the difference between the wines. Taking the mean of all wines from each vineyard, there were only two attributes that were different between vineyards: pepper spice and vegetal. These same two attributes were identified as areas where judges did not perform as reliably in rating the intensity.

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Table 4-1: Descriptive analysis sensory attributes, definitions as described by panelists, and corresponding reference standards for Ontario Pinot noir wines. All standards were added to 100 mL of base wine (2008 Pinot noir from the Red Paw vineyards) unless otherwise noted.

Attribute	Definition	Reference standard
Tart fruit aroma	Aroma of unripe or sour red fruits (sour cherry, cranberry)	9 sour cherries + 50mL syrup (S&F Foods) 30mL cranberry cocktail (Irresistibles)
Sweet fruit aroma	Aroma of ripe red fruits (strawberry, raspberry, red cherry)	3 strawberries (frozen, Green Giant) 5 raspberries (frozen, Green Giant), 2 Tbs cherry jam (President's Choice)
sweet aroma	Aroma of dark chocolate, vanilla, butterscotch	14g unsweetened chocolate (Baker's) 5 drops pure vanilla extract (McCormick), 2 Tbs butterscotch spread (Smuckers)
Pepper spice aroma	Aroma of black and/or white pepper	1 drizzle cracked black pepper (McCormick) 1 drizzle ground white pepper (No Name)
Baking spice aroma	Aroma of clove and/or anise	1 drizzle ground cloves (McCormick), 3 drizzles anise seeds (McCormick)
Tobacco aroma	Aroma of dried tobacco	3 large pinches cigarette tobacco (Player's)
Vegetal aroma	Aroma of canned vegetables (beans, asparagus, mushrooms)	3 pieces cut green beans (DelMonte) 3 pieces asparagus cuts (No Name) 5 mushrooms, chopped (No Name)
Other aroma	Reductive aromas, or faults	No reference standard
Red fruit flavour	Flavour of cherry, cranberry, strawberry, raspberry	No reference standard
Spices flavour	Flavour of pepper, baking spices	No reference standard
Vegetal flavour	Flavour of canned vegetables	No reference standard
Earthy flavour	Flavour of soil, beetroot	No reference standard
Acidity	Sour taste	1.5 g/L tartaric acid in water
Bittemess	Bitter taste	0.3 g/L caffeine in water
Astringency	Drying mouthfeel	0.3 g/L aluminum sulfate in water

Table 4-2: Means of descriptive analysis attributes by vineyard; 2008 Pinot noir wines from Red Paw 1, Red Paw 2 and Lowrey's vineyards, St. Davids, ON.

Vineyard	Tart Fruit Aroma	Sweet Fruit Aroma	sweet Aroma	Pepper Spice Aroma	Baking Spice Aroma	Tobacco Aroma	Vegetal Aroma
Red Paw 1	5.69	4.93	2.95	3.69a	2.89	3.20	2.19b
Red Paw 2	5.50	4.55	2.57	3.34ab	2.64	3.28	2.84ab
Lowrey's	5.34	4.71	2.47	2.75b	2.73	3.12	3.33a
Significance[d]	ns	ns	ns	*	ns	ns	*
Vineyard	**Red Fruit Flavour**	**Spices Flavour**	**Vegetal Flavour**	**Earthy Flavour**	**Acidity**	**Bitterness**	**Astringency**
Red Paw 1	6.41	4.50	2.27	4.08	4.38	1.81	3.22
Red Paw 2	6.31	4.14	2.50	4.13	4.55	1.86	3.26
Lowrey's	6.53	3.61	2.99	4.19	4.44	1.73	3.51
Significance	ns	ns	ns	ns	ns	ns	ns

[d] Mean separation at a=0.05 using the LSD test; *, **, ***, ns: Significant at p≤ 0.05, 0.01, 0.001, not significant, respectively.

Table 4-3: Means of descriptive analysis attributes by water status zone; 2008 Pinot noir wines from Red Paw 1and 2 and Lowrey's vineyards, St. Davids, ON.

Water Status Zone	Tart Fruit Aroma	Sweet Fruit Aroma	sweet Aroma	Pepper Spice Aroma	Baking Spice Aroma	Tobacco Aroma	Vegetal Aroma
Red Paw 1							
Low	5.77	4.94	2.89	3.79	2.87	3.05	2.24
High	5.62	4.91	3.02	3.58	2.92	3.35	2.13
Significance[d]	ns	ns	ns	ns	ns	ns	ns
Red Paw 2							
Low	5.35	4.58	2.53	3.33	2.52	3.32	2.67
High	5.64	4.52	2.62	3.34	2.76	3.24	3.00
Significance	ns	ns	ns	ns	ns	ns	ns
Lowrey's							
Low	5.71	5.30	3.17a	2.55	2.98	3.40	2.52
Medium	5.15	4.51	2.37ab	2.89	2.51	3.02	3.51
High	5.15	4.32	1.84b	2.80	2.71	2.95	3.96
Significance	ns	ns	*	ns	ns	ns	ns

Water Status Zone	Red Fruit Flavour	Spices Flavour	Vegetal Flavour	Earthy Flavour	Acidity	Bitterness	Astringency
Red Paw 1							
Low	6.30	4.45	2.09	3.81	4.44	1.64	3.08
High	6.52	4.56	2.46	4.34	4.32	1.99	3.36
Significance	ns	ns	ns	ns	ns	ns	ns
Red Paw 2							
Low	6.26	4.32	2.23	4.21	4.69	1.73	3.32
High	6.36	3.97	2.77	4.04	4.42	1.99	3.19
Significance	ns	ns	ns	ns	ns	ns	ns
Lowrey's							
Low	6.81	3.90	2.51	4.21	4.45	1.85	3.52
Medium	6.42	3.37	3.32	4.09	4.44	1.69	3.50
High	6.37	3.57	3.13	4.26	4.44	1.66	3.52
Significance	ns	ns	ns	ns	ns	ns	ns

[d] Mean separation at a=0.05 using the LSD test; *, **, ***, ns: Significant at p≤ 0.05, 0.01, 0.001, not significant, respectively.

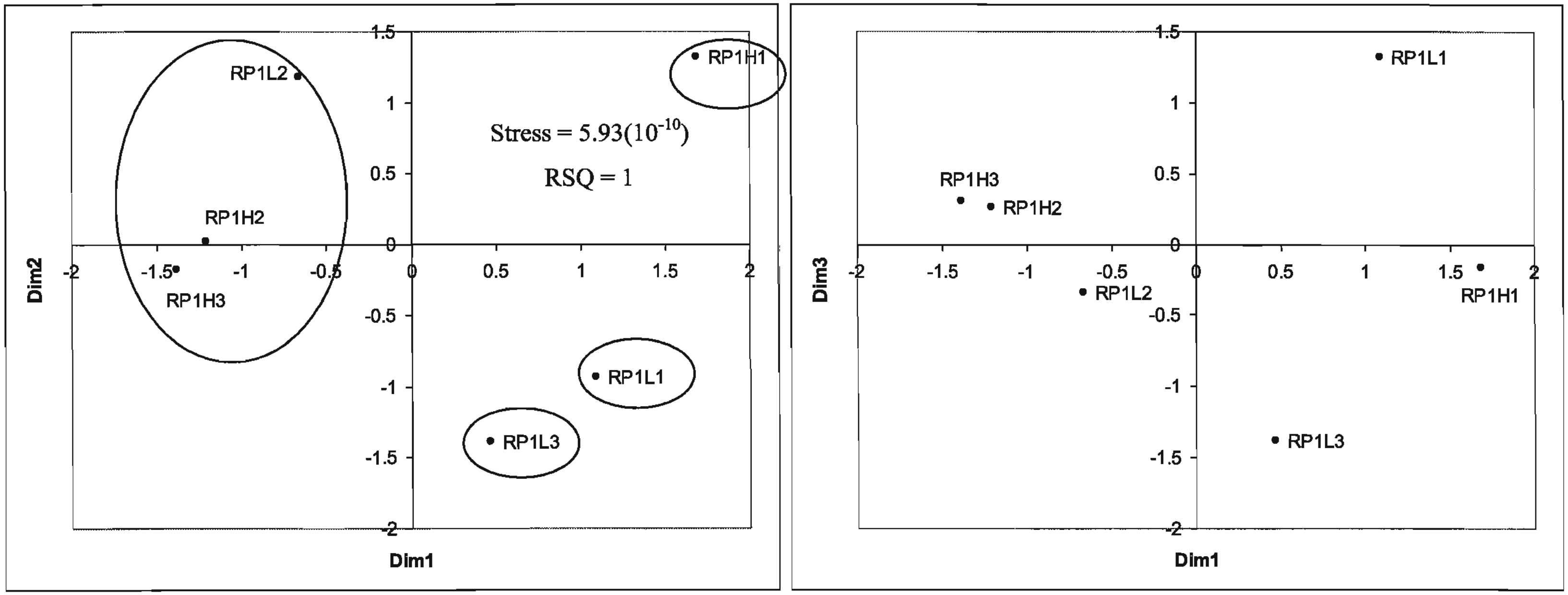

Figure 4-1: Three dimensional stimulus configurations from multidimensional sorting of 2008 Red Paw 1 Pinot noir wines, St. Davids, ON. Circled wines represented a subgroup suggested by cluster analysis. (RP1H1 – Red Paw 1 high water status Rep 1, RP1H2 –high water status Rep 2, RP1H3 – high water status Rep 3, RP1L1 – Red Paw 1 Low water status Rep 1, RP1L2 – Low water status Rep 2, RP1L3 – Low water status Rep 3).

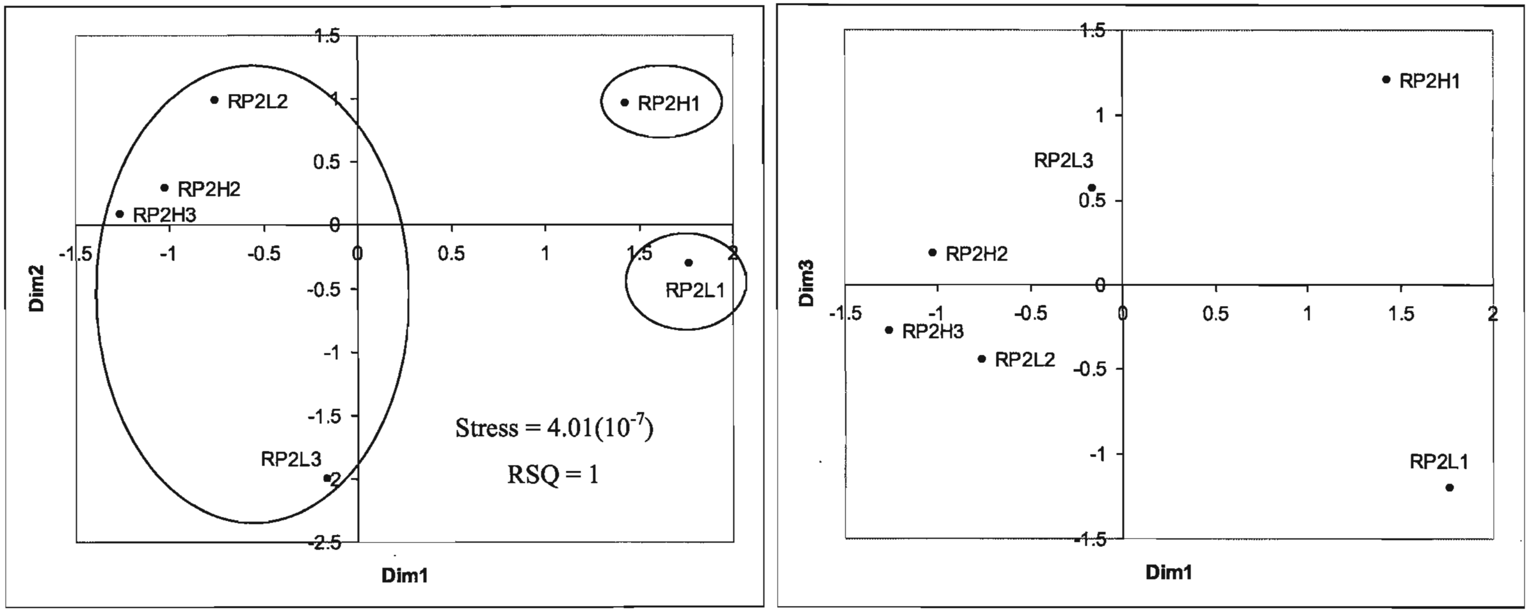

Figure 4-2: Three dimensional stimulus configurations from multidimensional sorting of 2008 Red Paw 2 Pinot noir wines, St. Davids, ON. Circled wines represented a subgroup suggested by cluster analysis. (RP2H1 – Red Paw 2 high water status Rep 1, RP2H2 –high water status Rep 2, RP2H3 – high water status Rep 3, RP2L1 – Red Paw 2 Low water status Rep 1, RP2L2 – Low water status Rep 2, RP2L3 – Low water status Rep 3)

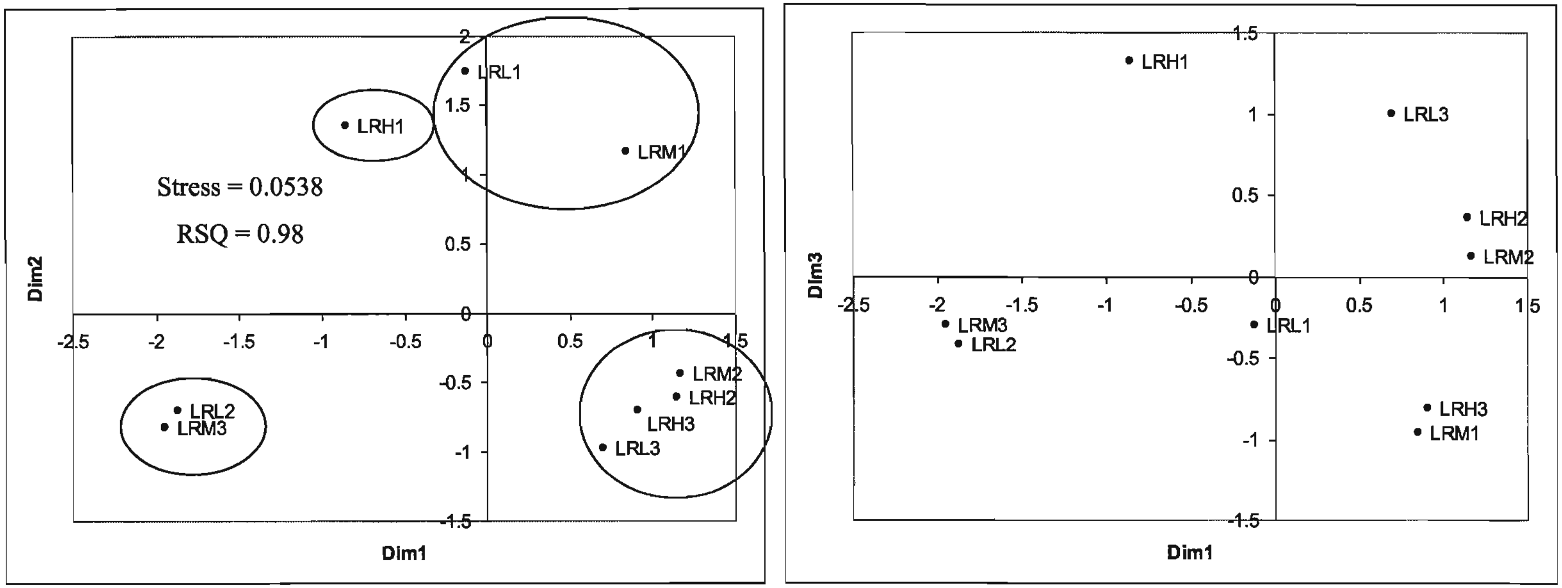

Figure 4-3: Three dimensional stimulus configurations from multidimensional sorting of 2008 Lowrey's Pinot noir wines, St. Davids, ON. Circled wines represented a subgroup suggested by cluster analysis. (LRH1 – Lowrey's high water status Rep 1, LRH2 – high water status Rep 2, LRH3 – high water status Rep 3, LRM1 – Lowrey's medium water status Rep 1, LRM2 – Medium water status Rep 2, LRM3 – Medium water status Rep 3, LRL1 – Lowrey's Low water status Rep 1, LRL2 – Low water status Rep 2, LRL3 – Low water status Rep 3).

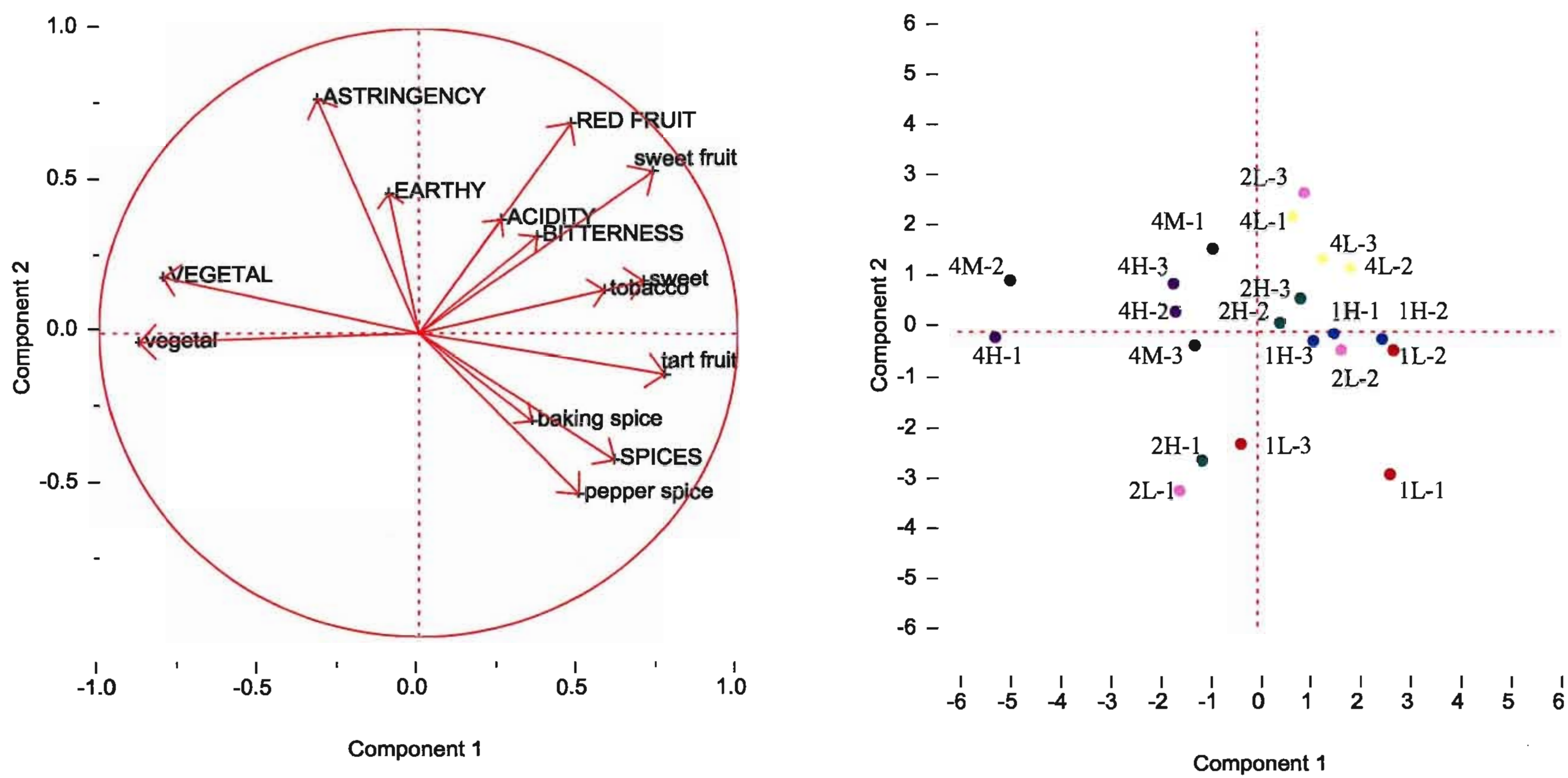

Figure 4-4: PCA of sensory attribute intensity of 2008 Pinot noir wines from three vineyards, St. Davids, ON. Principal component 1 (PC1) (33.82%) and PC2 (17.35%) explain 50.73% of the variation in the data. Left: variable loadings of sensory attributes on PC1 & PC2 (lower case – aroma, upper case – flavour). Right: observation loadings (1H – Red Paw 1, high water status; 1L – Red Paw 1, low water status; 2H – Red Paw 2, high water status; 2L – Red Paw 2, low water status; 4H – Lowrey's, high water status; 4M – Lowrey's, medium water status; 4L – Lowrey's, low water status).

5.0 Using Remote Sensing to Understand Vineyard Variability

5.1 Introduction

In New World winegrowing regions, especially young regions such as the Niagara Peninsula in Ontario, consumers are left to be the judge of a wine's value without a history of its geographic origin. The degree of variation within New World regions cannot be over-estimated; there is a wide range of soil parent material, slope & aspect, distance from the moderating influence of Lake Ontario and associated mesoclimate conditions in the Niagara Peninsula (Shaw 2005). This variation, the relatively young age of the grape-growing industry, and the lack of a strict Appellation of Origin system means that growers and wineries are left to find and adapt new tools for understanding and managing their vineyards.

The basic premise of precision agriculture (PA) is that inputs to farming practices are in response to information gathered with the intent of affecting outputs through an information feedback-loop system (Bramley et al. 2001). When applied to viticulture, there is a focus on understanding the spatial and temporal variability in the production of winegrapes (Hall et al. 2003). Grapegrowers have traditionally accepted the variability within vineyards as inherent to the underlying qualities of the site itself, the terroir. With many years of experience, vineyard areas have been subdivided into individually rated vineyards of higher or lower quality.

The emergence of geomatics software has allowed grape growers to geographically link information from their vineyards into the PA feedback loop, and target inputs to specific regions of their vineyards. PA has been used successfully in grape production in New World regions including California (Johnson et al. 2001), Australia (Hall et al. 2003; Lamb et al. 2004), and Chile (Acevedo-Opazo 2008) as well as Old World regions such as Spain (Zarco-Tejada et al. 2001).

In viticultural applications, optical remote sensing has been used in modeling vegetative growth, and to infer grape composition from those measurements. Johnson et al. (2001) used remotely sensed spectral data to delineate a vineyard site of Chardonnay into small-lot production zones. They found that the vine size was related to the vigour zones, as identified by the airborne image. The vigour zones were also related to vine water status, and grape composition variables. Thus, indirectly, remote sensing was used to predict vineyard status and grape composition, with direct implications for wine quality (Johnson et al. 2001).

The relationship between vegetation indices (VI) and vegetative growth was further explored by Dobrowski et al. (2003). There was a strong, positive correlation between the extracted VI and the pruning weight in two years. Additionally, the relationship established in the first season was able to predict the pruning weights in the second study vintage (Dobrowski et al. 2003).

The ability of remote sensing to be used to directly predict grape composition variables was explored by Lamb et al. (2004). They found that re-sampling the image to a final pixel size approximately the same as the distance between rows, effectively combining vine size and density information into a single pixel, resulted in the strongest correlations to total phenolics and colour. They also reported that the strongest correlations (most negative) between NDVI and total phenolics and colour occurred around the time of veraison (Lamb et al. 2004).

In the Languedoc region of France, Acevedo-Opazo et al. (2008) performed a study on remotely sensed VI, vine water status, and grape composition on a number of winegrape varieties in non-irrigated vineyards. They found temporally stable relationships between zones delineated based on the normalized difference vegetation index (NDVI) and vegetative growth, vine water status, and yield. These zones were also consistent with soil type. They concluded that a combination of remotely sensed data with intimate vineyard knowledge, especially of the soil, is needed to predict grape composition and ultimately wine quality (Acevedo-Opazo et al. 2008).

Overall, remote sensing has been proven as a tool for monitoring vineyard vegetative growth, and for making inferences into grape composition from the spectral measurements. The purpose of this study was to validate the use of remote sensing as an information gathering and observational tool in precision viticulture to understand terroir in a New World growing region. Four individual commercial vineyards planted to *Vitis vinifera* L. cv. Pinot noir in the Four Mile Creek and St. David's Bench sub-appellations, Niagara Region, Canada were the study locations.

It was hypothesized that information extracted from multispectral remotely sensed images could be used to identify variations in vineyard metrics and berry composition.

5.2 Materials & Methods

Selection of vineyard sites, sentinel vine sampling strategy, soil sampling, observation of leaf water potential (Ψ) and soil moisture, harvest and winemaking, berry sampling and measurement of vine size by recording pruning shoot weights were described in detail in an earlier paper in this series (Chapter 3.2).

5.2.1 Airborne Multispectral Images

Airborne image capture by aircraft-mounted camera was coordinated by Dr. Ralph Brown (School of Engineering, University of Guelph, Guelph, ON) from the Guelph Airport. A custom-built door mounting held a cluster of four confocal digital cameras with individual passband interference filters centred on red (650nm), green (550nm), blue (450nm) and near-infrared (NIR, 770nm) wavebands . Raw image bands were 1280x1024 pixels, with a spatial resolution dependent on altitude, nominally 3500 feet above ground level. This resulted in a pixel size of roughly 38.6x38.6cm, with a 48 acre (19.5ha) footprint. In 2008 images were captured on 29 May, 1 July, 29 July and 21 August on days with clear skies and as close to solar noon as practical. In 2009, images were captured on 22 June, 5 August, and 1 September under clear sky conditions as close to solar noon as possible.

In both years, bud-burst occurred early in May, bloom in mid-June, hedging was performed in early July. Veraison occurred late in August in 2008 and early September in 2009.

Camera gain settings were adjusted at time of capture to saturate all four wavebands in pixels displaying a white Tyvek® target placed on the ground in the vineyard for each flight. This had the dual purpose of removing the need to correct the images for radiometric or atmospheric interference, as well as making it possible for a direct conversion from digital number (DN) pixel values to reflectance values.

5.2.2 Image Processing

Images were processed using ENVI 4.6 (ITT Visual Information Solutions, Boulder, CO). Band-to-band registration was performed using tie points gathered from an image of streets and buildings in nearby Virgil, Ontario taken with each flight. Pixel size was also verified from landmarks in this image. Images were georeferenced using ground control points (GCPs) which were geolocated using a Trimble GeoXT GPS unit (Trimble Navigation Ltd., Sunnyvale, CA) as described in section 3.2.1. GCPs included corners of vineyard blocks, easily identifiable rocks, wind machines and gas tanks, and the end-posts of sentinel rows. There were 28 GCPs at Coyotes Run, and seven at Lowrey's, not including sentinel row end-posts. No less than 10 GCPs were used in any image registration, keeping the root mean square error (RMSE) below 1.0 where possible. For image to map registration, a first degree rotation stretch translation (RST) method was used with cubic convolution re-sampling.

5.2.3 Data Extraction

In order to extract spectral information from remotely sensed images, the pixels of interest must be first identified, and in this case those pixels represented sentinel vines. The Vinecrawler algorithm (Hall et al. 2003) was modified for isolation of sentinel vines for the purpose of data extraction. Unlike the situation reported in Hall et al. (2003), Hall et al. (2008), Johnson et al. (2001), and Johnson (2003), there was a large amount of vegetation growing on the vineyard floor between rows and under vines. Every other inter-row was tilled in the spring, but was quickly overtaken with fresh vegetation as the season progressed. In addition, there was vegetation between the rows that were not tilled from the summer before. This is illustrated in Figure 7-23.

The Vinecrawler algorithm relies on the easy separation of vine and non-vine pixels (Hall et al. 2003). This is only possible where the vineyard floor is not covered with dense vegetation. A histogram of NDVI pixel counts forms a bimodal distribution where there is little or no vegetation on the vineyard floor, this was observed by Hall et al. (2003), and was the basis of using a threshold NDVI value to create a mask over non-vine pixels. The histogram was divided into three categories: vine, inter-row space, and mixed pixels (Hall et al. 2003). The inter-row space had a low NDVI indicative of dead vegetation and soil. The mixed pixels represented pixels that have a larger contribution as a result of the soil underneath the canopy, and were largely along the edges of the vine rows. Where there is vegetation other than vines, the frequency of high NDVI values increases, and the bimodal distribution is lost. Figure 7-24 is a histogram of NDVI values extracted from Red Paw 2 on 22 June 2009, demonstrating this effect. Instead of dead vegetation or bare soil between the vine rows, there was green vegetation with high NDVI values, similar and in many cases higher than that of the vines. Mixed pixels represented a combination of vine and soil as well as inter-row vegetation and soil. Applying a threshold mask to these images did not isolate vines from other vegetation or from the soil.

Spectral information is the key decision-making criterion for the Vinecrawler algorithm in identifying pixels of interest. Since spectral information alone could not be used in this study due to the presence of background vegetation, the use of geographic information was used as a first step in data extraction. The GPS locations of the sentinel vines were overlaid on the geo-referenced images as a vector file. Small residual error from geolocating the vines, and the error introduced by georeferencing the images meant that these vector points were not aligned with vine rows. The points were manually shifted to the most likely location of the sentinel vine. Using knowledge of the vineyard layout, the first sentinel row was identified for each site. The vector points were shifted as little as possible, using the value of the NIR waveband to guide the placement of the points.

Hall et al. (2003) reported that the center of the row was a pixel with the highest local NDVI value bound by pixels with lower NDVI values in addition to mixed pixels. This relationship did not hold with dense inter-row vegetation. Figure 7-25 shows a sample of Red Paw 2 from 22 June 2009. At the far left is inter-row vegetation, followed by vine, inter-row soil, another vine row, inter-row vegetation, a third vine row, and finally inter-row soil. As shown in Table 7-19, the highest local NIR band value and the highest NDVI value were not always at the same pixel. The highest of each value were seen in the inter-row space, and so the location of the vector point must be made in relation to a known edge of a vine row. These edges are easily found next to soil. Knowing that each pixel is 38.6 cm across, and that the vine rows are roughly 2.4 m apart, the vine row most likely includes the first three pixels (1.2m) from the first mixed pixel. The vector was placed as a seed point where the NIR band is highest, within a reasonable distance from where an edge of a vine row was discernable. Where there was dense vegetation between every row, this required tracing the row along its length from the last point where it could be distinguished from soil or inter-row vegetation.

After placing the vector seed point, it was converted into a larger region of interest (ROI) to extract the band values at that point. Lamb et al. (2001; 2004) found that low-resolution images, when the pixel size was roughly equal to the vine row spacing, were better for extracting information about canopy size and density as well as for predicting total phenolics and colour. To that end, each seed point was extended to a 5x5 pixel matrix with the vector point at its centre. Band values were extracted from individual wavebands (NIR and red) and re-sampled to 1x1, 3x3, and 5x5 pixel sizes before taking the NDVI. Note that taking the NDVI of each pixel in the matrix and averaging them is not mathematically equivalent to averaging each of the wavebands and calculating the NDVI from the mean band values. For example, Figure 7-26 shows a highlighted vine from Red Paw 2, 1 September 2009. The values of these pixels in the NIR and Red wavebands are shown in Table 7-20. Taking the NDVI of each pixel and averaging those value results in an NDVI of

0.212. Conversely, taking the mean pixel value from each waveband and then calculated the NDVI resulted in a value of 0.186, the true NDVI of the re-sampled ROI.

5.2.4 Ground-based Leaf Reflectance

The reflectance spectra of individual leaves were measured on water status vines. Measurements were performed on or around the same day as the airborne image capture so long as leaf surfaces were dry. In 2008 the dates were: 26 June, 25 July, and 22 August. There were not enough fully expanded leaves at the first airborne image capture date to measure ground-based leaf reflectance around 29 May. In 2009 the dates were: 24 June, 5 August, and 11 September.

A Stellarnet EPP2000 (UV-Vis-100nm) spectrometer, controlled by a small laptop computer running SpectraWiz software (Stellarnet Inc., Tampa, FL) was used to record the reflectance spectra. A custom-built enclosure held the leaf as well as the 5W halogen bulb light-source. The detector fiber optic cable was fixed to the enclosure, at a 45° angle to the incident light. References were set before the first leaf, and again after every four to six vines. The dark reference, or 0% reflectance, was taken with the light off, and the leaf enclosure empty and held shut over the black felt base. The white reference, representing 100% reflectance, was performed with the light on and the enclosure firmly sealed around matte white Teflon® square. Integration time from 15 to 30 ms was adjusted as necessary to maintain the white standard without saturating the spectrometer, and five samples were taken to mean to maintain computer performance and a smooth response curve.

Three healthy, fully expanded leaves, from across the vine canopy, were chosen at random. Leaves that were too small for the enclosure were rejected. The accepted leaf was held flat in the enclosure, and exposed to the light source. The reflectance spectra was saved from 350 to 850nm, at 2nm increments.

5.2.5 Statistical Methods

Analysis of variance (ANOVA) was performed on the data collected at each vineyard site individually, for each vintage. Sentinel vines were grouped within sites first by water status zone, and then by vigour status zone. Data were submitted to the PROC GLM in SAS (Version 9.1.3; SAS Institute, Cary, NC), with means separation by the LSD (α=0.1). Pearson's correlation matrices were generated between all variables using PROC CORR for all sentinel vines. Principal component analysis (PCA) was performed on the mean values grouped by water status zone for all vineyard sites using JMP (Version 8.0.1; SAS Institute, Cary, NC).

5.3 Results

The PCA of yield components, grape composition, vineyard soil and moisture variables, and leaf reflectance (both ground-based and airborne) when grouped by water status zone as well as observation loadings for 2008 at all four vineyard sites is shown in Figure 5-1. PC1 accounted for 55.25% of the variation in the data, and PC2 for 29.11% for a total of 84.36% in the first two principal components. Similarly, Figure 5-2 shows 2009 data from all four vineyard sites. PC1 accounted for 53.15% of the variation in the data, and PC2 for 21.29% for a total of 74.44% in the first two principal components. Figure 5-3 shows all four vineyard sites in both years, PC1 accounts for 42.02% and PC2 for 18.60% of the variation in the data, accounting for 60.62% of the variation in the first two principal components. Clustering of the vineyard blocks was consistent for Black Paw and Lowrey's but less distinct for the Red Paw blocks in the PCA of both years.

Means of seasonal mean NDVI-red extracted from airborne images with vines grouped by water status category are shown in Table 5-1. This table includes 1x1, 3x3, and 5x5 pixel re-sampling for all four vineyard sites. Similarly, means of mean NDVI-green are shown in Table 5-2. There were no differences between water status zones within a vineyard at 1x1 pixel for either VI in either year, in fact there were no differences at all in 2009. At 3x3 and 5x5 pixels, there was a difference between water status zones in Lowrey's vineyard using both VI in 2008, and a difference in Red Paw 1 using NDVI-green in Red Paw 1. NDVI-green, proposed by Gitelson et al. (1996), is identical to the traditional NDVI, but the red waveband is replaced by the green, and has been shown to be more sensitive to the chlorophyll content of leaves.

With vines grouped by vigour status zone, means of seasonal mean NDVI-red are shown in Table 7-21, and NDVI-green in Table 7-22. In 2008, Black Paw vineyard was different between vigour status groups based on pruning shoot weights for all re-sampling rates except 5x5 using NDVI-green. No other vineyard was different between vigour zone for either index or re-sampling rate in 2008. As was discussed in an earlier paper in the series, (Chapter 3.2), after the 2009 season only vines at Lowrey's vineyard were pruned. Lowrey's was different between vigour zones using NDVI-green at 1x1 and 5x5 pixel re-sampling.

Table 7-24 through Table 7-31 are included in supplemental materials. Pearson correlation coefficients and corresponding significance levels of NDVI-red extracted from individual airborne images against seasonal mean Ψ for all sentinel vines, in both vintages, are shown in Table 7-24, and the same relationships for NDVI-green are shown in Table 7-25. These tables include 1x1, 3x3, and 5x5 pixel re-sampling. Similarly, Table 7-26 and Table 7-27 show the Pearson correlation coefficients of NDVI-red and green against vine size, Table 7-28 and Table 7-29 are against total phenolics, Table 7-30 and Table 7-31 are against total anthocyanins. Graphical representations of how these Pearson correlation coefficient changed over the growing season are also given, for NDVI-red only, all sentinel vines, from both years, 3x3 pixel re-sampling. Figure 5-5-a, -b, -c and -d are against mean Ψ, vine size, total phenolic compounds, and total anthocyanins respectively. There is no clear relationship as to how the strength of any of these correlations changed over time, or as the re-sampling increased from 1x1 to 5x5 pixels. The Pearson correlation coefficients between the mean NDVI-red and -green for 2008 are shown in Table 7-32 and for 2009 in Table 7-33. The only moderate correlation was between NDVI-red and Ψ (1x1, 3x3 and 5x5 pixel re-sampling, $r=0.70$, 0.65 and 0.56; $p \leq 0.0001$).

The relationship between airborne and ground-based vegetation indices on individual dates are shown with Pearson correlation coefficients for all sentinel vines in Table 5-3 for 2008 and Table 5-4 for 2009. There was no pattern to the relationship between VI on individual dates, and very few of the correlations were significant ($p \leq 0.01$), there was no relationship between the airborne VI and those measured using individual leaf reflectance.

5.4 Discussion

5.4.1 Method Development

The key difference between this study and those before it is presence of dense inter-row vegetation. The clear bimodal distribution of pixel values observed by Hall et al. (2001; 2003) did not occur here, as was shown in Figure 7-24. Indeed, many of the pixels with values of NDVI higher than the 0.67 cut-off used by Hall were observed to be area other than vine, and pixels showing entirely vine could be found in the entire range of positive values of NDVI.

Using the method described above in Section 5.2.3, a best approximation of the location of a seed-point for the vine was located using the local maximum of the NIR reflectance within a reasonable distance from the edge of a boundary between soil and vine. The characteristic spectral response curve of vegetation includes a dramatic increase in reflectance from the red wavelengths into the near-infrared around 750 nm, the greater the contribution of soil in a mixed pixel, the lower the pixel value in the NIR waveband (Hall et al. 2002). A fully-automated process was not developed because of the frequency of high NIR reflectance values between vine rows; a cut-off distance from a discernable soil edge was needed to place many of the seed points. Ultimately, this method proved to be effective and consistent. It was not complicated, but was time consuming.

In order to speed up the process of extracting information from aerial images, the intelligent digitizer feature of the ENVI software package was used. Geolocated endposts and approximate locations of sentinel vines were used as guides, to rapidly highlight vine rows, and create a mask to select only those pixels containing vine and some mixed pixels. Figure 5-6 shows the masking process on an image of Red Paw 2 vineyard from 1 September, 2009. This process loses information about canopy shape by assuming a 3-pixel (or any pre-selected integer value) width, but using the mask makes the process of identifying the location of sentinel vines much faster. In commercial applications, where individual vines are not the targets, this process is a more efficient method of creating a map of vine performance and is similar to the maps produced by using the GreenSeeker NDVI sensor (Drissi et al. 2009).

5.4.2 Remote Sensing and Vineyard Performance

The PCAs from 2008 and 2009 in Figure 5-1 and Figure 5-2 show that there was a distinct separation of the four vineyard sites in both years. The two Red Paw vineyards were clustered in 2008, apart from Black Paw and Lowrey's vineyards. In both years, the 1x1, 3x3, and 5x5 pixel re-sampling were highly correlated to each of the others. This was verified by the Pearson correlation coefficients, where the same index was highly correlated to the re-sampled indices in Table 7-32 and Table 7-33.

In 2008, Black Paw was heavily loaded with colour, soil organic matter and clay. Lowrey's was heavily loaded with the mean Ψ, cluster size, vine size, and the remotely sensed vegetation indices (NDVI-red, NDVI-green). The Red Paw vineyards were loaded with berry size, number of clusters and soil silt content.

In 2009, Black Paw was heavily loaded again with soil clay content and organic matter. Lowrey's was loaded against cluster size, berry pH and berry soluble solids. Red

Paw 1 was loaded with soil silt content and the VI, and Red Paw 2 was loaded with berry colour intensity, hue, and total anthocyanins.

The pooled data from both vintages showed that Black Paw is distinctly different from the other three sites, and again was described by the clay and soil organic matter. Red Paw 1 and 2 were more similar in 2009 with the consideration of the entire data set, where they did not cluster in the 2009 data alone. Red Paw 1 and Lowrey's were clustered in the larger data set, and were loaded with yield, cluster size and sand.

It is likely that the colour of the soil, which was distinctly different in each site, contributed to the mixed pixels surrounding the sentinel vines. Since remote sensing has been used in predicting soil albedo (Post et al. 2000), it follows that different surface soil appearances would behave differently in this analysis.

The means of NDVI-red and NDVI-green for all four vineyard sites, with sentinel vines divided by water status reveal that remote sensing was not able to differentiate within vineyard differences in water status. In 2008, using 3x3 and 5x5 pixel re-sampling, there were differences between water status zones using NDVI-red and NDVI-green in the Lowrey's vineyard. The low water status zone had the lowest NDVI using both Red and Green. Using NDVI-green there was also a difference in Red Paw 1 in 2008. With 5x5 pixel re-sampling, the low water status zone was the smaller value. In 2009 there were no differences between water status zones in any vineyard using either index.

Remote sensing was not useful as a tool in determining water status zones in these vineyards in 2008 and 2009. The Pearson's correlation coefficient between the mean NDVI and the mean Ψ revealed a reasonable correlation between the two in 2008. For 1x1, 3x3 and 5x5 pixel re-sampling, $r=0.70$, 0.65 and 0.56 ($p\leq0.0001$), respectively. The correlations were less strong for NDVI-green, for 1x1, 3x3 and 5x5 pixel re-sampling, $r=0.35$, 0.45 ($p\leq0.01$) and $r=0.62$ ($p\leq0.0001$), respectively. The small difference between water status zones likely masked the strength of remote sensing for monitoring the water status of the vines. Whereas the mean NDVI of each water status zone was not different, there was a strong relationship between the water status of individual vines and the NDVI in 2008.

In 2009 the correlation between NDVI and mean Ψ was not as strong. For NDVI-red, there were no significant correlations to mean water status. For NDVI-green, 1x1, 3x3 pixel re-sampling, $r=0.29$ ($p<0.05$), $r=0.38$ and 0.32 ($p<0.01$) respectively. As previously discussed, there were not large differences between these zones as a result of the weather, and the differences may not have been present to be detected.

The means of NDVI-red and green with vines grouped by vigour status zone for 2008 at all four vineyards, and for Lowrey's vineyard in 2009 are shown in Table 7-21 and Table 7-22. Using NDVI-red, there were differences between vigour zones in the Black Paw vineyard, but counter-intuitively the low vigour zone has the higher mean NDVI. In Red Paw 1, at 5x5 pixel re-sampling there was a difference between vigour zones, with the high vigour zone having the larger NDVI. With NDVI-green, there were differences between vigour zones in Black Paw, but with the high vigour zone having the lower NDVI. In 2009 there were differences between vigour zones using 1x1 and 5x5 re-sampling in Lowrey's vineyard, with the high vigour zone having the higher NDVI.

The division by vigour status did not yield a more useful application of remote sensing than division by water status; however, there was a moderate correlation between shoot weight and NDVI-red and green in 2008. For 1x1, 3x3 and 5x5 pixel re-sampling, the Pearson correlation coefficients were $r=0.51$, 0.46 and 0.36 ($p\leq0.0001$) respectively. The correlations were less strong between shoot weight and NDVI-green, using 1x1, 3x3, and 5x5 pixel re-sampling, $r=0.14$ ($p\leq0.05$), $r=0.23$ and 0.40 ($p\leq0.0001$) respectively. NDVI-red was better correlated to vine size than NDVI-green in 2008, but neither was a strong correlation.

In general, the strength of correlations between NDVI and any other parameter was strongest at 1x1 pixel size, and decreased with the addition of more pixels. However, the 3x3 pixel re-sampling was most likely to include the entire canopy, and more likely to include the actual sentinel vine. It is also the pixel size that would be captured using the masked NDVI images. In Figure 5-4, the NDVI values extracted from 29 July and 21 August 2008 images of Lowrey's vineyard were mapped using the procedure of Section 3.2.10. Maps from each date are of the 1x1, 3x3, and 5x5 pixel re-sampling. The map of 1x1 pixel skews towards higher NDVI values, and the map of 5x5 pixel re-sampling skews towards the lower values. The 3x3 pixel re-sampling includes a large range of values, while maintaining the spatial distribution of trends in NDVI differences. For these reasons, the following discussion will focus on this re-sampling rate.

In terms of grape composition metrics, in 2008 3x3 pixel NDVI-red correlated best with cluster size ($r=0.39$; $p\leq0.0001$), berry pH ($r=-0.48$; $p\leq0.0001$), berry soluble solids ($r=-0.43$; $p\leq0.0001$), total anthocyanins ($r=-0.65$; $p\leq0.0001$), and colour ($r=-0.58$; $p\leq0.0001$). In 2009, NDVI-red correlated marginally with anthocyanins ($r=0.49$; $p\leq0.0001$) and well with mean soil moisture ($r=-0.89$; $p\leq0.0001$). Although there was a reasonable correlation between NDVI and anthocyanins in both years, the sign is different. Based on the findings of

Cortell & Kennedy (2006), Reynolds et al. (1994), and Spayd et al. (2002), one would expect an inverse relationship between NDVI and anthocyanins, with increasing light exposure from smaller canopies leading to higher concentrations of these and other phenolics. This was not found in this study.

Lamb et al. (2004) found that the strength of the correlation between NDVI-red and total grape phenolics was best at veraison, while Hall et al. (2010) found that the correlation continued to improve even after veraison. Neither of these trends was observed in either vintage for phenolics or anthocyanins. Figure 5-5-c and -d show the change in the correlation between NDVI-red and phenolics and anthocyanins over time. The two years did not agree in the pattern over time, and do not clearly peak at any time.

In remote sensing studies, the absolute magnitude of the Pearson correlation coefficients is not always expected to be large. Lamb et al. (2004), in comparing spatial resolution and timing of data capture in predicting total phenolics reported values no larger than $r=-0.59$. The emphasis was on the change in the correlation over time, and a proof-of-concept in the ability of remote sensing systems to predict grape composition metrics.

The trend in change over time in correlation between NDVI-red and mean Ψ is seen in Figure 5-5-a. There is some agreement between the two vintages, with the correlation at its weakest through the end of July and beginning of August, around the same time that hedging operations dramatically changed the canopy architecture and density. The same trend is seen in Figure 5-5-b, which trends the correlation between NDVI-red and weight of cane prunings in 2008. There was a dip in late-July, after which the correlation coefficient continued to increase.

This study did not reveal an ideal time for remote sensing aerial image capture in predicting grape composition or vine size. The seasonal mean from both vintages indicated that VI extracted from aerial images have some limited potential for use in predicting grape composition and vine vigour in a cool climate, but the lack of clear trends makes it impossible to make recommendations as to ideal flight scheduling, or the true predictive power of VI.

Using the mask of a vineyard, NDVI values at individual pixels are retained. In contrast, a map drawn from extracted values at sentinel vines required interpolation, and may miss small spatial trends. Figure 5-7 shows the masked and mapped NDVI values from Red Paw 2 vineyard on 1 September 2009. The areas of high and low NDVI were generally the same, confirming the validity of the gridding process, but there was more detail contained in the masked image. In addition, after the application of the mask, an automatic algorithm, such as Vinecrawler (Hall et al. 2001) could be applied. The use of threshold values to mask non-vine area could not be used in this study, but using the process described above, the end result of a masked image is the same. It must be noted again, however, that while Vinecrawler was able to describe canopy architecture in its original application, the masking process used here eliminates that ability.

Concurrent to the airborne images, spectral information was collected with a hand-held spectrometer. Table 5-3 and Table 5-4 show the Pearson correlation coefficients between the vegetation indices extracted from the airborne images and the hand-held spectrometer on individual dates of data capture.

There was not a strong correlation between the two methods of data capture. Comparing the same VI measured using the hand-held unit and remotely sensed, the correlation coefficient rarely exceeded 0.30, and was often negative. There were several major differences between the two measurement techniques. The hand-held reflectance was hyperspectral, saved at 2-nm increments where the airborne images were captured in four large wavebands. The hand-held measurements were taken on three leaves per vine, and by nature of sampling they tended to be large leaves, and while randomly chosen from across the available canopy, they may not have been representative of the entire canopy. They were also sampled individually, where the airborne images account for many layers of leaves, seen from above.

The characteristic spectral response curve of a grapevine leaf, such as that given by Hall et al. (2002), is for a single leaf with hyperspectral resolution. Increasing the layering of leaves increases the total reflectance in the NIR wavebands, because of transmittance and reflectance between layers (Lillesand & Kiefer 2000). Seen from above at a 38cm spatial resolution, each pixel will contain information about the leaves from one or more vines, the soil, and the under-vine vegetation.

The red edge inflection point (REIP) is the inflection point of the curve where reflectance increases sharply from the red to the NIR wavelengths. It could not be calculated from the airborne images as they lacked the spectral resolution.

A ground-based optical remote sensing device such as GreenSeeker offers yet another option for remote sensing. The entire canopy is viewed laterally (Drissi et al. 2009), and converted into a NDVI value. The orientation of a vertically shoot positioned canopy means that this method of observation provides a great deal of information as to the spectral response of the canopy, and is not hampered by the issue of ground-cover.

5.5 Conclusions

A process was developed here to extract spectral information from airborne images when the presence of inter-row vegetation complicates the use of fully automated algorithms. An alternate method of masking vineyards to remove the effect of background vegetation was also developed. Both of these methods were effective when the bimodal distribution of vine and non-vine pixels was not evident in an image due to extensive non-vine vegetation.

Re-sampling the images to a 3x3 pixel area of interest (approximately 1.15x1.15m) resulted in comparatively stronger correlations to vine performance and grape composition metrics, while using a large range of values of NDVI.

There was no clear trend in terms of what phase of vine growth would provide the most useful information, but there were some correlations to vine metrics. Remotely sensed NDVI correlated moderately well with berry pH, soluble solids, vine size, total anthocyanins, colour, and soil clay and sand content in 2008. In 2009, NDVI correlated well with TA, total anthocyanins, mean soil moisture, and soil clay and silt content. The potential of remote sensing for use in understanding variability within Pinot noir vineyards has been explored with some evidence of a relationship to berry composition including key colour and anthocyanin metrics. Further study is recommended to reconcile the use of NDVI for delineation of selective harvest zones in a cool climate, and to find patterns in year-to-year differences in remotely sensed indices and how they related to vineyard performance over time.

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Table 5-1: Means of NDVI-red extracted from 2008 & 2009 airborne images in four Pinot noir vineyard sites, St. Davids, ON, 2008 and 2009 with vines grouped by water status zone. Images were re-sampled at 1x1, 3x3, and 5x5 pixel target areas.

Water Status Category	NDVI-red 1x1pixel		NDVI-red 3x3pixel		NDVI-red 5x5pixel	
Red Paw 1	2008	2009	2008	2009	2008	2009
Low	0.25	0.60	0.13	0.40	0.06	0.29
High	0.25	0.63	0.12	0.43	0.06	0.31
Significance[a]	ns	ns	ns	ns	ns	ns
Red Paw 2						
Low	0.24	0.54	0.11	0.44	0.08	0.41
High	0.23	0.54	0.11	0.45	0.08	0.41
Significance	ns	ns	ns	ns	ns	ns
Black Paw						
Low	0.03	0.12	-0.05	-0.07	-0.05	-0.12
High	0.03	0.13	-0.06	-0.07	-0.06	-0.12
Significance	ns	ns	ns	ns	ns	ns
Lowrey's						
Low	0.62	0.35	0.25c	0.19	0.11b	0.10
Medium	0.62	-[b]	0.31b	-	0.18a	-
High	0.66	0.35	0.36a	0.19	0.22a	0.10
Significance	ns	ns	****	ns	****	ns

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at p≤0.1, 0.05, 0.01, 0.001, not significant, respectively
[b]In 2009, Lowrey's vineyard was divided into two water status zones.

Table 5-2: Means of NDVI-green extracted from 2008 & 2009 airborne images in four Pinot noir vineyard sites, St. Davids, ON, 2008 and 2009 with vines grouped by water status zone. Images were re-sampled at 1x1, 3x3, and 5x5 pixel target areas.

Water Status Category	NDVI-green 1x1pixel		NDVI-green 3x3pixel		NDVI-green 5x5pixel	
Red Paw 1	2008	2009	2008	2009	2008	2009
Low	0.38	0.15	0.22	0.18	0.09b	0.17
High	0.38	0.15	0.24	0.19	0.10a	0.18
Significance[a]	ns	ns	ns	ns	*	ns
Red Paw 2						
Low	0.16	0.33	0.03	0.31	0.01	0.25
High	0.15	0.32	0.01	0.32	0.00	0.24
Significance	ns	ns	ns	ns	ns	ns
Black Paw						
Low	-0.06	-0.03	-0.12	-0.17	-0.10	-0.23
High	-0.06	-0.03	-0.13	-0.17	-0.12	-0.23
Significance	ns	ns	ns	ns	ns	ns
Lowrey's						
Low	0.22	0.14	0.08c	0.11	0.09c	0.03
Medium	0.23	-[b]	0.13b	-	0.14b	-
High	0.27	0.16	0.16a	0.12	0.18a	0.04
Significance	ns	ns	**	ns	***	ns

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at p$\leq$0.1, 0.05, 0.01, 0.001, not significant, respectively
[b]In 2009, Lowrey's vineyard was divided into two water status zones.

Table 5-3: Pearson correlation coefficients and significance level (p-value) of vegetation indices extracted from airborne images against vegetation indices calculated using ground-based reflectance measurements for individual data collection dates in 2008 in four Pinot noir vineyard sites, St. Davids, ON.

Correlation	01-Jul-08				29-Jul-08				21-Aug-08			
(r-value)	NDVI-R	NDVI-G	GR	REIP	NDVI-R	NDVI-G	GR	REIP	NDVI-R	NDVI-G	GR	REIP
NDVI-R 1x1	-0.43	0.35	0.36	0.19	0.01	-0.66	-0.68	0.09	0.38	0.05	0.07	-0.37
NDVI-R 3x3	-0.30	0.43	0.44	0.07	-0.35	0.16	0.17	0.27	-0.35	0.39	0.40	-0.02
NDVI-R 5x5	-0.25	0.41	0.41	0.06	-0.38	0.11	0.10	0.25	-0.24	0.37	0.38	-0.01
NDVI-G 1x1	-0.60	0.31	0.31	0.33	0.00	-0.14	-0.13	0.14	0.14	0.05	0.06	-0.20
NDVI-G 3x3	-0.37	0.49	0.50	0.09	-0.35	0.21	0.24	0.29	-0.32	0.41	0.41	-0.06
NDVI-G 5x5	-0.32	0.48	0.49	0.06	-0.33	0.25	0.29	0.21	-0.28	0.43	0.43	-0.08
GR 1x1	-0.62	0.09	0.06	0.39	0.11	0.04	0.04	0.12	-0.08	-0.01	-0.01	0.00
GR 3x3	-0.49	0.38	0.38	0.20	-0.22	-0.06	-0.02	0.29	-0.29	0.32	0.32	-0.05
GR 5x5	-0.44	0.38	0.38	0.17	-0.25	-0.10	-0.07	0.28	-0.28	0.32	0.32	-0.05

Significance	01-Jul-08				29-Jul-08				21-Aug-08			
(p-value)	NDVI-R	NDVI-G	GR	REIP	NDVI-R	NDVI-G	GR	REIP	NDVI-R	NDVI-G	GR	REIP
NDVI-R 1x1	0.0026	0.0181	0.0139	0.1986	0.9416	<.0001	<.0001	0.4954	0.0015	0.6835	0.5571	0.0025
NDVI-R 3x3	0.0414	0.0028	0.0023	0.6641	0.0039	0.1916	0.1614	0.0305	0.0038	0.0011	0.0008	0.8861
NDVI-R 5x5	0.0962	0.0049	0.0047	0.7027	0.0014	0.3949	0.4170	0.0457	0.0547	0.0020	0.0016	0.9128
NDVI-G 1x1	<.0001	0.0333	0.0391	0.0241	0.9795	0.2480	0.3029	0.2760	0.2629	0.6960	0.6572	0.1008
NDVI-G 3x3	0.0115	0.0005	0.0004	0.5468	0.0043	0.0925	0.0499	0.0201	0.0084	0.0006	0.0006	0.6286
NDVI-G 5x5	0.0327	0.0007	0.0005	0.6795	0.0071	0.0412	0.0196	0.0973	0.0220	0.0004	0.0003	0.5199
GR 1x1	<.0001	0.5663	0.7007	0.0069	0.3945	0.7506	0.7350	0.3562	0.5312	0.9614	0.9525	0.9708
GR 3x3	0.0006	0.0086	0.0091	0.1897	0.0771	0.6508	0.8833	0.0186	0.0185	0.0096	0.0091	0.6994
GR 5x5	0.0021	0.0095	0.0095	0.2731	0.0396	0.4278	0.5790	0.0242	0.0215	0.0088	0.0084	0.6697

Table 5-4: Pearson correlation coefficients and significance level (p-value) of vegetation indices extracted from airborne images against vegetation indices calculated using ground-based reflectance measurements for individual data collection dates in 2009 in four Pinot noir vineyard sites, St. Davids, ON.

Correlation (r-value)	22-Jun-09				05-Aug-09				01-Sep-09			
	NDVI-R	NDVI-G	GR	REIP	NDVI-R	NDVI-G	GR	REIP	NDVI-R	NDVI-G	GR	REIP
NDVI-R 1x1	-0.12	0.47	0.41	-0.13	-0.44	0.11	0.09	-0.13	-0.43	-0.43	-0.42	-0.08
NDVI-R 3x3	-0.29	0.31	0.29	0.00	-0.45	-0.02	-0.03	0.00	-0.19	-0.19	-0.20	-0.11
NDVI-R 5x5	-0.33	0.22	0.19	0.06	-0.43	-0.11	-0.11	0.07	-0.14	-0.14	-0.14	-0.11
NDVI-G 1x1	-0.25	0.44	0.38	-0.09	-0.48	0.05	0.04	-0.08	-0.51	-0.50	-0.49	-0.13
NDVI-G 3x3	-0.30	0.45	0.40	-0.06	-0.49	0.03	0.03	-0.09	-0.32	-0.31	-0.33	-0.15
NDVI-G 5x5	-0.40	0.29	0.25	0.09	-0.47	-0.04	-0.04	0.01	-0.34	-0.33	-0.33	-0.12
GR 1x1	-0.30	0.44	0.38	-0.06	-0.54	0.00	-0.01	-0.05	-0.62	-0.61	-0.61	-0.14
GR 3x3	-0.28	0.49	0.44	-0.09	-0.56	0.01	-0.01	-0.08	-0.49	-0.49	-0.50	-0.17
GR 5x5	-0.41	0.33	0.28	0.09	-0.56	-0.01	-0.01	-0.06	-0.54	-0.53	-0.53	-0.15

Significance (p-value)	22-Jun-09				05-Aug-09				01-Sep-09			
	NDVI-R	NDVI-G	GR	REIP	NDVI-R	NDVI-G	GR	REIP	NDVI-R	NDVI-G	GR	REIP
NDVI-R 1x1	0.3238	<.0001	0.0006	0.2803	0.0002	0.3854	0.4547	0.3068	0.0004	0.0004	0.0007	0.5416
NDVI-R 3x3	0.0163	0.0101	0.0194	0.9956	0.0001	0.8599	0.8294	0.9816	0.1379	0.1479	0.1252	0.4125
NDVI-R 5x5	0.0074	0.0801	0.1191	0.6494	0.0003	0.3864	0.3793	0.5664	0.2664	0.2951	0.2866	0.3858
NDVI-G 1x1	0.0391	0.0002	0.0017	0.4830	<.0001	0.7076	0.7352	0.5325	<.0001	<.0001	<.0001	0.3271
NDVI-G 3x3	0.0139	0.0001	0.0008	0.6099	<.0001	0.7854	0.8115	0.4954	0.0122	0.0131	0.0093	0.2338
NDVI-G 5x5	0.0008	0.0188	0.0462	0.4942	<.0001	0.7446	0.7383	0.9545	0.0074	0.0097	0.0079	0.3366
GR 1x1	0.0158	0.0003	0.0017	0.6156	<.0001	0.9799	0.9562	0.6936	<.0001	<.0001	<.0001	0.2720
GR 3x3	0.0210	<.0001	0.0002	0.4971	<.0001	0.9613	0.9653	0.5294	<.0001	<.0001	<.0001	0.1791
GR 5x5	0.0006	0.0064	0.0220	0.4808	<.0001	0.9663	0.9100	0.6484	<.0001	<.0001	<.0001	0.2474

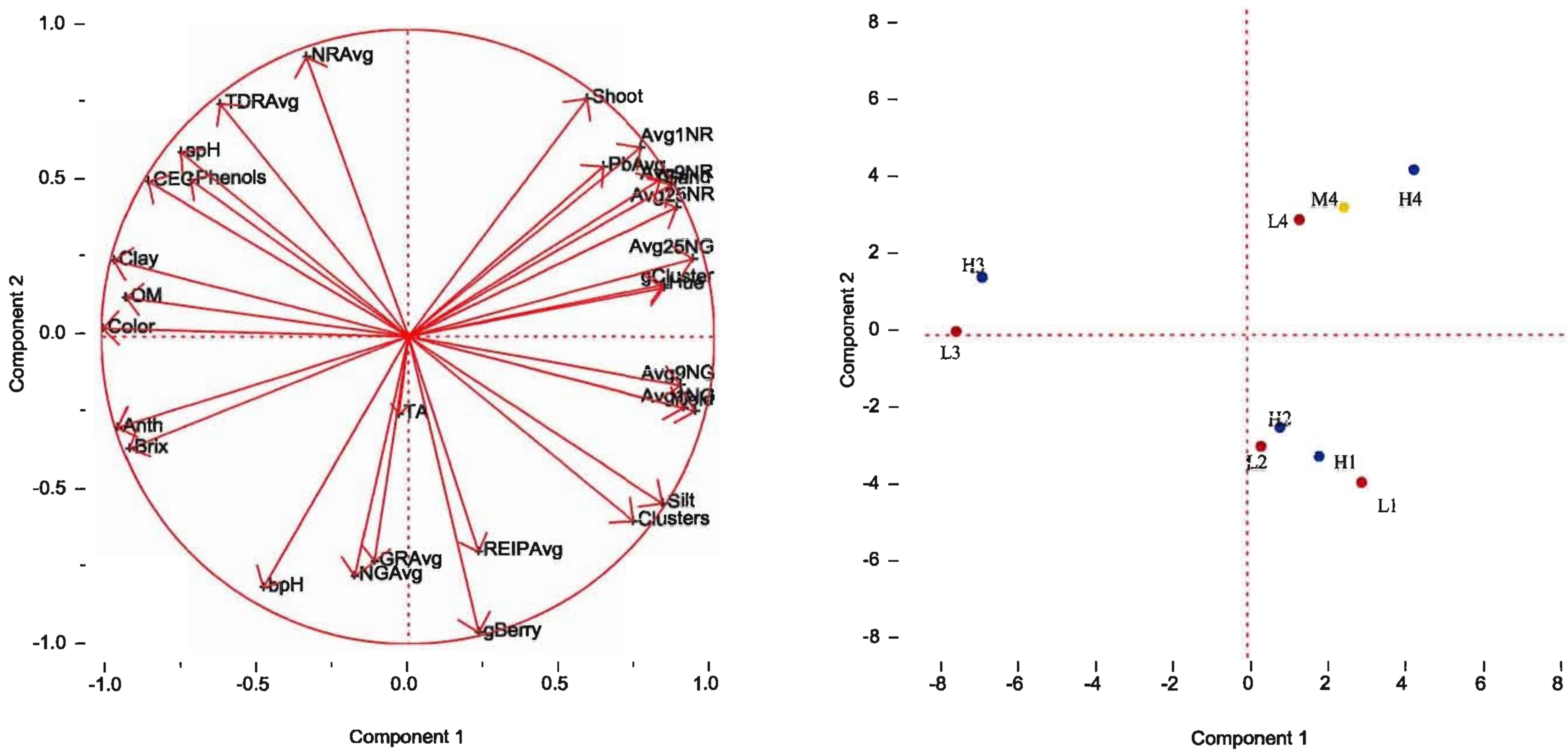


Figure 5-1: PCA of 2008 yield components, grape composition, vineyard variables and leaf reflectance (ground-based and airborne) in four Pinot noir vineyard sites, St. Davids, ON. Principal component 1 (PC1) (55.25%) and PC2 (29.11%) explain 84.36% of the variation in the data. Left: variable loadings of variables on PC1 & PC2 (Yield – yield per vine, Clusters – number of clusters per vine, gCluster – g/cluster, gBerry – g/berry, bpH – berry pH, Brix – berry Brix, TA – titratable acidity, Shoot – dormant shoot weights, Anth – total anthocyanins (mg/L), Colour (a.u.), Hue (a.u.), Phenols – total phenolics (mg/L), TDRAvg – mean soil moisture, PBAvg – mean Ψ, Clay - % clay, Silt - % silt, Sand - % sand, OM - % organic matter, CEC – cation exchange capacity (meq/100g), spH – soil pH, NR – NDVI-red, NG – NDVI-green, GR – Greenness Ratio, REIP – Red Edge Inflection Point, Avg1,9,25 – 1x1, 3x3, 5x5 pixel). Right: observation loadings (Blue – high water status, Red – low water status, Yellow – medium water status; 1 – Red Paw 1, 2 – Red Paw 2, 3 – Black Paw, 4 – Lowrey's).

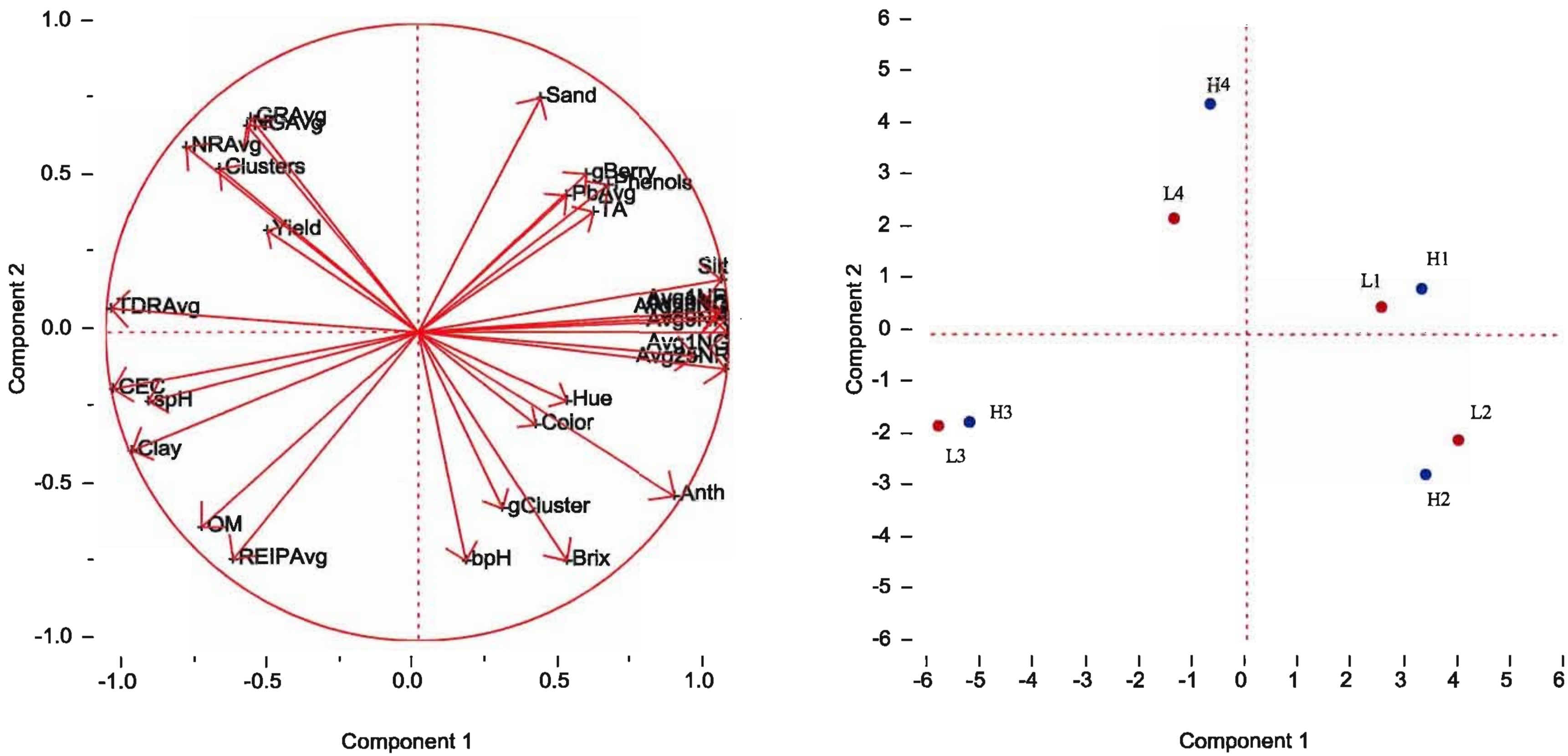


Figure 5-2: PCA of 2009 yield components, grape composition, vineyard variables and leaf reflectance (ground-based and airborne) in four Pinot noir vineyard sites, St. Davids, ON. Principal component 1 (PC1) (53.15%) and PC2 (21.29%) explain 74.44% of the variation in the data. Left: variable loadings of variables on PC1 & PC2 (Yield – yield per vine, Clusters – number of clusters per vine, gCluster – g/cluster, gBerry – g/berry, bpH – berry pH, Brix – berry Brix, TA – titratable acidity, Anth – total anthocyanins (mg/L), Colour (a.u.), Hue (a.u.), Phenols – total phenolics (mg/L), TDRAvg – mean soil moisture, PBAvg – mean Ψ, Clay - % clay, Silt - % silt, Sand - % sand, OM - % organic matter, CEC – cation exchange capacity (meq/100g), spH – soil pH, NR – NDVI-red, NG – NDVI-green, GR – Greenness Ratio, REIP – Red Edge Inflection Point, Avg1,9,25 – 1x1, 3x3, 5x5 pixel). Right: observation loadings (Blue – high water status, Red – low water status; 1 – Red Paw 1, 2 – Red Paw 2, 3 – Black Paw, 4 – Lowrey's).

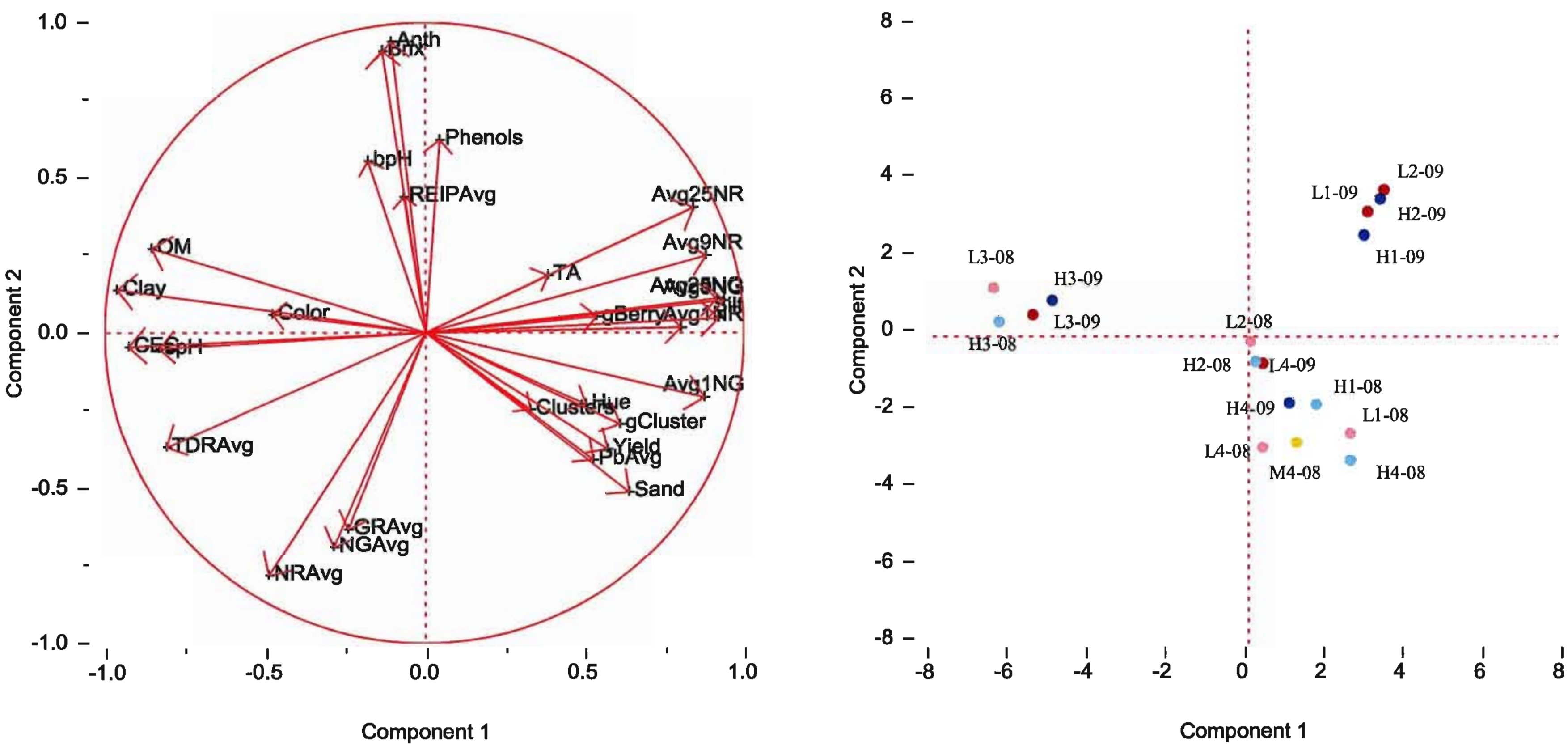


Figure 5-3: PCA of 2008 & 2009 yield components, grape composition, vineyard variables and leaf reflectance (ground-based and airborne) in four Pinot noir vineyard sites, St. Davids, ON. Principal component 1 (PC1) (42.02%) and PC2 (18.60%) explain 60.62% of the variation in the data. Left: variable loadings of variables on PC1 & PC2 (Yield – yield per vine, Clusters – number of clusters per vine, gCluster – g/cluster, gBerry – g/berry, bpH – berry pH, Brix – berry Brix, TA – titratable acidity, Anth – total anthocyanins (mg/L), Colour (a.u.), Hue (a.u.), Phenols – total phenolics (mg/L), TDRAvg – mean soil moisture, PBAvg – mean Ψ, Clay - % clay, Silt - % silt, Sand - % sand, OM - % organic matter, CEC – cation exchange capacity (meq/100g), spH – soil pH, NR – NDVI-red, NG – NDVI-green, GR – Greenness Ratio, REIP – Red Edge Inflection Point, Avg1,9,25 – 1x1, 3x3, 5x5 pixel). Right: observation loadings (Blue – high water status, Red – low water status, Yellow – medium water status; 1 – Red Paw 1, 2 – Red Paw 2, 3 – Black Paw, 4 – Lowrey's).

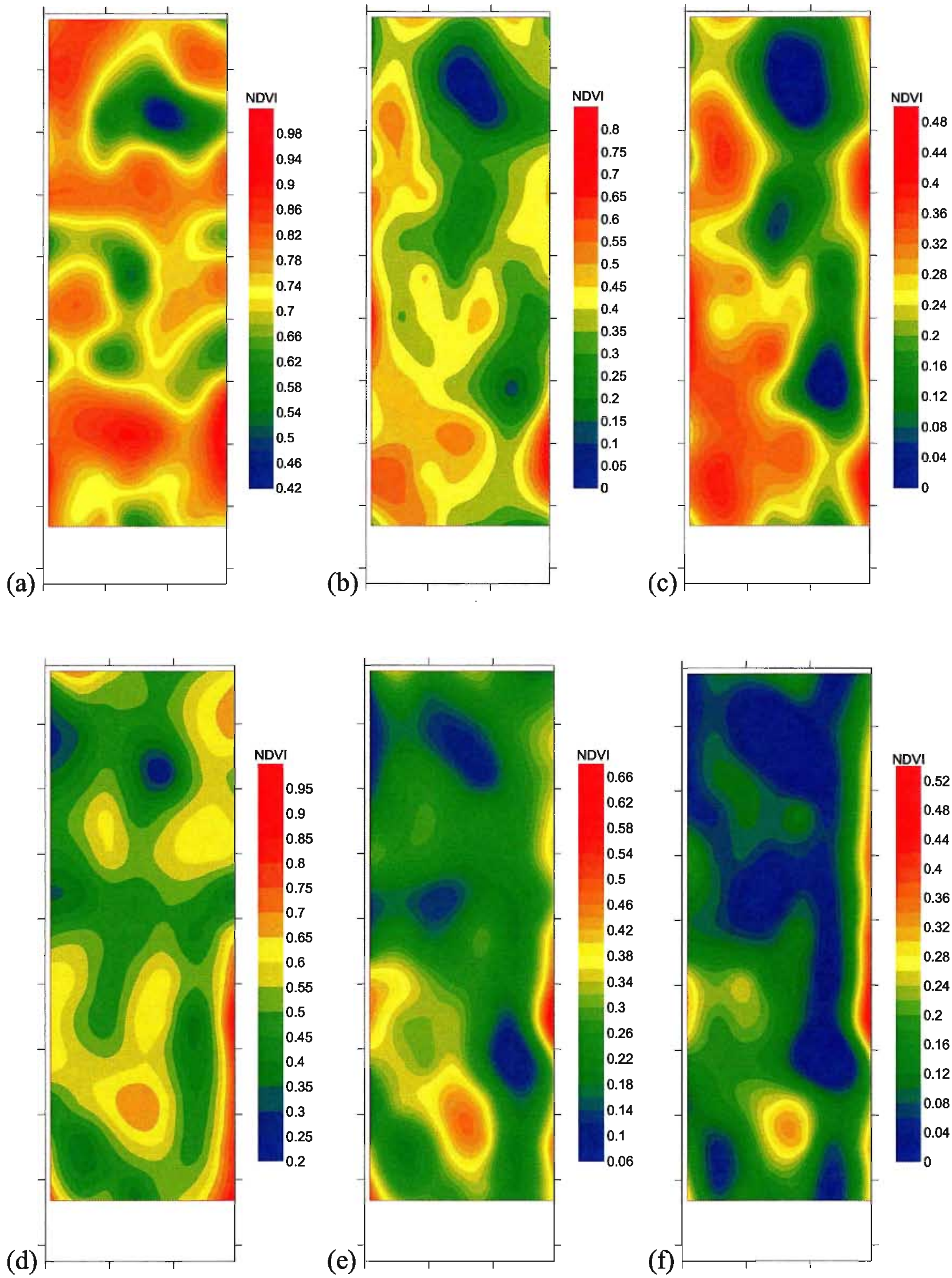
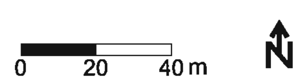


Figure 5-4: Maps of NDVI-red, extracted from Lowrey's Pinot noir vineyard (St. Davids, ON) airborne images. 29 July 2008: (a) 1x1 pixel, (b) 3x3 pixel, (c) 5x5 pixel; 21 August 2008: (d) 1x1 pixel, (e) 3x3 pixel, (f) 5x5 pixel.



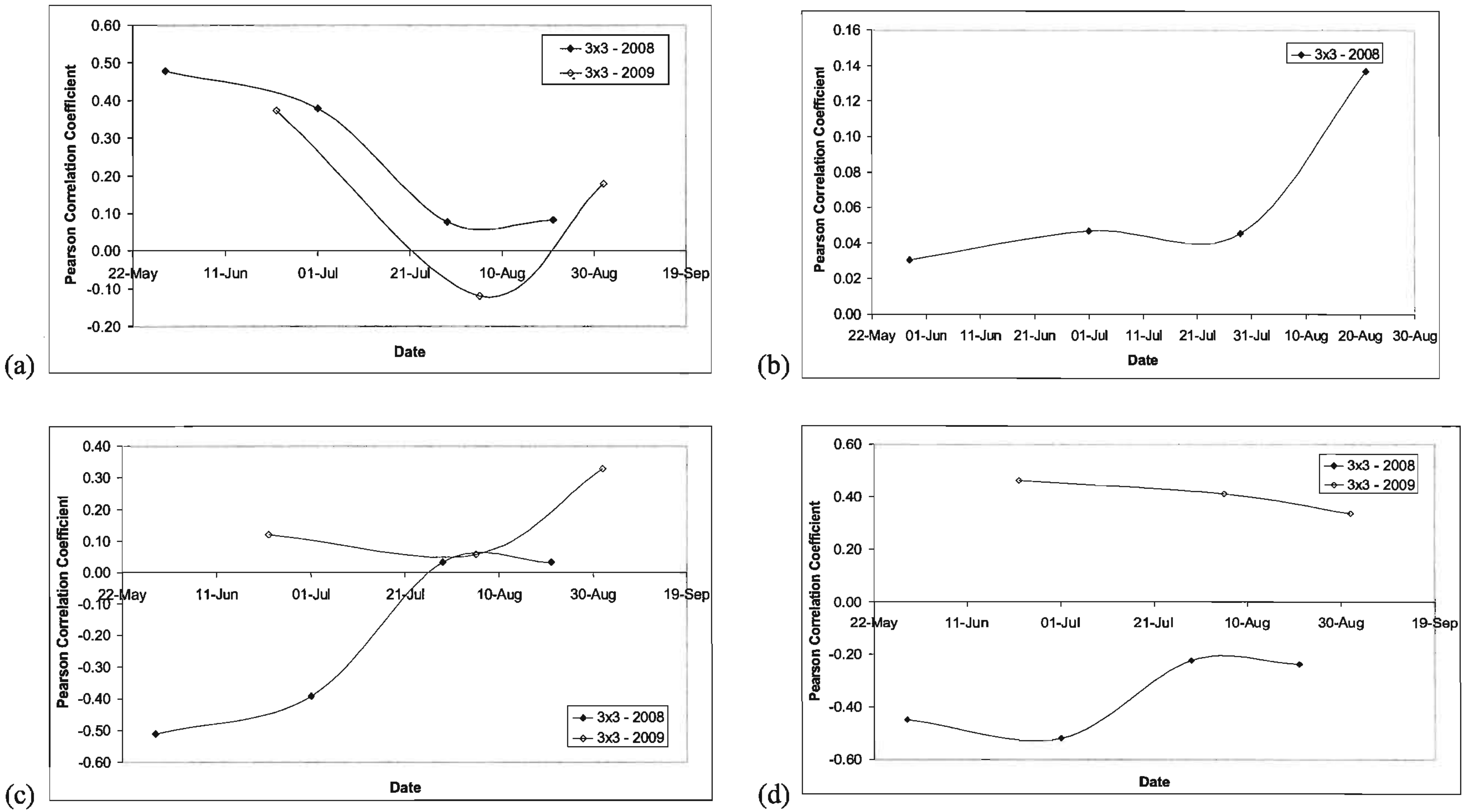


Figure 5-5: Trend of Pearson correlation coefficient of NDVI-red against (a) Ψ, (b) weight of cane prunings, (c) total phenols, (d) total anthocyanins for 3x3 pixel sample size at in four Pinot noir vineyard sites, St. Davids, ON, 2008 & 2009.

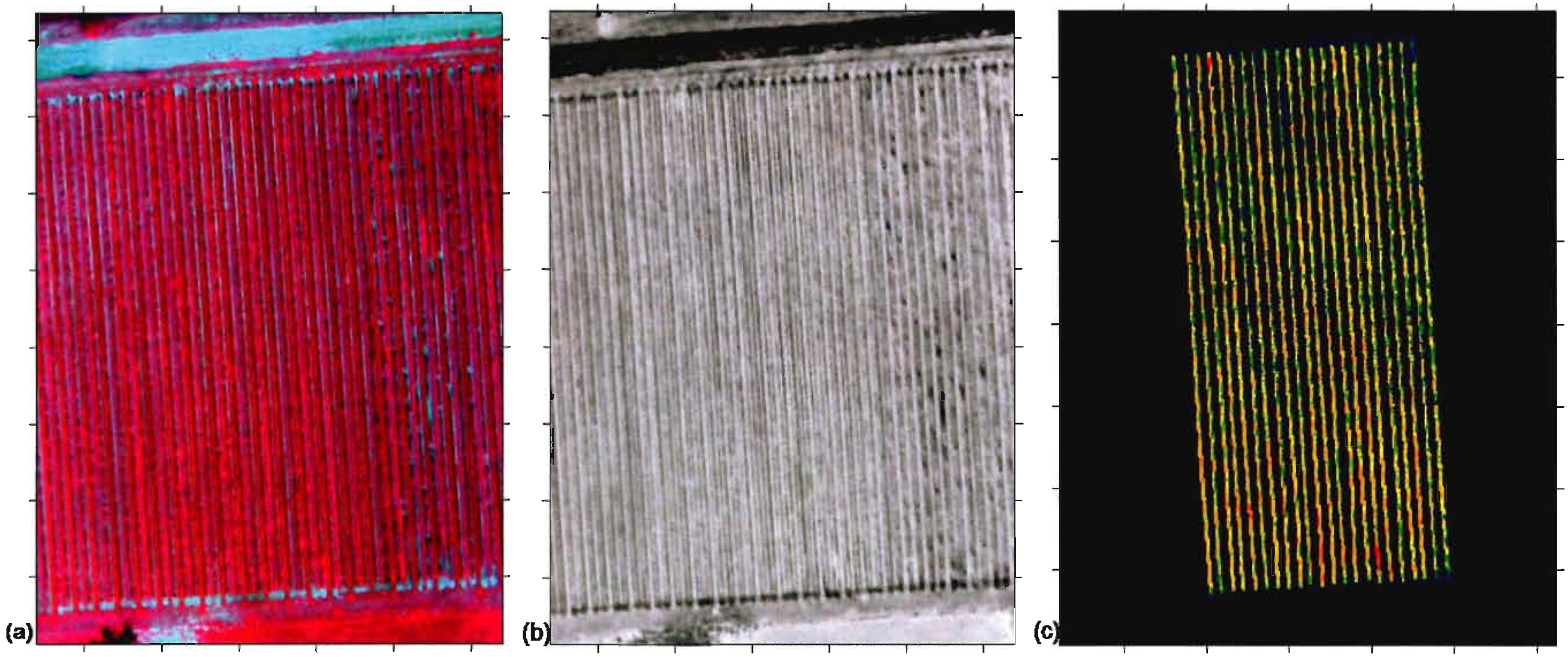
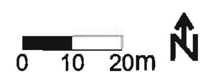


Figure 5-6: (a) CIR, (b) grayscale NDVI, (c) masked NDVI with density slice: Red Paw 2 Pinot noir vineyard, St. Davids, ON, 1 September 2009. In the grayscale image (b), darker areas are the lowest values of NDVI and white areas are the highest. When masked (c), only the areas most likely to be vine canopy remain, the blue areas are the lowest values of NDVI (0-0.15), followed by green (0,15-0.30), yellow (0.30-0.50), orange (0.50-0.70) and red (0.70-1.0).



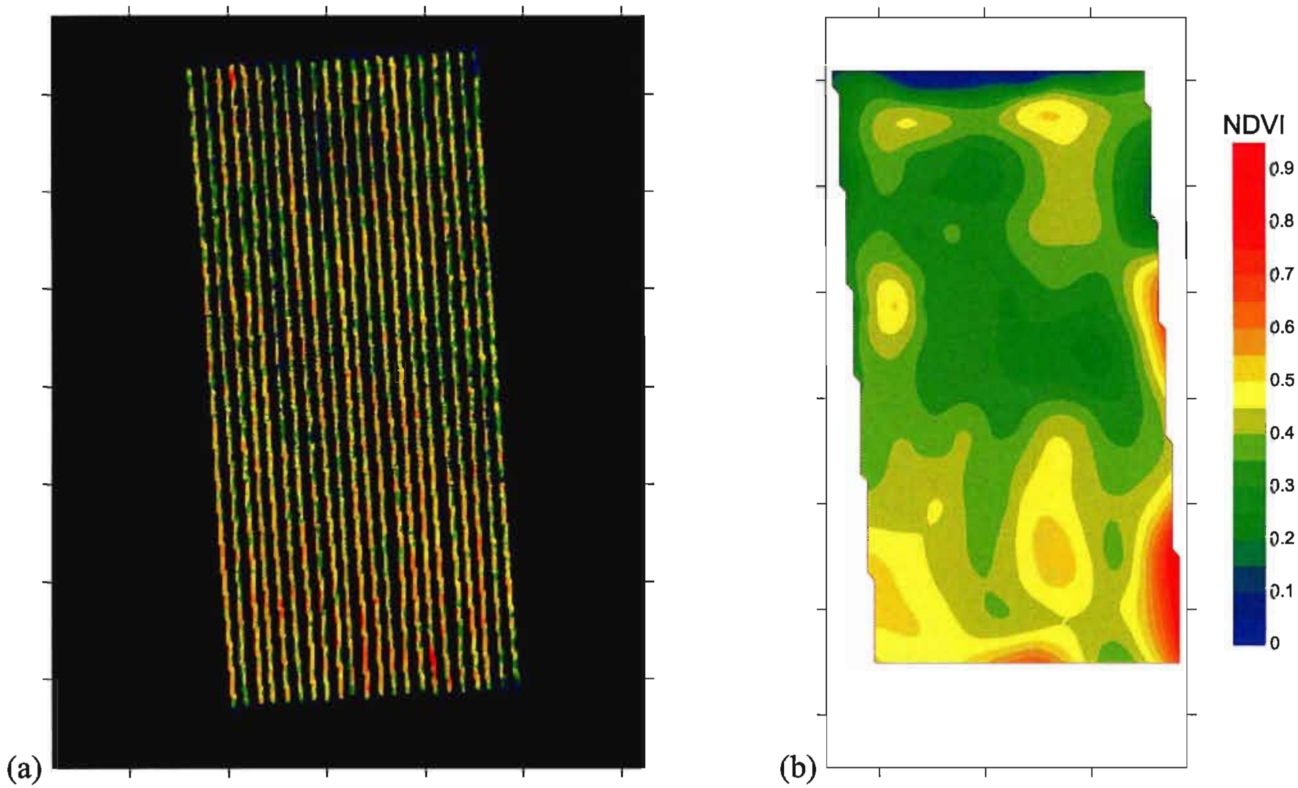
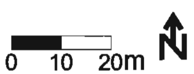


Figure 5-7: Red Paw 2 Pinot noir vineyard, St. Davids, ON, 1 September 2009; (a) masked NDVI and (b) map of NDVI extracted from 3x3 pixel re-sampling of the original multiband image. Note that the density slice applied to (a) is not the same colour scale as that created for the map in (b), but the relative meaning colours is the same.



6.0 General Discussion & Conclusions

The soil texture and nutrient content, vine water status, soil moisture, yield components and grape composition were measured in four Niagara, Ontario vineyards planted with Pinot noir in a study of within vineyard variability. Sentinel vines were geolocated using global GPS and a subset of these vines were identified as water status vines. Soil samples were collected in spring of 2008 at the water status vines to a depth of 75cm. During the 2008 and 2009 growing seasons, midday leaf water potential (Ψ) was measured bi-weekly at the water status vines using the pressure chamber technique. Soil moisture was measured bi-weekly using time domain reflectometry (TDR) with 20cm probes at all sentinel vines. Variables were mapped using GIS for delineation into zones based on water status and vigour status, and for qualitative analysis of spatial trends.

Both 2008 and 2009 were extremely wet years, resulting in a narrow range of soil and vine moisture status. Between 1 April and 31 October, there was 495mm of rain in 2008, and 553mm in 2009. While the total rainfall from April to October was less than the long-term average in 2008, monthly rainfall was higher than average in June, July and August in 2008 and May, June, July, August and October in 2009. These months are the key periods of fruit set, berry development, veraison and harvest respectively, and represent the field measurement period used in this study.

Yield was best correlated to the number of clusters (2008: $r=0.89$; $p\leq0.0001$, 2009: $r=0.88$; $p\leq0.0001$), and cluster size (2008: $r=65$; $p\leq0.0001$; 2009: $r=0.57$; $p\leq0.0001$), but not to berry size. In 2008, yield was also marginally correlated with berry soluble solids ($r=-0.43$; $p\leq0.0001$), total anthocyanins ($r=-0.49$; $p\leq0.0001$), and colour ($r=-0.51$; $p\leq0.0001$). Increasing yield had the effect of decreased ripening in the grapes. Higher yielding vines tended to have berries with a lower concentration of soluble solids and anthocyanins. Bramley (2005) found that high and low yielding zones were spatially distributed in agreement with distribution in colour and phenolics, and inconsistently with pH and TA. He concluded that while spatial distribution trends in yield are important, how this affects grape composition is not consistent across all vineyard sites (Bramley 2005). Reynolds et al. (1994) found that berry soluble solids, pH and colour were increased with a reduction in crop level in Pinot noir, but the canopy density and fruit shading, which are related to vigour and vine balance are likely also playing a role in fruit ripeness.

Also in 2008, mean Ψ was marginally correlated with berry pH ($r=-0.48$; $p \leq 0.0001$), berry soluble solids ($r=-0.43$; $p \leq 0.01$), shoot weight ($r=0.46$; $p \leq 0.01$), total anthocyanins ($r=-0.65$; $p \leq 0.0001$), colour ($r=-0.58$; $p \leq 0.0001$), clay content ($r=-0.43$; $p \leq 0.01$), and sand content ($r=0.47$; $p \leq 0.0001$). In 2009, mean Ψ was marginally correlated with the soil clay content ($r=-0.47$; $p<0.0001$), and sand content ($r=0.52$; $p<0.0001$). There was a relationship between the vine water status and the ripening of the grapes, as Ψ became more negative, the grapes accumulated more sugars and anthocyanins. This occurred in soils with more clay and less sand, the higher clay soils may have had higher water content, but the vines were not accessing it. Soils with more sand were likely better drained, with less available water. Shoot weight was not highly correlated to any other variable.

Black Paw was defined by its soil, in particular the clay content and the organic matter. The two Red Paw vineyards were most similar to one another, and the Lowrey's vineyard was more like the Red Paw vineyards than it was like Black Paw, set apart primarily by the sand component of the soil.

In 2009, there were fewer strong correlations between variables. Mean soil moisture was reasonably correlated with total anthocyanins ($r=-0.51$; $p \leq 0.0001$), soil clay content ($r=0.69$; $p \leq 0.0001$), silt content ($r=-0.81$; $p \leq 0.0001$), cation exchange capacity ($r=0.81$; $p \leq 0.0001$), and soil pH ($r=0.64$; $p \leq 0.0001$). In both years the soil type was a factor in the soil moisture. In 2009, the clay content was also marginally correlated with berry size ($r=-0.43$; $p<0.01$), and silt was correlated with total anthocyanins ($r=0.45$; $p<0.01$). Soil texture and water status were both factors in variability in grape composition.

In both years, but especially true in 2008, there was an effect of both Ψ and soil texture on grape composition. Soil moisture was not a strong indicator of vine water status, and vigour did not play a significant role in driving vineyard variability. It was hypothesized that vine water status is related to yield components and berry composition. It was found that while mean vine water status was correlated to some grape and soil variables, these relationships were not consistent across two vintages, and did not cover all of the key grape composition metrics. The weather was the likely cause of this; the higher than average rainfall during grape development meant that vines did not experience water stress during the growing season.

Findings relating to the relationships between vine water status and fruit compistion observed by Hardie & Considine (1976), Koundouras et al. (2006), Reynolds et al. 2007 were not confirmed in this study. An irrigation regime was not applied to the vines, and as has been extensively discussed, all of the vines were excessively watered by rainfall in both years of this study.

GIS was used to divide the vineyard sites by water status zone, and ANOVAs were performed to test for differences in the means of yield components, berry composition, vine growth, vineyard moisture status and soil variables. There was no metric, in either of the years, which was significantly different between water status zones for all four vineyard sites. In 2008 cluster size, berry TA and colour intensity were significantly different between water status zones in three of the four vineyards; however, for each of these metrics, the direction of the trend was not the same in the three vineyards. For example, the low water status zone has the higher TA in the Black Paw vineyard, but it was the high water status zone with the higher TA in Red Paw 2 and Lowrey's vineyards. In 2009, there were never more than two of the four vineyards with differences between water status zones. The gross variation in Ψ was relatively low as seen in Table 7-1 through Table 7-4; the range from maximum to minimum Ψ was not large, and with excess moisture the vine water status was not the primary factor in variability within or between vineyards.

The same GIS tool was used to divide the vineyards by vigour zone as determined by pruning cane weight. Means of yield components, berry composition, vine growth, vineyard moisture status and soil variables were not different between vigour status zones at all four sites in either vintage. In 2008 berry size and soil sand content were different between vigour status zones in three of the four vineyards. In berry size, the trend was the same in each of those three vineyards, with the high vigour status zone having the larger berries. The trend is not consistent for all three vineyards in terms of sand. In 2009 only the Lowrey's block was evaluated by vine size. Vigour zones were significantly different for all yield components, berry TA, colour intensity, soil clay and sand, and organic matter. In 2008 and 2009, vigour was not a primary factor in grape composition or vineyard performance.

There was a relatively strong correlation between the mean NDVI and the mean Ψ in 2008. For 1x1, 3x3 and 5x5 pixel re-sampling, r=0.70, 0.65 and 0.56 ($p \leq 0.0001$) respectively. The correlations were far less strong for NDVI-green, for 1x1, 3x3 and 5x5 pixel re-sampling, r=0.35, 0.45 ($p \leq 0.01$) and r=0.62 ($p \leq 0.0001$) respectively. In 2009, they were not well correlated.

There were some differences between the mean VI for vigour zones; using NDVI-red, there were differences between vigour zones in the Black Paw vineyard, but counter-intuitively the low vigour zone had the higher mean NDVI. In Red Paw 1, at 5x5 pixel re-sampling, there was a difference between vigour zones, with the high vigour zone having the larger NDVI. With NDVI-green, there were differences between vigour zones in Black Paw, but with the high vigour zone having the lower NDVI. In 2009 there were differences between vigour zones using 1x1 and 5x5 re-sampling in Lowrey's vineyard, with the high vigour zone having the higher NDVI.

The division by vigour status did not yield a more useful application of remote sensing than division by water status. There was a strong correlation between shoot weight and NDVI-red and -green in 2008 and this may indicate support for use of remote sensing to delineate vigour zones for selective vineyard management, or identification of trouble-spots in a vineyard. For 1x1, 3x3 and 5x5 pixel re-sampling, the Pearson correlation coefficients between pruning weight and NDVI-red were r=0.51, 0.46 and 0.36 ($p \leq 0.0001$) respectively. The correlations were weaker between shoot weight and NDVI-green, using 1x1, 3x3, and 5x5 pixel re-sampling: r=0.14 ($p \leq 0.05$), r=0.23 and 0.40 ($p \leq 0.0001$) respectively. NDVI-red was better correlated to vine size than NDVI-green in 2008. Gitelson et al. (1996) proposed using the green waveband as a sensitive indicator of chlorophyll content with an advantage of existing satellite-based systems in that using the green-band proved less affected by atmospheric interference. In this study gain settings on the aircraft-mounted camera were corrected at each imaging site, eliminating the need for atmospheric correction and perhaps nullifying the advantage of using the green waveband.

In grape composition metrics, 2008 3x3 pixel NDVI-red correlated best with cluster size (r=0.39; $p \leq 0.0001$), berry pH (r=-0.48; $p \leq 0.0001$), berry soluble solids (r=-0.43; $p \leq 0.0001$), total anthocyanins (r=-0.65; $p \leq 0.0001$), and colour (r=-0.58; $p \leq 0.0001$). In 2009, NDVI-red correlated best with anthocyanins (r=0.49; $p \leq 0.0001$) and mean soil moisture (r=-0.89; $p \leq 0.0001$). The change in sign of the correlations between years, and the sometimes counter-intuitive trends suggest that further years of data collection would be beneficial in understand the true potential of using remote sensing for predicting grape composition in Niagara, Ontario Pinot noir.

This study did not reveal an ideal time for remote sensing aerial image capture in predicting grape composition or vine size as was predicted by Lamb et al. (2004). The seasonal mean from both vintages indicated that vegetation indices extracted from aerial images have limited potential for use in predicting grape composition and vine vigour in a cool climate, but the lack of clear trends made it impossible to make recommendations as to ideal flight scheduling. Physiological changes associated with some degree of water stress, as is expected in a dry climate such as Australia where Lamb et al. performed their study, may result in changes in the absorbance spectra of the grapevine canopy that did not occur in Ontario in 2008 and 2009.

Geomatics and remote sensing tend to work well at predicting spatial trends, but this study investigated individual vines as targets. Without the application of a treatment, increasing the number of sentinel vines did not increase the range of values experiences by the vines. There may have been some benefit in sampling a panel of vines on a per metre basis, rather than sampling individual sentinel vines. This would have allowed for sample points to be an average of the local vineyard area, eliminating weighted effects of differences between individual vines and allowing within-vineyard regional differences to emerge. Variations of this type of sampling was used by Dobrowski et al. (2003), and Acevedo-Opazo et al. (2008) and Hall et al. (2008).

The chemical composition of musts and wines revealed that in no measured parameter were the wines from water status zones within each vineyard significantly different from more than two of the vineyards in either vintage. Differences between the must soluble solids in Red Paw 1 and Lowrey's vineyards did not translate to differences in wine ethanol content, although in general, the water status group with the higher soluble solids concentration became the wine with the higher ethanol content.

Reverse-phase HPLC was used to quantify the concentration of individual anthocyanins, flavonol-3 phenolics, non-flavonoid phenolics, and trans-resveratrol in the wines. There were no differences in the concentrations of any of the compounds between water status zones in all four vineyards. As was seen in the other wine chemical composition metrics, there was not a difference between the wines.

Malvidin represented the largest proportion of anthocyanins, followed by peonidin, petunidin, delphinidin and cyanidin. In general, the concentrations of all anthocyanins were higher in 2009 than in 2008. Trans-resveratrol concentrations were higher in 2009 than in 2008, in some cases by more than double, with the exception of Red Paw 2 low water status wines.

The hypothesis that must and wine chemical attributes are related to water status was not proven. Once more, the wetter and cooler than average weather meant that the range of water status values observed was very narrow, with a small difference between zones that did not translate to a physiological difference.

In terms of sensory attributes, the MDS revealed that the replicate fermentations resulted in unique wines inconsistent with water status. The winemaking in this study was standardized as much as possible through the bulking of fruit, and consistent handling of the musts, fermenting and final wines through water status zones. It is likely that there were simply not large differences between the water status zones to begin with, and so fermentation effects were pronounced.

There were only two sensory attributes that were different between all wines from Red Paw 1, two attributes from Red Paw 2 wines, and three attributes from Lowrey's wines. Averaging all wines from the water status zones in each vineyard, there was a difference between Lowrey's water status zones in sweet aroma; otherwise there were no differences between attribute intensities for any of the water status zones in any other vineyard. In the case of Lowrey's, the low water status zone had the highest intensity of sweet aroma, and the high water status zone had the lowest intensity. The medium water status zone was not significantly different from the other two.

Taking the mean of all wines from each vineyard, there were only two attributes that were different between vineyards: pepper spice and vegetal. These same two attributes were identified as areas where judges did not perform as reliably in rating the intensity. Red Paw 1 had the highest intensity for pepper spice aroma, and Lowrey's had the lowest, while Red Paw 2 was not significantly different from either. Lowrey's wines had the highest vegetal aroma intensity, Red Paw 1 had the lowest, and Red Paw 2 was not significantly different from either. In the PCA, the wines did not cluster by water status or vineyard, and it is not possible to draw any conclusions as to the effect of water status on the sensory attributes of the wines.

Generally, the Lowrey's vineyard wines were described by vegetal aroma and flavour. Red Paw 1 wines were described by tart fruit aroma, baking spice and pepper spice aroma, and spice flavour. Red Paw 2 wines were the least clustered, and not clearly described by any of the attributes.

The relationship between water status and vine size revealed that there was some relationship between vine size and water status in 2008. It was marginal statistical relationship ($r=0.46$; $p\leq0.01$) but a reasonable spatial relationship was not seen in all four vineyard sites. The vine vigour may have been playing a role in the sensory profile of the wines, but was not aligned with the water status zones.

There were qualitative similarities between maps of soil texture, Ψ and soil moisture. Soil texture and vineyard water status were related, even in two wet vintages, and are collectively likely responsible for some within vineyard variability. The lack of differences between the chemical attributes of the musts and wines emphasized that there was not a great difference between water status zones in the vineyards.

Within the same vintage, the maps of berry composition variables were very similar. Maps of total anthocyanins, colour, hue and phenols were very similar to one another within vineyard sites, within vintage. In general, the Black Paw maps were difficult to interpret as a result of the site geometry. The site is very narrow compared to the length of the rows, and difficult for gridding to produce a meaningful surface map.

Spatial variation in water status zones, the basis for site divisions in this study, was somewhat stable between vintages. The soil texture of the vineyards, one of the other drivers of variability, matched spatial trends seen in other variables.

Vine size, measured by weight of cane pruning, showed spatial distribution somewhat similar to other variables, even though there were not strong correlations between this variable and others. Regions of higher shoot weight in Red Paw 1 also showed higher soil moisture, lower total anthocyanins, and higher soluble solids. This trend did not appear in the other vineyards though, and is consistent with the lack of strong correlation. In 2009, Lowrey's was the only vineyard with shoot weight measurements, and again there was not a strong similarity to the maps of soil moisture, total anthocyanins or any other grape composition metric.

The similarity of the weather in the two years, while a complicating factor for observing the effect of water status may have been at least partially responsible for the stability in some of the spatial trends between years. Further years of study are recommended to gain a better appreciation of trends in spatial variation over time, in varied weather conditions. One of the objectives of this study was to test the use of GPS and GIS as tools in the understanding of Niagara terroir. Although the results of this study do not confirm the hypotheses about the effect of vine water status on grape composition, they were used successfully for monitoring trends in vineyard performance, a key decision-making tool in the precision viticulture feedback cycle.

Using remote sensing and GIS co-operatively has the greatest potential for the implementation of PV. The masked images proved to be a quick method of viewing spatial trends in airborne images without the data extraction process. There were qualitative similarities between maps of vineyard and grape composition variables to the maps of extracted data and the masked images.

Using the mask of a vineyard, true NDVI values at individual pixels are retained. In contrast, a map drawn from extracted values at sentinel vines required interpolation averaging, and may miss small spatial trends. An additional objective of this study was to test the use of remote sensing to monitor or predict trends in berry composition and vineyard performance. This was proven using both extracted values, and spatially by qualitative comparison.

Further years of study are warranted to test whether geomatics and remote sensing tools can be used to monitor Niagara vineyard conditions in all years, no matter how abnormal the weather. There was clear variability in all of the vineyard sites, and the lack of relationships between the spatially delineated water status zones and the variation in the fruit and wine suggests that water status in combination with other factors such as soil type should be combined in a more complex model of within vineyard terroir.

The alternate measurements of vine vigour taken in 2009 were not successful. The risk of missing data, as was the case in 2009, suggests that alternate vigour measurements should be further explored. Other methods of measuring vine vigour, such as shoot length, trunk cross-sectional area and leaf chlorophyll content used by Cortell et al. (2007a, 2007b, 2008) may prove more reliable than weight of cane pruning alone.

Other potential sources of variation within vineyards of potential interest to winemakers include the variability of yeast assimilable nitrogen compounds, and differences in vineyard temperature, especially through the winter and spring frost periods. The degree of cold experienced by a vine, and its ability to survive the exposure, may be linked to soil and moisture, as well as the topography of the vineyard. PV and remote sensing could play a role in monitoring and acting on any of these factors, and more, in Niagara and around the world.

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7.0 Supplemental Materials

Table 7-1: Summary statistics for harvest components, grape composition, and vineyard soil variables for the Red Paw 1 Pinot noir vineyard, St. Davids, ON, 2008-2009.

		Red Paw 1				
	Year	Median	Max	Min	CV (%)	Spread[a]
Yield (kg/vine)	2008	2.80	5.48	0.75	38.5	169.4
	2009	2.52	4.67	0.57	37.2	162.7
Cluster weight (g)	2008	107.18	177.97	63.29	17.8	107.0
	2009	100.90	139.42	64.55	15.7	74.2
Berry weight (g)	2008	1.69	1.98	1.22	9.1	45.3
	2009	1.53	1.81	1.10	9.2	46.3
Soluble solids (Brix)	2008	21.4	24.2	15.8	7.5	39.3
	2009	22.9	25.6	17.7	6.9	34.5
Berry pH	2008	3.58	3.73	3.44	1.6	7.9
	2009	3.54	3.64	3.40	1.6	6.9
TA (g/L)	2008	9.1	10.7	6.5	8.0	46.0
	2009	9.8	12.8	8.2	8.4	47.0
Vine size (kg)	2008	0.41	0.88	0.06	39.4	200.8
	2009[b]	-	-	-	-	-
Crop load (kg/kg)	2008	7.72	58.35	1.33	84.2	739.0
	2009[b]	-	-	-	-	-
Total anthocyanins (mg/L)	2008	257.0	371.4	186.9	17.9	71.8
	2009	346.4	475.5	191.4	16.1	82.0
Total phenols (mg/L)	2008	1742.5	2609.17	880.0	17.2	99.2
	2009	2386.6	3048.3	1779.4	11.5	53.2
Colour (au)	2008	9.4	13.91	7.09	17.0	72.3
	2009	10.0	13.0	5.8	14.5	72.2
Hue (au)	2008	0.6	0.7	0.5	6.5	37.1
	2009	0.6	0.6	0.5	4.9	21.9
Mean soil moisture (%)	2008	12.7	20.7	10.1	14.1	83.7
	2009	10.3	14.8	7.1	15.5	75.1
Mean Ψ (bar)	2008	-7.9	-7.3	-8.6	5.6	17.7
	2009	-8.2	-7.1	-9.5	8.5	28.9
Clay (%)	-[c]	37.0	45.0	33.0	8.9	32.4
Sand (%)	-[c]	6.5	12.0	1.0	49.0	169.2
Silt (%)	-[c]	56.5	63.0	49.0	6.6	24.8
OM (%)	-[c]	2.4	5.2	1.4	36.8	158.3
CEC (meq/100g)	-[c]	16.1	27.9	13.8	21.8	87.6
Soil pH	-[c]	5.6	7.2	5.0	10.9	39.6

[a] Spread (Bramley 2005) is defined as the range (max-min) divided by the median, expressed as a percent.
[b] Pruning shoot weights were not measured in 2009 at this site.
[c] Soil samples were taken in 2008 only.

Table 7-2: Summary statistics for harvest components, grape composition, and vineyard soil variables for the Red Paw 2 Pinot noir vineyard, St. Davids, ON, 2008-2009.

		Red Paw 2				
	Year	Median	Max	Min	CV (%)	Spread[a]
Yield (kg/vine)	2008	2.61	5.38	0.48	43.1	188.0
	2009	2.32	3.90	0.35	33.8	153.1
Cluster weight (g)	2008	94.98	127.67	62.00	16.6	69.1
	2009	106.62	141.43	58.17	15.3	78.1
Berry weight (g)	2008	1.65	2.03	1.15	12.0	53.5
	2009	1.67	2.00	1.25	8.0	45.0
Soluble solids (Brix)	2008	21.8	24.3	17.7	7.3	30.3
	2009	23.9	25.7	20.6	4.4	21.3
Berry pH	2008	3.62	3.78	3.48	1.8	8.2
	2009	3.65	3.81	3.46	2.0	9.6
TA (g/L)	2008	7.9	9.3	7.0	5.8	29.1
	2009	8.1	9.4	7.1	5.8	27.7
Vine size (kg)	2008	0.29	0.71	0.06	45.1	221.3
	2009[b]					
Crop load (kg/kg)	2008	8.42	49.66	1.66	76.9	570.3
	2009[b]					
Total anthocyanins (mg/L)	2008	288.1	416.4	170.2	19.2	85.5
	2009	383.9	465.2	279.8	10.4	48.3
Total phenols (mg/L)	2008	1582.4	2516.4	798.2	17.5	108.6
	2009	2014.2	2947.9	1432.9	17.8	75.2
Colour (au)	2008	10.5	14.8	6.6	17.3	78.0
	2009	7.9	10.4	5.6	12.2	61.1
Hue (au)	2008	0.6	1.0	0.5	11.1	69.3
	2009	0.7	0.8	0.6	4.0	21.3
Mean soil moisture (%)	2008	12.6	17.6	9.8	12.2	61.4
	2009	10.6	13.2	8.5	10.1	44.1
Mean Ψ (bar)	2008	-8.1	-7.6	-8.8	3.6	15.4
	2009	-7.7	-6.5	-8.5	7.5	26.3
Clay (%)	-[c]	38.0	51.0	30.0	16.8	55.3
Sand (%)	-[c]	6.0	24.0	1.0	80.8	383.3
Silt (%)	-[c]	54.0	67.0	44.0	9.4	42.6
OM (%)	-[c]	3.7	5.4	2.7	20.9	73.0
CEC (meq/100g)	-[c]	17.6	28.6	15.6	20.3	73.9
Soil pH	-[c]	6.4	7.4	5.8	7.7	25.0

[a] Spread (Bramley 2005) is defined as the range (max-min) divided by the median, expressed as a percent.
[b]Pruning shoot weights were not measured in 2009 at this site.
[c]Soil samples were taken in 2008 only.

Table 7-3: Summary statistics for harvest components, grape composition, and vineyard soil variables for the Black Paw Pinot noir vineyard, St. Davids, ON, 2008-2009.

		Black Paw				
	Year	Median	Max	Min	CV (%)	Spread[a]
Yield (kg/vine)	2008	1.09	3.88	0.12	65.0	344.5
	2009	2.51	5.08	1.00	29.2	163.0
Cluster weight (g)	2008	72.51	107.09	43.80	22.5	87.3
	2009	103.50	170.57	40.62	21.8	125.6
Berry weight (g)	2008	1.50	1.89	1.04	12.0	56.4
	2009	1.39	1.69	1.03	9.1	46.8
Soluble solids (Brix)	2008	22.6	27.5	17.9	6.8	42.5
	2009	22.9	25.1	17.2	7.8	34.6
Berry pH	2008	3.60	3.70	3.46	1.5	6.8
	2009	3.58	3.74	3.45	1.8	8.1
TA (g/L)	2008	8.6	12.3	7.4	10.2	56.5
	2009	7.8	9.2	0.6	14.3	110.3
Vine size (kg)	2008	0.29	0.82	0.06	57.2	261.5
	2009[b]	-	-	-	-	-
Crop load (kg/kg)	2008	3.37	17.2	0.77	78.2	487.3
	2009[b]	-	-	-	-	-
Total anthocyanins (mg/L)	2008	358.9	613.3	234.5	17.6	105.5
	2009	296.3	416.7	194.5	13.9	75.0
Total phenols (mg/L)	2008	2090.7	3039.4	1595.0	12.5	69.1
	2009	2001.7	2556.3	1450.4	11.2	55.2
Colour (au)	2008	14.5	28.9	9.6	19.9	133.7
	2009	8.0	11.5	5.2	15.3	77.9
Hue (au)	2008	0.6	0.9	0.4	12.6	84.7
	2009	0.6	0.7	0.5	6.1	36.1
Mean soil moisture (%)	2008	29.2	39.3	19.7	17.6	66.9
	2009	25.4	33.1	17.4	15.7	61.8
Mean Ψ (bar)	2008	-8.7	-7.8	-9.4	6.3	18.5
	2009	-8.7	-8.0	-9.3	4.9	14.7
Clay (%)	-[c]	64.0	68.0	61.0	3.6	10.9
Sand (%)	-[c]	4.0	6.0	1.0	61.5	125.0
Silt (%)	-[c]	33.0	36.0	30.0	5.1	18.2
OM (%)	-[c]	5.1	6.5	3.2	18.4	64.7
CEC (meq/100g)	-[c]	38.8	46.2	34.3	11.6	30.7
Soil pH	-[c]	7.4	7.5	7.2	1.4	4.1

[a] Spread (Bramley 2005) is defined as the range (max-min) divided by the median, expressed as a percent.
[b] Pruning shoot weights were not measured in 2009 at this site.
[c] Soil samples were taken in 2008 only.

Table 7-4: Summary statistics for harvest components, grape composition, and vineyard soil variables for the Lowrey's Pinot noir vineyard, St. Davids, ON, 2008-2009.

				Lowrey's		
	Year	Median	Max	Min	CV (%)	Spread[a]
Yield (kg/vine)	2008	2.60	5.33	0.25	43.9	195.0
	2009	2.72	6.50	0.62	39.8	216.2
Cluster weight (g)	2008	110.29	210.40	45.83	24.1	149.2
	2009	99.83	144.35	62.20	17.0	82.3
Berry weight (g)	2008	1.46	1.72	1.13	8.4	40.8
	2009	1.73	2.14	1.41	8.4	42.3
Soluble solids (Brix)	2008	20.4	22.3	17.4	5.4	24.0
	2009	22.2	23.6	19.4	3.7	18.9
Berry pH	2008	3.47	3.61	3.34	1.5	7.6
	2009	3.55	3.70	3.41	1.7	8.2
TA (g/L)	2008	8.3	9.6	7.1	6.1	30.3
	2009	8.3	11.0	7.5	7.5	41.5
Vine size (kg)	2008	0.60	1.48	0.20	39.0	214.3
	2009	0.68	1.56	0.06	39.4	220.8
Crop load (kg/kg)	2008	4.59	11.44	0.59	45.0	236.3
	2009	3.65	12.87	0.84	51.5	329.5
Total anthocyanins (mg/L)	2008	224.1	373.8	150.7	18.6	99.6
	2009	283.8	386.7	173.3	12.1	75.2
Total phenols (mg/L)	2008	1835.0	3155.8	1212.7	16.1	105.9
	2009	2241.6	2753.7	1785.2	9.1	43.2
Colour (au)	2008	9.2	14.2	6.9	16.5	80.1
	2009	6.5	8.7	4.7	13.4	62.2
Hue (au)	2008	0.7	0.8	0.5	9.0	37.0
	2009	0.6	0.7	0.6	3.9	22.7
Mean soil moisture (%)	2008	22.5	31.1	15.9	14.9	67.5
	2009	23.3	32.2	14.8	16.3	74.8
Mean Ψ (bar)	2008	-7.2	-6.0	-8.3	9.6	32.0
	2009	-7.8	-5.9	-9.5	12.0	46.9
Clay (%)	-[c]	40.0	48.0	30.0	13.2	45.0
Sand (%)	-[c]	11.0	29.0	4.0	50.6	227.3
Silt (%)	-[c]	48.0	52.0	41.0	7.0	22.9
OM (%)	-[c]	2.9	4.5	2.0	21.1	86.2
CEC (meq/100g)	-[c]	24.5	37.9	19.9	17.5	73.5
Soil pH	-[c]	6.7	7.4	6.3	3.8	16.4

[a] Spread (Bramley 2005) is defined as the range (max-min) divided by the median, expressed as a percent.
[c]Soil samples were taken in 2008 only.

Table 7-5: Means of yield components grouped by vigour status zone at four Pinot noir vineyard sites, St. Davids, ON, 2008-2009.

Vigour Status Category	Yield (kg)		No. of clusters		Cluster weight (g)		Berry weight (g)	
Red Paw 1	2008	2009[b]	2008	2009	2008	2009	2008	2009
Low	2.62b	-	24.1b	-	107.9	-	1.63b	-
High	3.17a	-	28.7a	-	108.8	-	1.71a	-
Significance[a]	**	-	**	-	ns	-	**	-
Red Paw 2								
Low	2.54	-	26.3	-	94.9	-	1.56b	-
High	2.67	-	27.7	-	95.4	-	1.66a	-
Significance	ns	-	ns	-	ns	-	**	-
Black Paw								
Low	1.22	-	16.3	-	72.3	-	1.45b	-
High	1.51	-	20.5	-	72.3	-	1.56a	-
Significance	ns	-	ns	-	ns	-	**	-
Lowrey's								
Low	2.23b	2.39b	20.0b	22.9a	110.3	103.7a	1.45	1.70b
High	2.85a	2.88a	24.3a	29.1b	113.7	97.2b	1.46	1.75a
Significance	***	**	***	****	ns	*	ns	*

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at $p \leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively

[b]In 2009, Lowrey's vineyard was the only site where pruning shoot weights were measured.

Table 7-6: Means of soil and vine water status and weight of cane pruning grouped by vigour status zone at four Pinot noir vineyard sites, St. Davids, ON, 2008-2009.

Vigour Status Category	Soil moisture (%)		Ψ (bar)		Weight of cane pruning (kg)	
Red Paw 1	2008	2009[b]	2008	2009	2008	2009
Low	13.4	-	-7.9	-	0.29b	-
High	13.0	-	-7.9	-	0.49a	-
Significance[a]	ns	-	ns	-	****	-
Red Paw 2						
Low	13.2	-	-8.0	-	0.19b	-
High	12.3	-	-9.2	-	0.41a	-
Significance	**	-	ns	-	****	-
Black Paw						
Low	30.0	-	-8.6	-	0.22b	-
High	25.4	-	-8.7	-	0.47a	-
Significance	****	-	ns	-	****	-
Lowrey's						
Low	22.5	19.8	-7.2	-7.7	0.43b	0.48b
High	23.4	19.3	-7.0	-7.2	0.77a	0.89a
Significance	ns	ns	ns	ns	****	****

[a]Mean separation at $\alpha=0.1$ using the LSD test *, **, ***, ****, ns: Significant at $p\leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively

[b]In 2009, Lowrey's vineyard was the only site where pruning shoot weights were measured.

Table 7-7: Means of berry composition (soluble solids, TA, and pH) grouped by vigour status zone at four Pinot noir vineyard sites, St. Davids, ON, 2008-2009.

Vigour Status Category	Berry Brix		Berry TA (g/L)		Berry pH	
Red Paw 1	2008	2009[b]	2008	2009	2008	2009
Low	20.9	-	9.0	-	3.58	-
High	20.9	-	9.2	-	3.58	-
Significance[a]	ns	-	ns	-	ns	-
Red Paw 2						
Low	21.0b	-	7.9	-	3.61b	-
High	22.0a	-	7.9	-	3.64a	-
Significance	***	-	ns	-	**	-
Black Paw						
Low	22.5	-	8.7	-	3.59	-
High	22.6	-	8.8	-	3.60	-
Significance	ns	-	ns	-	ns	-
Lowrey's						
Low	20.3	22.2	8.3	8.3b	3.46b	3.54
High	20.3	22.1	8.3	8.6a	3.48a	3.55
Significance	ns	ns	ns	**	*	ns

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at $p \leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively.
[b]In 2009, Lowrey's vineyard was the only site where pruning shoot weights were measured.

Table 7-8: Means of berry composition (total anthocyanins, colour intensity, hue, and total phenols) grouped by vigour status zone at four Pinot noir vineyard sites, St. Davids, ON, 2008-2009.

Vigour Status Category	Total anthocyanins (mg/L)		Colour (au)		Hue (au)		Total phenols (mg/L)	
Red Paw 1	2008	2009[b]	2008	2009	2008	2009	2008	2009
Low	271.3a	-	9.9a	-	0.6b	-	1755.4	-
High	244.8b	-	9.0b	-	0.6a	-	1710.2	-
Significance[a]	**	-	*	-	*	-	ns	-
Red Paw 2								
Low	280.4	-	10.3	-	0.6	-	1647.8a	-
High	288.5	-	10.4	-	0.7	-	1546.7b	-
Significance	ns	-	ns	-	ns	-	***	-
Black Paw								
Low	369.3a	-	15.0	-	0.5	-	2122.6	-
High	339.2b	-	13.9	-	0.6	-	2070.5	-
Significance	*	-	ns	-	ns	-	ns	-
Lowrey's								
Low	227.9	282.4	9.4	6.2b	0.7	0.6	1893.7	2195.3
High	227.4	294.6	9.4	6.5a	0.7	0.6	1794.4	2251.9
Significance	ns	ns	ns	*	ns	ns	ns	ns

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at p$\leq$0.1, 0.05, 0.01, 0.001, not significant, respectively
[b]In 2009, Lowrey's vineyard was the only site where pruning shoot weights were measured.

Table 7-9: Means of soil variables grouped by vigour status zones at four Pinot noir vineyard sites, St. Davids, ON, 2008-2009.

Vigour Status Category	Clay (%)		Silt (%)		Sand (%)		OM (%)		CEC (meq/100g)		Soil pH	
Red Paw 1	2008	2009[b]	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
Low	38.4b	-	58.1a	-	6.5	-	2.2	-	18.0	-	6.0	-
High	35.5a	-	54.4b	-	7.1	-	2.9	-	17.1	-	5.6	-
Significance[a]	*	-	**	-	ns	-	ns	-	ns	-	ns	-
Red Paw 2												
Low	40.7	-	54.8	-	4.6	-	3.7	-	18.9	-	6.4	-
High	36.2	-	53.3	-	10.8	-	3.9	-	19.6	-	6.5	-
Significance	ns	-	ns	-	**	-	ns	-	ns	-	ns	-
Black Paw												
Low	65.3	-	32.7	-	2.0	-	4.8	-	41.3	-	7.4	-
High	62.4	-	33.4	-	4.2	-	5.2	-	38.3	-	7.3	-
Significance	**	-	ns	-	**	-	ns	-	ns	-	ns	-
Lowrey's												
Low	38.6	44.6a	45.6	46.4	15.9	9.0b	3.2	3.5a	25.2	30.0b	6.7	6.7
High	41.3	37.8b	48.1	47.6	10.7	14.7a	2.9	2.7b	26.3	23.5a	6.7	6.7
Significance	ns	***	ns	ns	*	*	ns	***	ns	****	ns	ns

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at $p \leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively.
[b]In 2009, Lowrey's vineyard was the only site where pruning shoot weights were measured.

Table 7-10: Pearson's correlation coefficients between yield components, berry composition and vineyard moisture and soil variables, 2008, at four Pinot noir vineyard sites, St. Davids, ON. Colour coding relates to significance (p-value) where yellow, blue and red represent $p \leq 0.0001$, 0.01, and 0.05 respectively.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1 - Yield	1	0.89	0.65	-0.05	-0.21	-0.43	0.00	0.22	0.41	-0.49	-0.51	0.18	-0.31	-0.34	0.17	-0.36	0.28	0.22	-0.27	-0.31	-0.34
2 - No. Clusters		1	0.28	-0.04	-0.03	-0.33	-0.06	0.13	0.40	-0.37	-0.42	0.15	-0.29	-0.36	0.14	-0.32	0.26	0.18	-0.20	-0.31	-0.29
3 - g/Cluster			1	-0.05	-0.38	-0.35	0.05	0.27	0.26	-0.43	-0.40	0.15	-0.20	-0.17	0.18	-0.32	0.23	0.22	-0.25	-0.22	-0.29
4 - g/Berry				1	0.39	0.19	0.31	-0.03	-0.11	0.02	-0.12	0.12	-0.14	-0.47	-0.12	-0.12	0.24	-0.12	0.06	-0.29	-0.27
5 - Berry pH					1	0.51	-0.17	-0.30	-0.01	0.35	0.17	0.16	-0.13	-0.33	-0.48	0.14	0.13	-0.43	0.26	-0.07	-0.09
6- Berry Brix						1	-0.10	-0.12	-0.27	0.63	0.58	-0.12	0.14	0.11	-0.43	0.48	-0.33	-0.37	0.37	0.31	0.23
7 - Berry TA							1	0.12	-0.13	0.04	0.12	-0.15	0.22	0.00	0.04	-0.08	0.06	0.04	-0.26	-0.07	-0.25
8 - Shoot Wt								1	-0.48	-0.34	-0.24	0.16	0.00	0.17	0.46	-0.14	-0.01	0.26	-0.25	0.01	-0.01
9 - Crop Load									1	-0.09	-0.16	-0.05	-0.21	-0.28	-0.14	-0.12	0.20	-0.10	0.02	-0.17	-0.04
10 - Anthocyanins										1	0.90	-0.65	0.27	0.25	-0.65	0.58	-0.43	-0.37	0.45	0.44	0.29
11 - Colour											1	-0.56	0.44	0.44	-0.58	0.68	-0.59	-0.34	0.49	0.58	0.38
12 - Hue												1	-0.20	-0.29	0.28	-0.39	0.41	0.10	-0.20	-0.37	-0.29
13 - Phenols													1	0.41	-0.22	0.46	-0.37	-0.29	0.24	0.35	0.21
14 - Soil Moisture														1	0.05	0.67	-0.79	-0.02	0.27	0.82	0.64
15 - Ψ															1	-0.43	0.20	0.47	-0.37	-0.23	-0.05
16 - % Clay																1	-0.83	-0.56	0.63	0.79	0.53
17 - % Silt																	1	0.01	-0.60	-0.82	-0.61
18 - % Sand																		1	-0.23	-0.20	-0.04
19 - OM																			1	0.53	0.41
20 - CEC																				1	0.76
21 - Soil pH																					1

Table 7-11: Pearson's correlation coefficients between yield components, berry composition and vineyard moisture and soil variables, 2009, at four Pinot noir vineyard sites, St. Davids, ON. Colour coding relates to significance (p-value) where yellow, blue and red represent p≤ 0.0001, 0.01, and 0.05 respectively.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1 - Yield	1	0.88	0.57	0.07	-0.20	-0.11	-0.03	-0.16	-0.15	-0.09	-0.15	0.08	-0.18	0.21	-0.16	-0.12	0.11	0.18	0.08
2 - No. Clusters		1	0.15	0.02	-0.25	-0.17	-0.03	-0.22	-0.12	-0.17	-0.09	0.14	-0.14	0.22	-0.25	-0.03	0.06	0.21	0.08
3 - g/Cluster			1	0.09	0.02	0.07	-0.02	0.02	-0.12	0.10	-0.16	-0.06	-0.18	0.04	0.12	-0.24	0.10	0.01	0.00
4 - g/Berry				1	0.07	0.04	0.04	-0.01	-0.30	0.35	0.08	-0.16	0.33	-0.43	0.37	0.22	-0.32	-0.30	-0.06
5 - Berry pH					1	0.50	-0.38	0.26	-0.07	0.53	-0.36	-0.18	0.00	0.06	0.00	-0.10	0.35	0.02	0.08
6- Berry Brix						1	-0.29	0.37	0.24	0.35	0.13	-0.26	0.06	-0.02	0.10	-0.10	0.25	-0.17	-0.08
7 - Berry TA							1	0.11	0.37	-0.38	0.33	-0.37	0.01	-0.36	0.39	0.07	-0.42	-0.37	-0.47
8 - Anthocyanins								1	0.62	0.06	0.18	-0.51	0.14	-0.34	0.45	-0.05	-0.02	-0.40	-0.25
9 - Colour									1	-0.46	0.44	-0.38	-0.25	-0.20	0.38	-0.21	-0.17	-0.35	-0.53
10 - Hue										1	-0.18	-0.27	0.32	-0.29	0.23	0.20	0.14	-0.23	0.04
11 - Phenols											1	-0.23	-0.01	-0.29	0.34	0.00	-0.27	-0.32	-0.34
12 - Soil Moisture												1	-0.10	0.69	-0.81	-0.04	0.30	0.81	0.64
13 - Ψ													1	-0.47	0.23	0.52	-0.30	-0.33	0.01
14 - % Clay														1	-0.83	-0.56	0.63	0.79	0.53
15 - % Silt															1	0.01	-0.60	-0.82	-0.61
16 - % Sand																1	-0.23	-0.20	-0.04
17 - OM																	1	0.53	0.41
18 - CEC																		1	0.76
19 - Soil pH																			1

Table 7-12: Monthly rainfall for 2008 (Virgil, Ontario), 2009 (St. David's, Ontario) and 1971-2000 average (St. Catharines, Ontario). Total rainfall over the growing season was less than the long term average in 2008, but above the average in June, July and August, key months in grape development.

	2008	2009	Average
April	40	40	70.2
May	46.8	78	74.6
June	112.2	98.2	82.6
July	93.2	99.8	73.6
August	74.4	129.4	72.1
September	86	34.8	91.5
October	43.2	73.6	68.5
Total	495.8	553.8	533.1

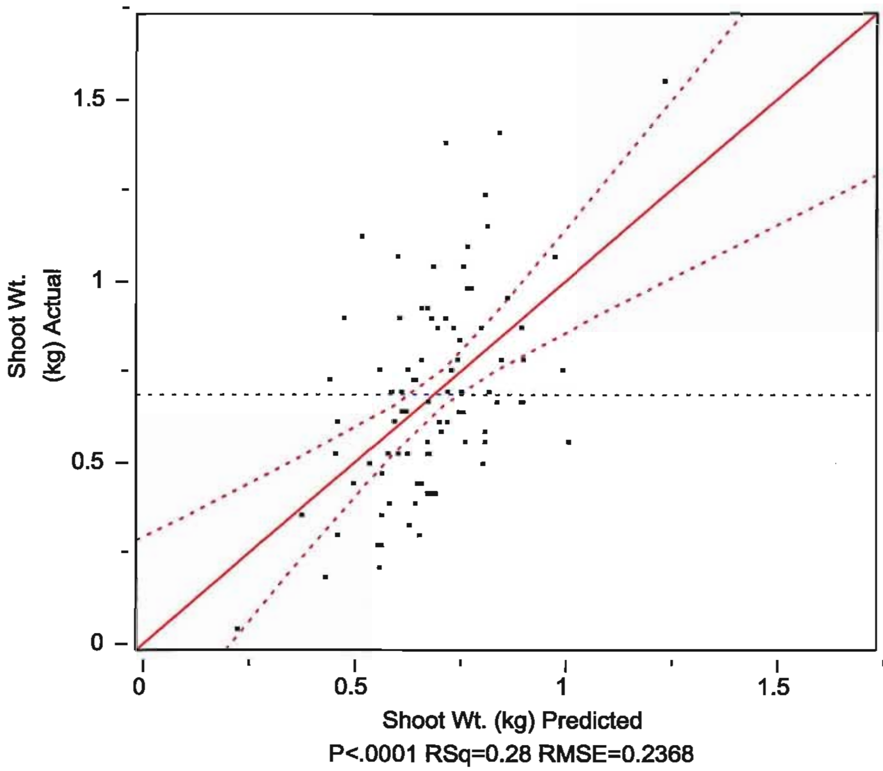


Figure 7-1: Plot of Lowrey's vineyard (Pinot noir, St. Davids, ON) 2009 actual vs. predicted weight of cane prunings (shoot weight) created using the multiple regression model of measured weight with cane diameter and internode length as model effects. The resulting R^2 is 0.28, and the model was not accepted.

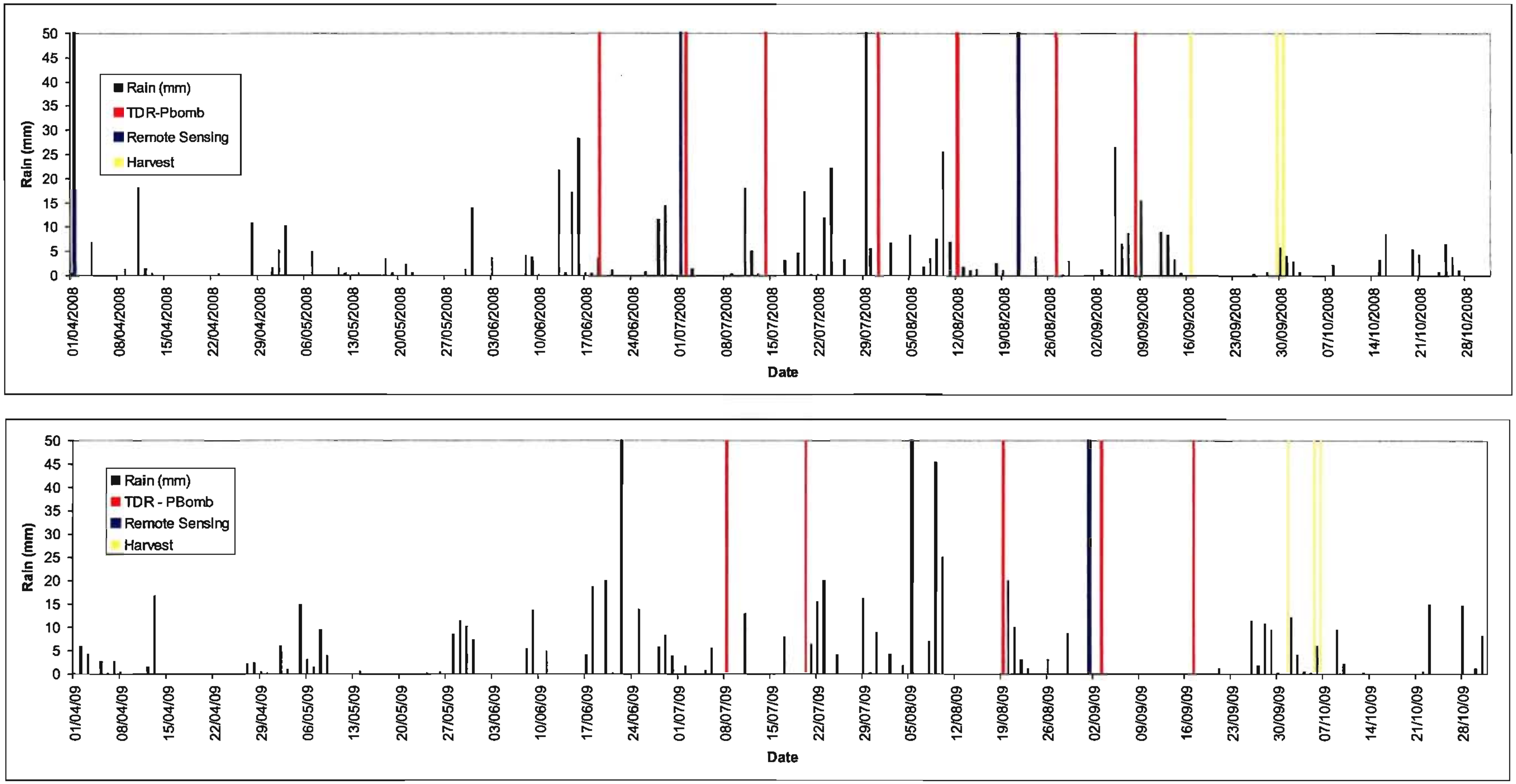


Figure 7-2: Rainfall data (courtesy of Weather Innovations Inc./ Vine & Tree Fruit Innovations Inc.) for 2008 (top) from the Virgil, Ontario station, and 2009 (bottom) from the St. David's, Ontario station. Both years were cooler than average and wetter than average.

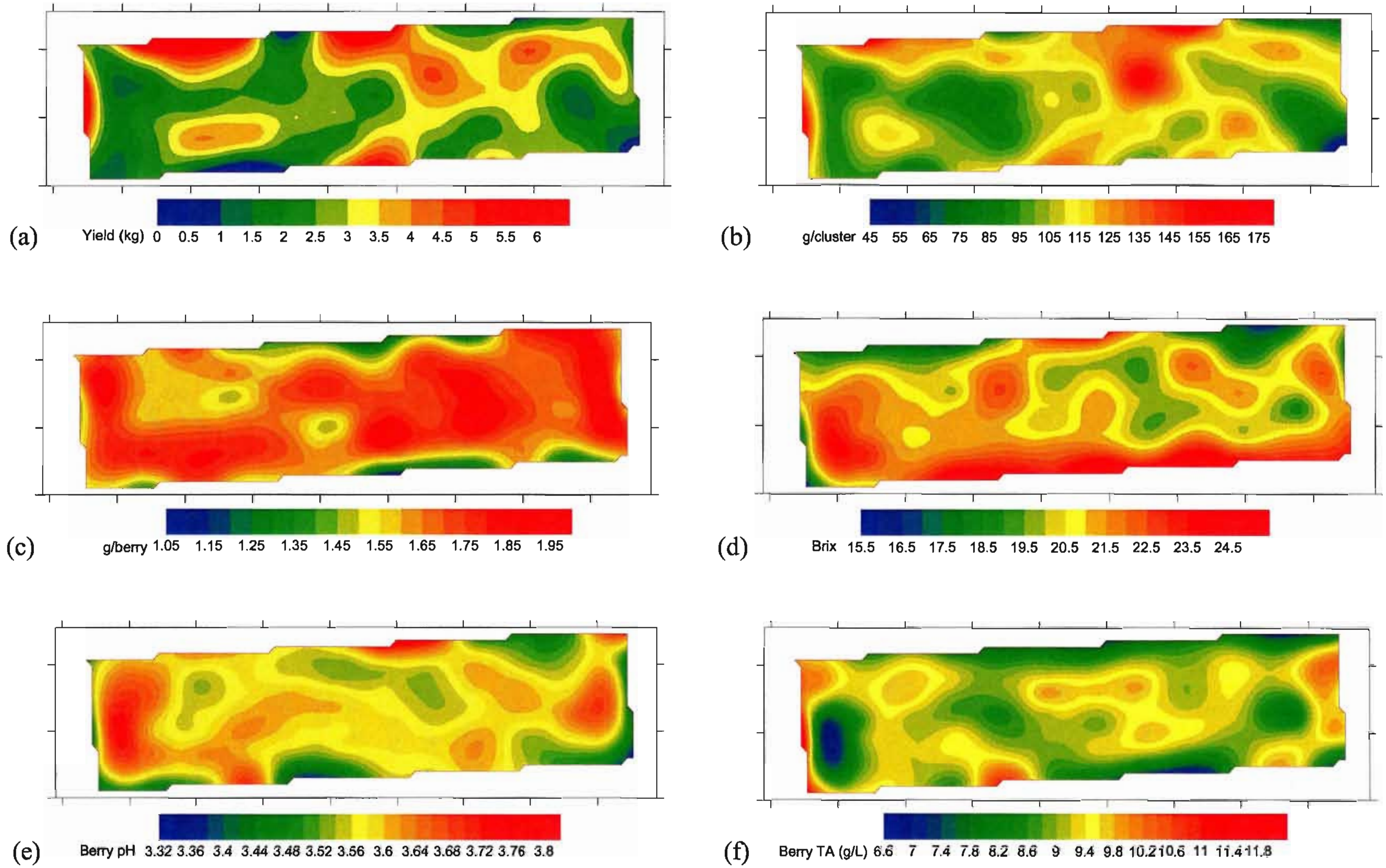
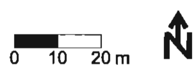


Figure 7-3: Red Paw 1, 2008 vintage. Yield components and grape composition variables in a Pinot noir vineyard, St. Davids, ON. (a) yield per vine, kg; (b) cluster size, g; (c) berry size, g; (d) soluble solids, Brix; (e) berry pH; (f) berry TA, g/L.



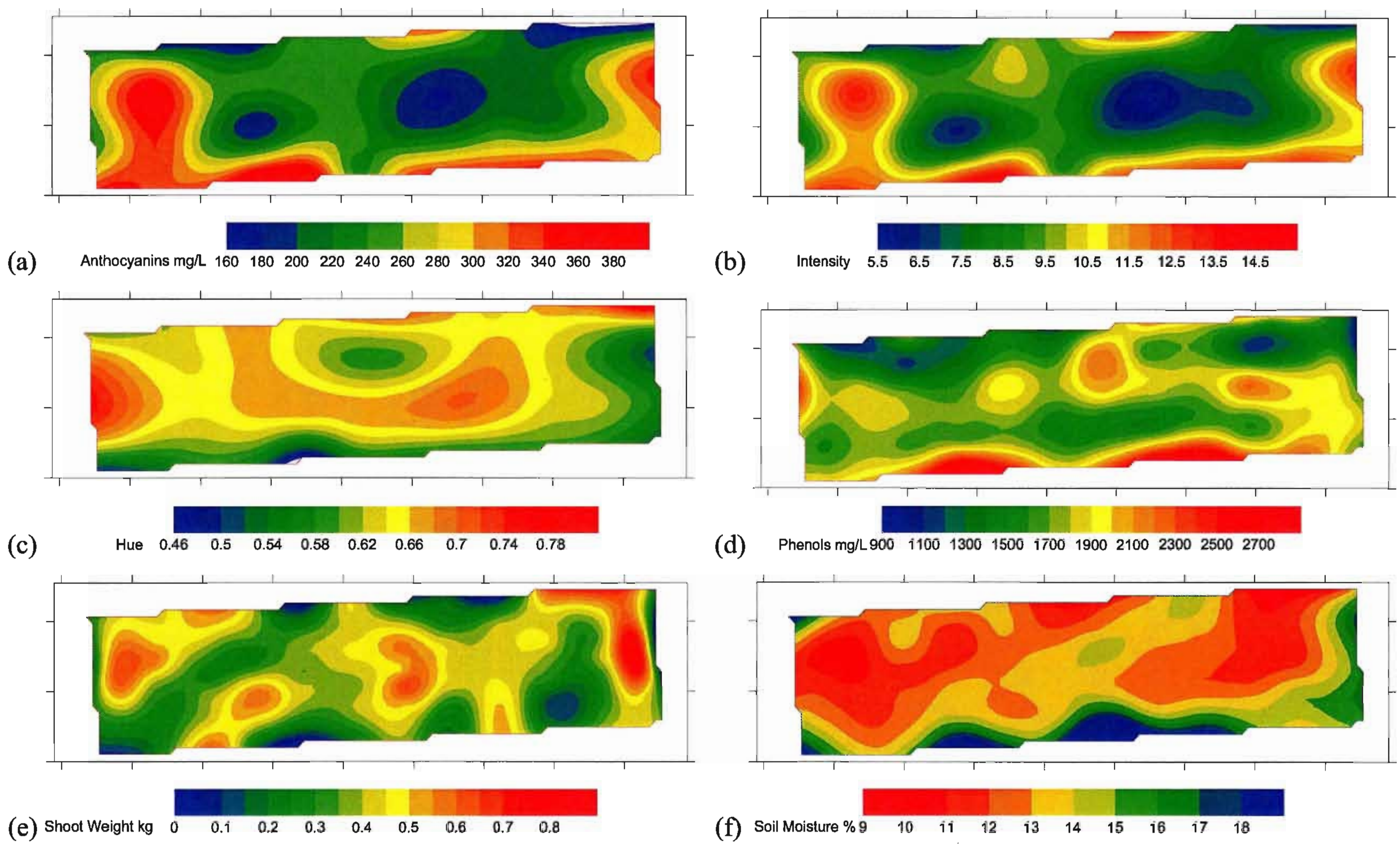
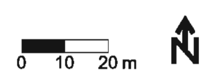


Figure 7-4: Red Paw 1, 2008 vintage. Grape composition, vine size, and soil moisture in a Pinot noir vineyard, St. Davids, ON. (a) total anthocyanins, mg/L; (b) colour intensity, $A_{420}+A_{520}$; (c) hue, A_{420}/A_{520}; (d) total phenols, mg/L; (e) weight of cane prunings, kg; (f) Mean soil moisture, %.



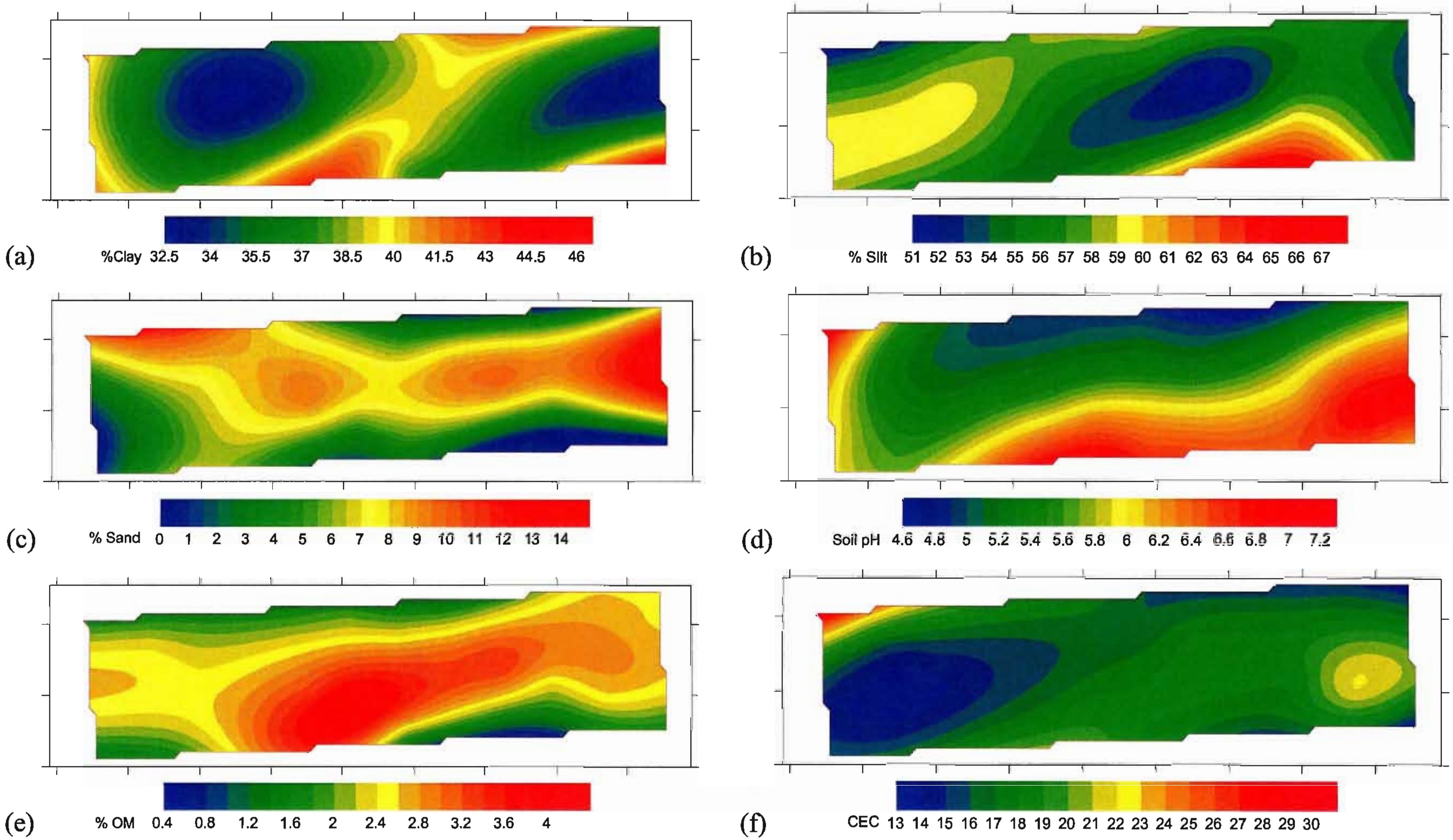
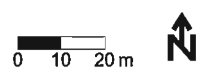


Figure 7-5: Red Paw 1 2008. Soil variables in a Pinot noir vineyard, St. Davids, ON. (a) % clay; (b) % silt; (c) % sand; (d) soil pH; (e) % organic matter; (f) cation exchange capacity, meq/100g.



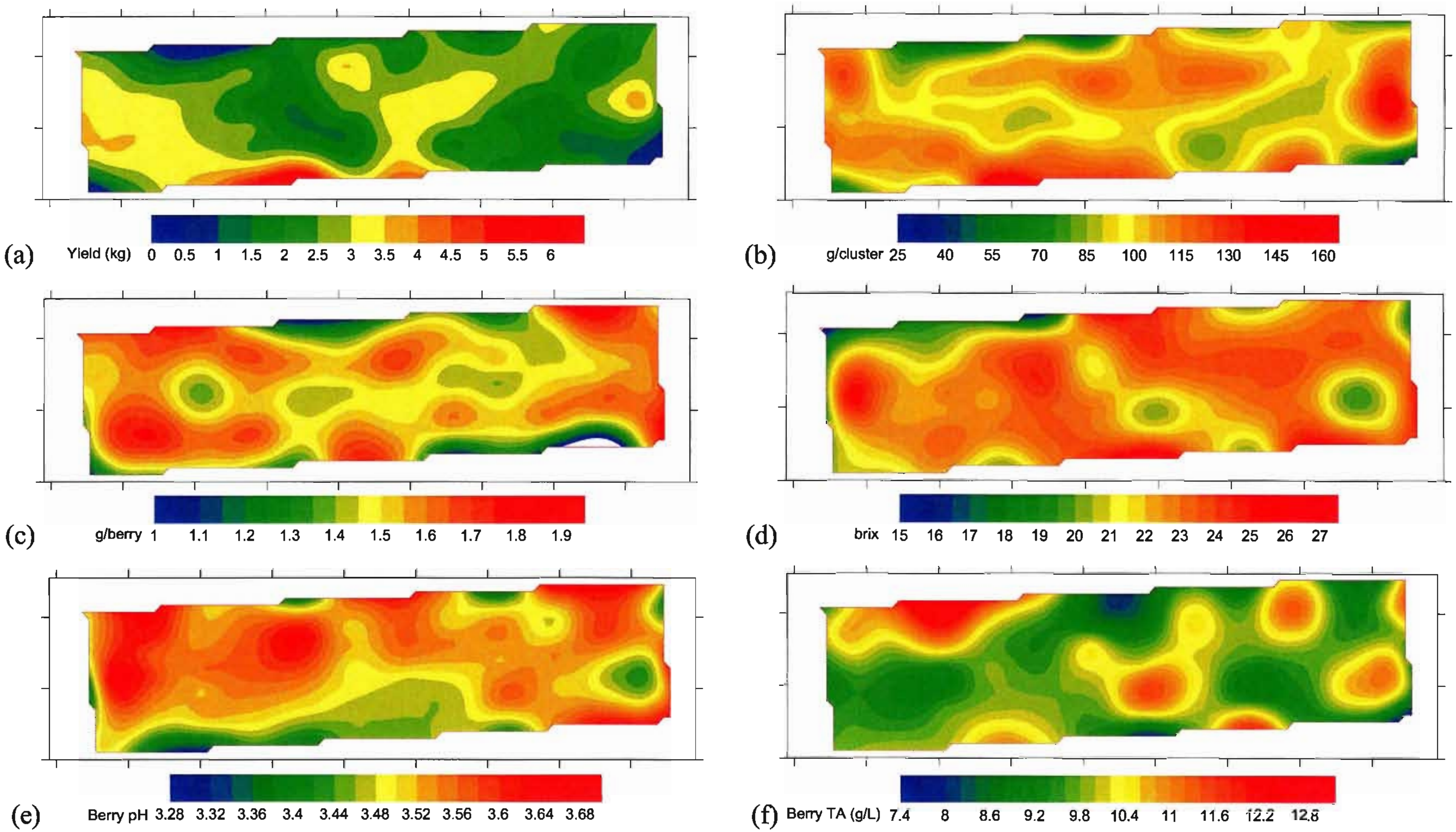
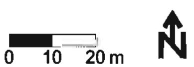


Figure 7-6: Red Paw 1, 2009 vintage. Yield components and grape composition variables in a Pinot noir vineyard, St. Davids, ON. (a) yield per vine, kg; (b) cluster weight, g; (c) berry weight, g; (d) soluble solids, Brix; (e) berry pH; (f) berry TA, g/L.



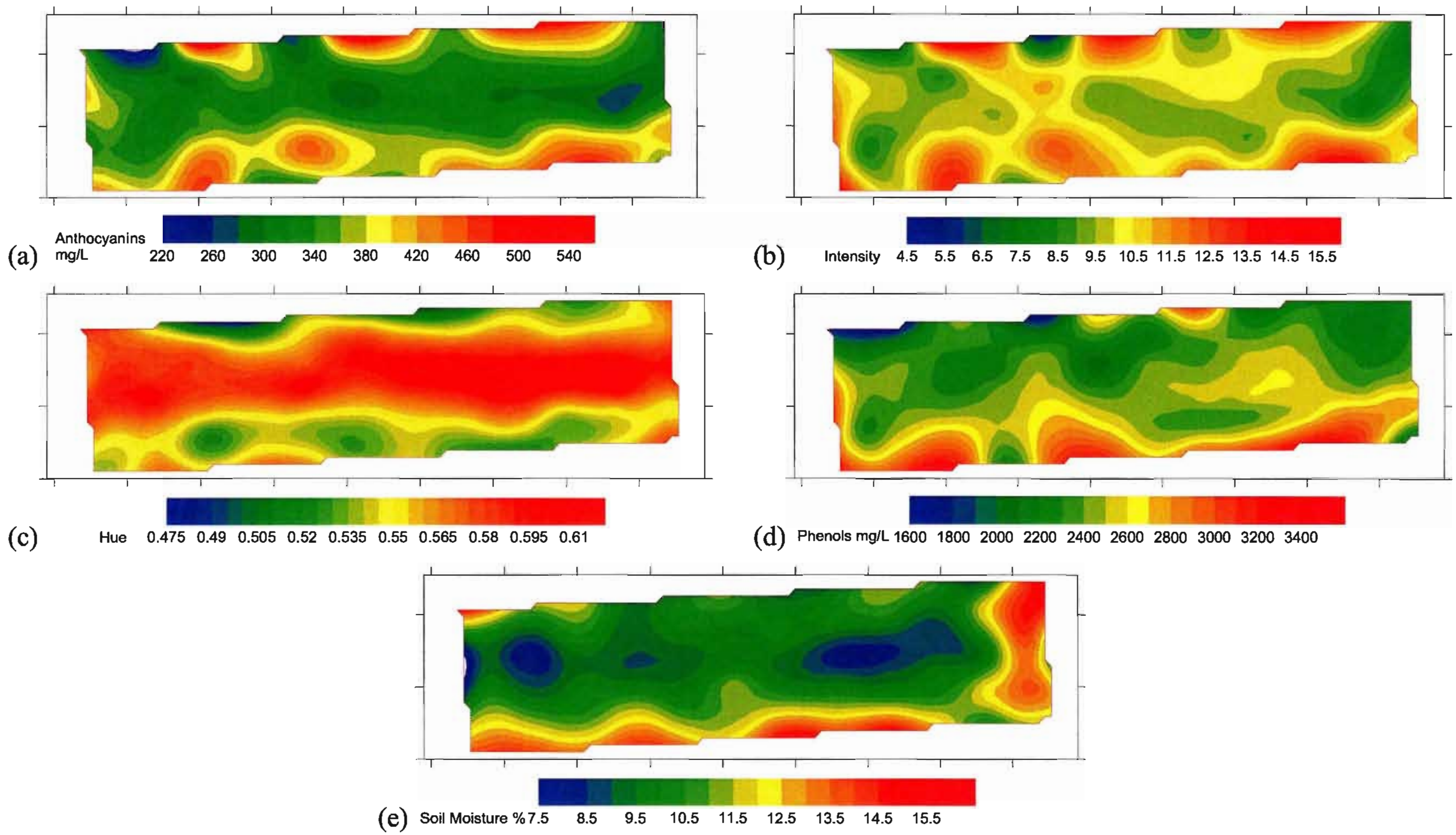
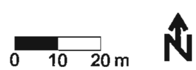


Figure 7-7: Red Paw 1, 2009 vintage. Grape composition, vine size, and soil moisture in a Pinot noir vineyard, St. Davids, ON. (a) total anthocyanins, mg/L; (b) colour intensity, $A_{420}+A_{520}$; (c) hue, A_{420}/A_{520}; (d) total phenols, mg/L; (e) mean soil moisture, %.



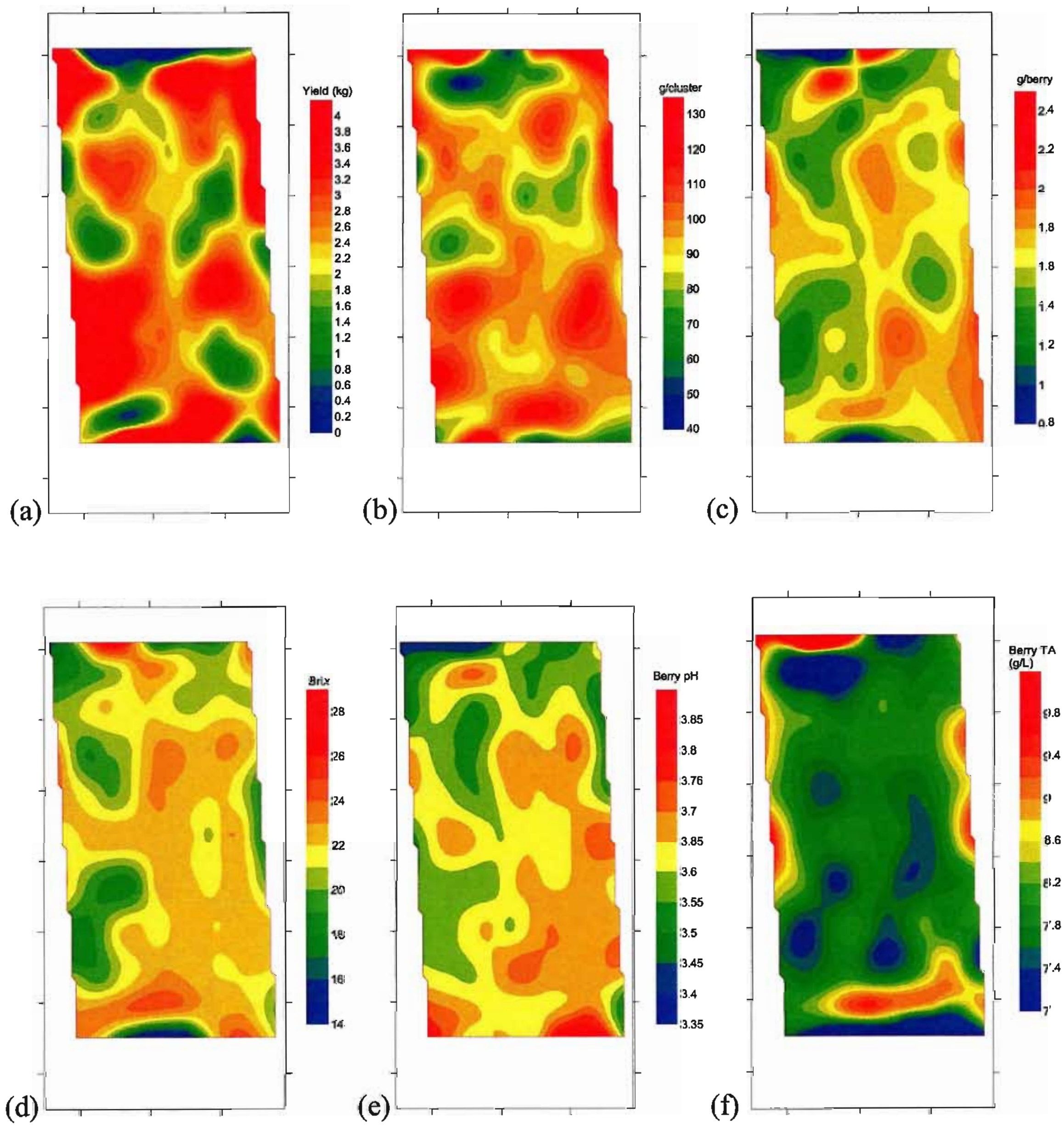


Figure 7-8: Red Paw 2, 2008 vintage. Yield components and grape composition variables in a Pinot noir vineyard, St. Davids, ON. (a) yield per vine, kg; (b) cluster weight, g; (c) berry weight, g; (d) soluble solids, Brix; (e) berry pH; (f) berry TA, g/L.

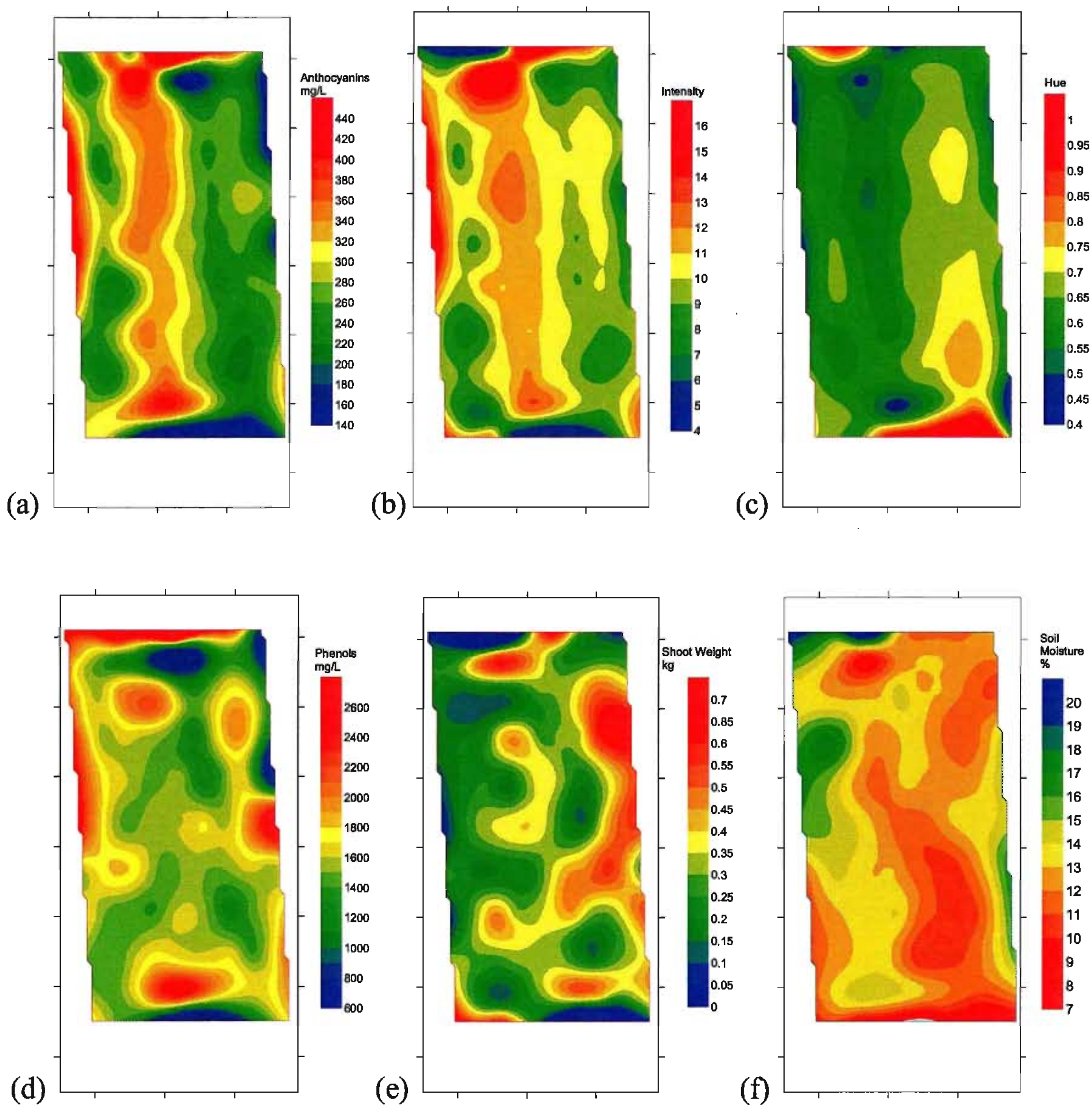
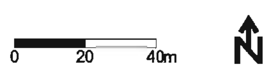


Figure 7-9: Red Paw 2, 2008 vintage. Grape composition, vine size, and soil moisture in a Pinot noir vineyard, St. Davids, ON. (a) total anthocyanins, mg/L; (b) colour intensity, $A_{420}+A_{520}$; (c) hue, A_{420}/A_{520}; (d) total phenols, mg/L; (e) weight of cane prunings, kg; (f) mean soil moisture, %.



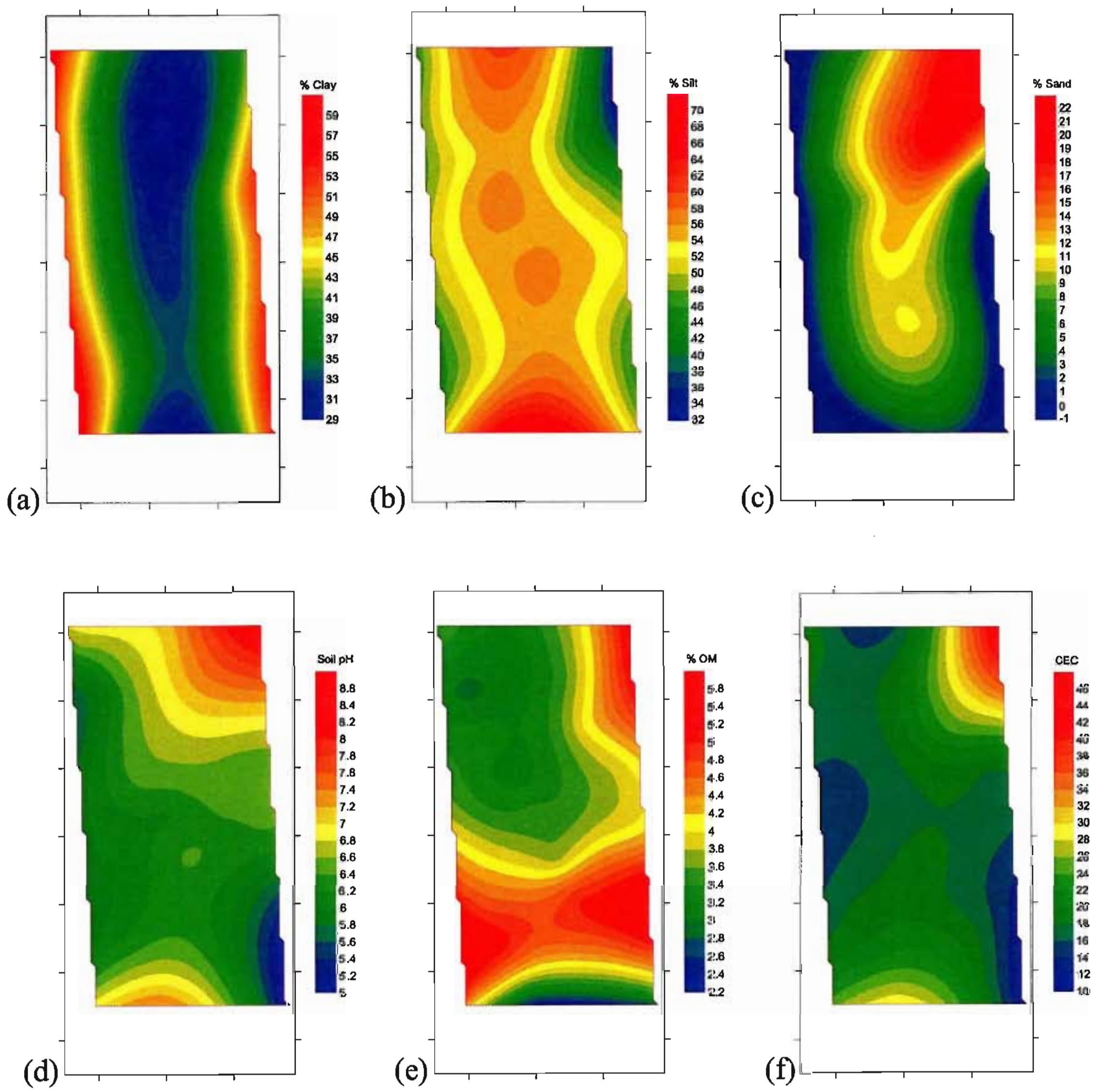
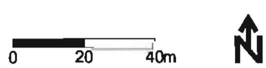


Figure 7-10: Red Paw 2 2008. Soil variables in a Pinot noir vineyard, St. Davids, ON. (a) % clay; (b) % silt; (c) % sand; (d) soil pH; (e) % organic matter; (f) cation exchange capacity, meq/100g.



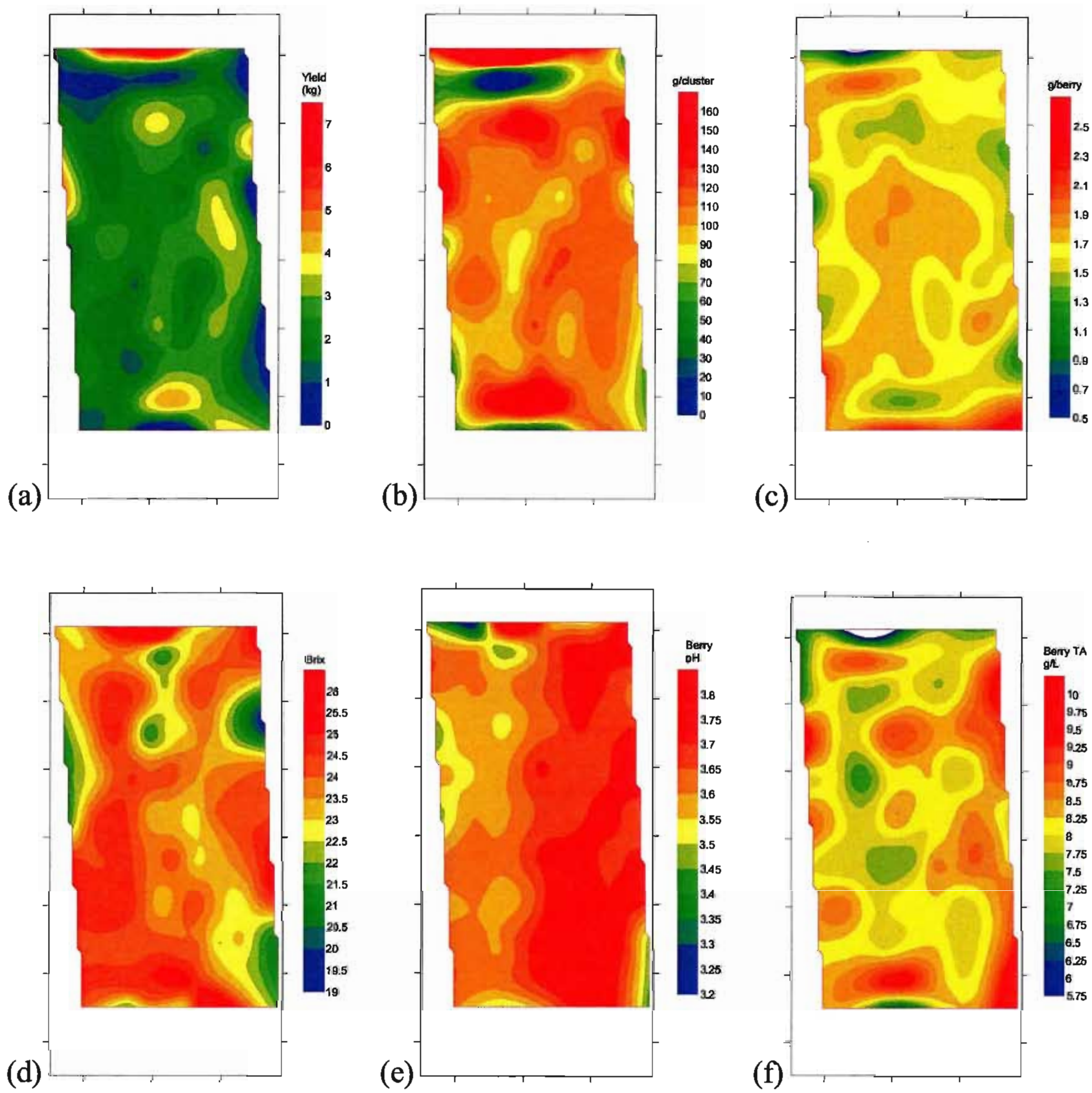


Figure 7-11: Red Paw 2, 2009 vintage. Yield components and grape composition variables in a Pinot noir vineyard, St. Davids, ON. (a) yield per vine, kg; (b) cluster weight, g; (c) berry weight, g; (d) soluble solids, Brix; (e) berry pH; (f) berry TA, g/L.

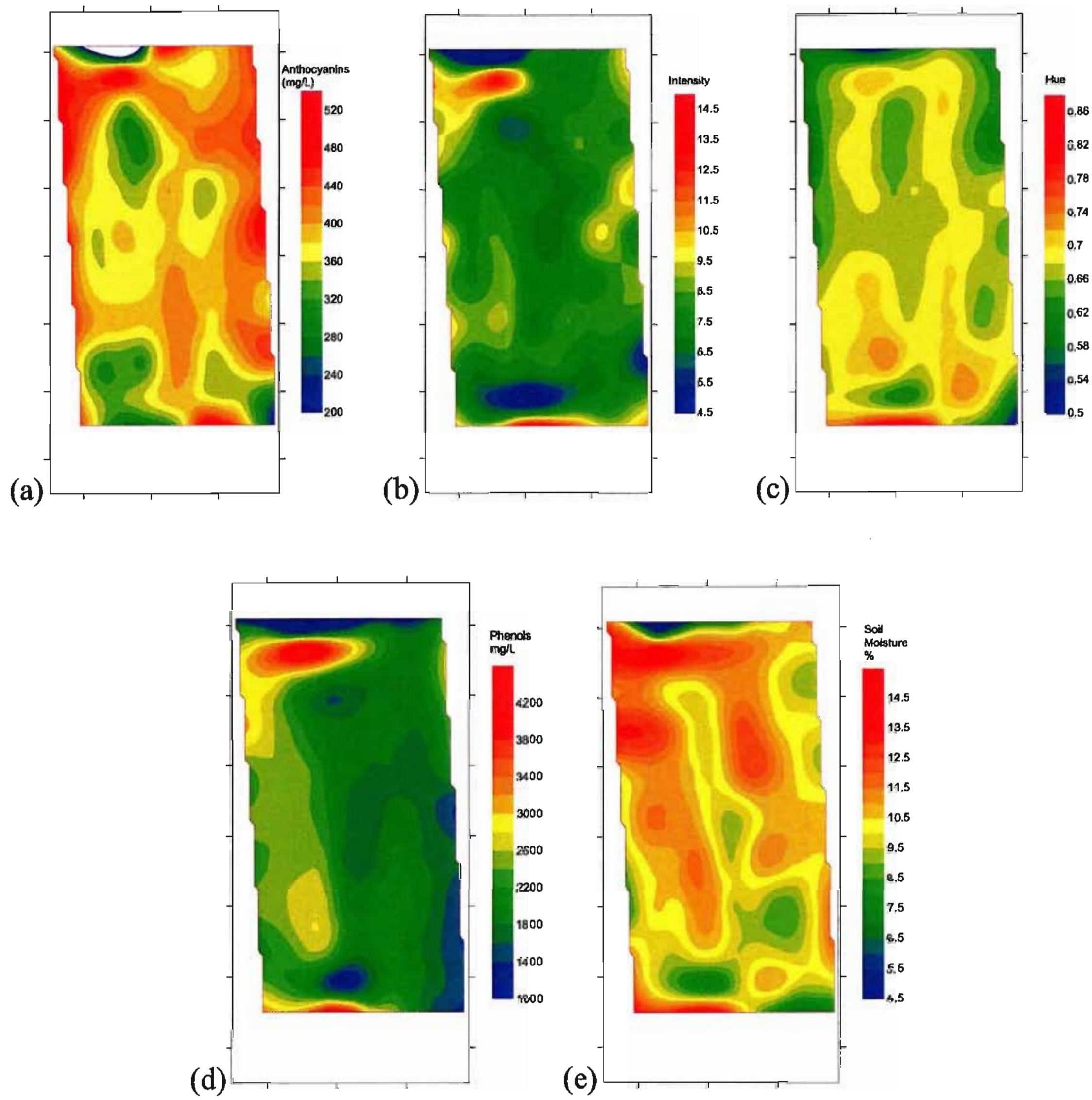
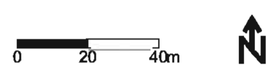


Figure 7-12: Red Paw 2, 2009 vintage. Grape composition, and soil moisture in a Pinot noir vineyard, St. Davids, ON. (a) total anthocyanins, mg/L; (b) colour intensity, $A_{420}+A_{520}$; (c) hue, A_{420}/A_{520}; (d) total phenols, mg/L; (e) mean soil moisture, %.



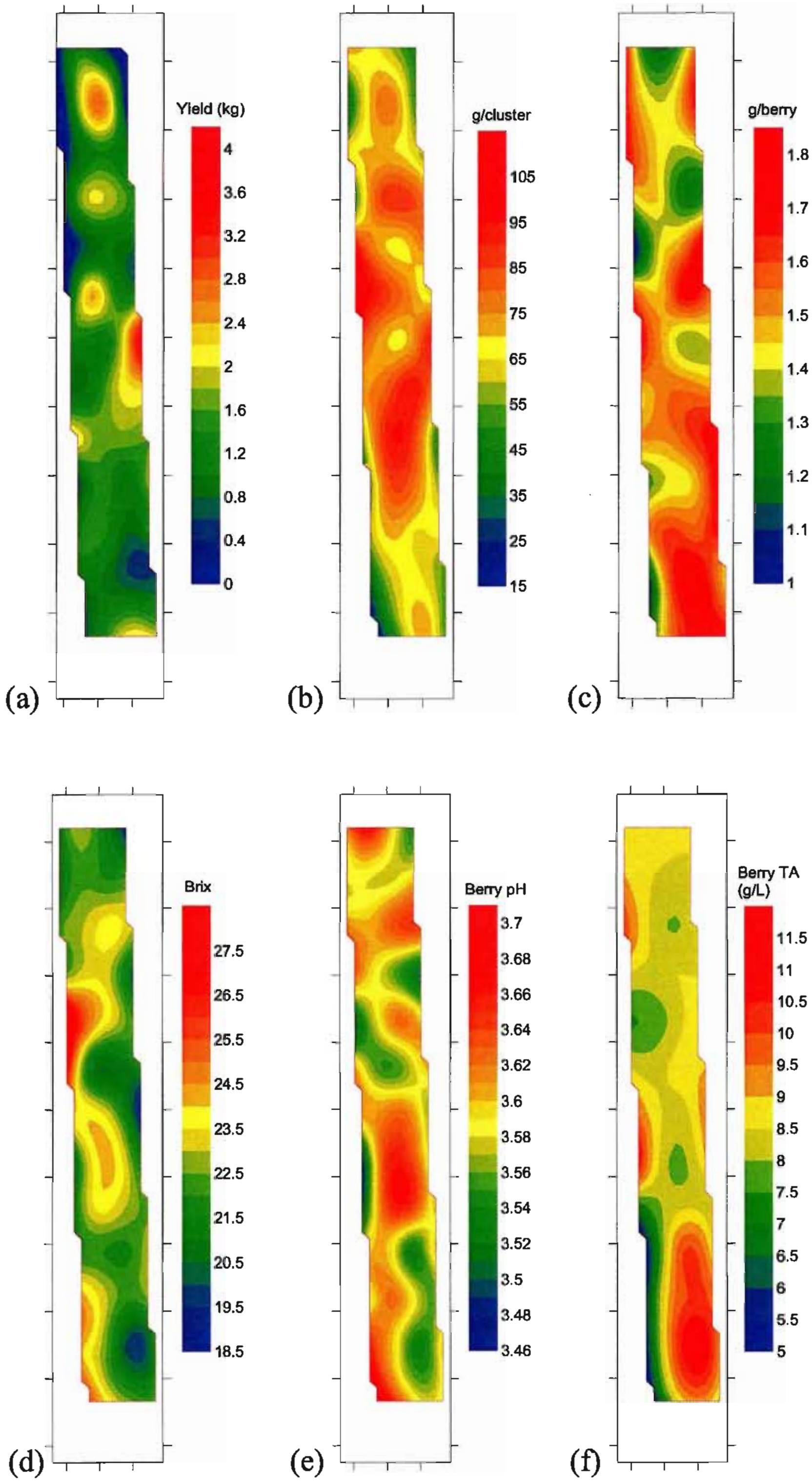
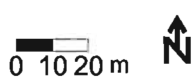


Figure 7-13: Black Paw, 2008 vintage. Yield components and grape composition variables in a Pinot noir vineyard, St. Davids, ON. (a) Yield per vine, kg; (b) cluster weight, g; (c) berry weight, g; (d) soluble solids, Brix; (e) berry pH; (f) berry TA, g/L.



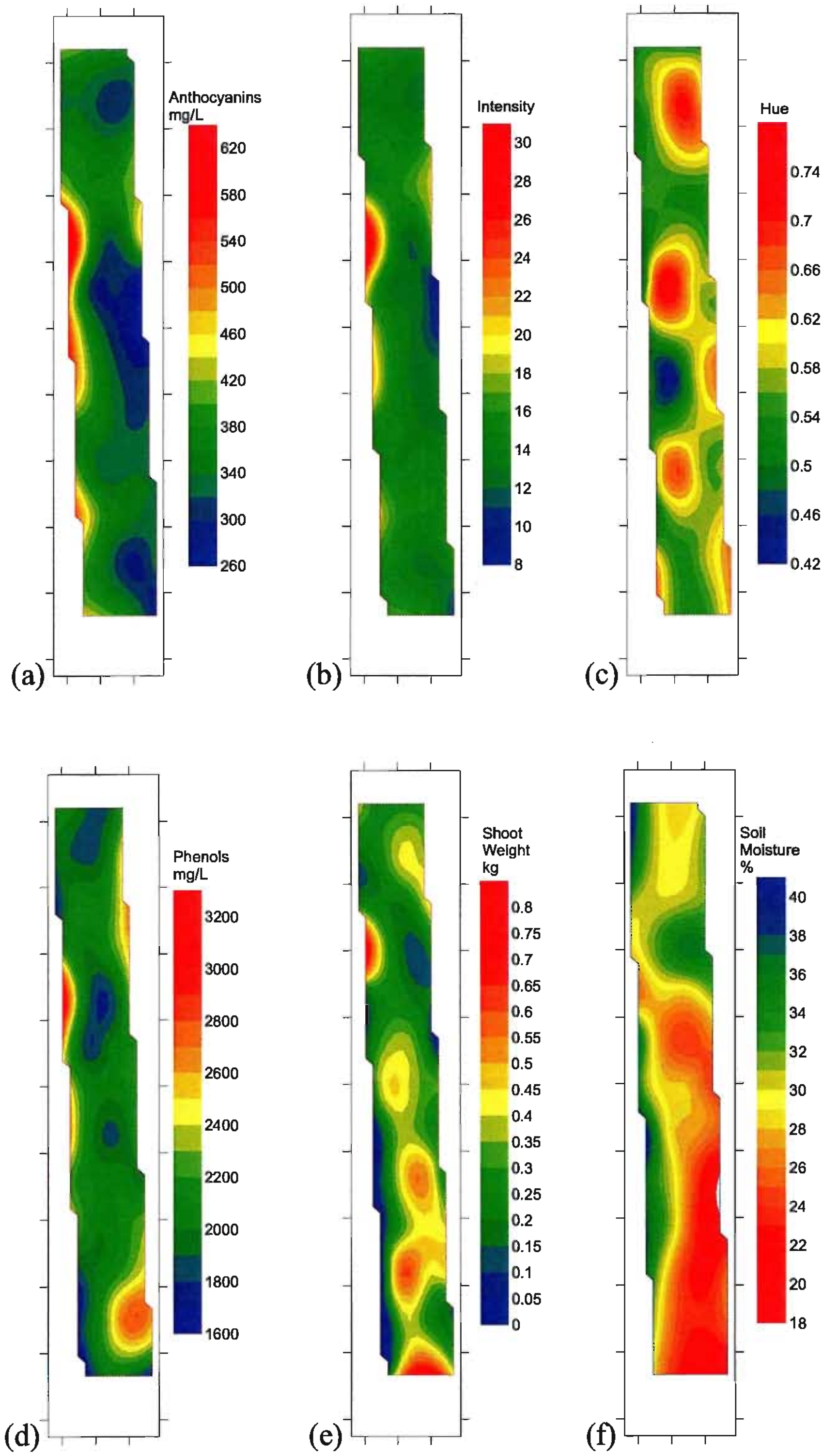
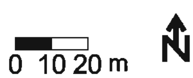


Figure 7-14: Black Paw, 2008 vintage. Grape composition, vine size, and soil moisture in a Pinot noir vineyard, St. Davids, ON. (a) total anthocyanins, mg/L; (b) colour intensity, $A_{420}+A_{520}$; (c) hue, A_{420}/A_{520}; (d) total phenols, mg/L; (e) weight of cane prunings, kg; (f) mean soil moisture, %.



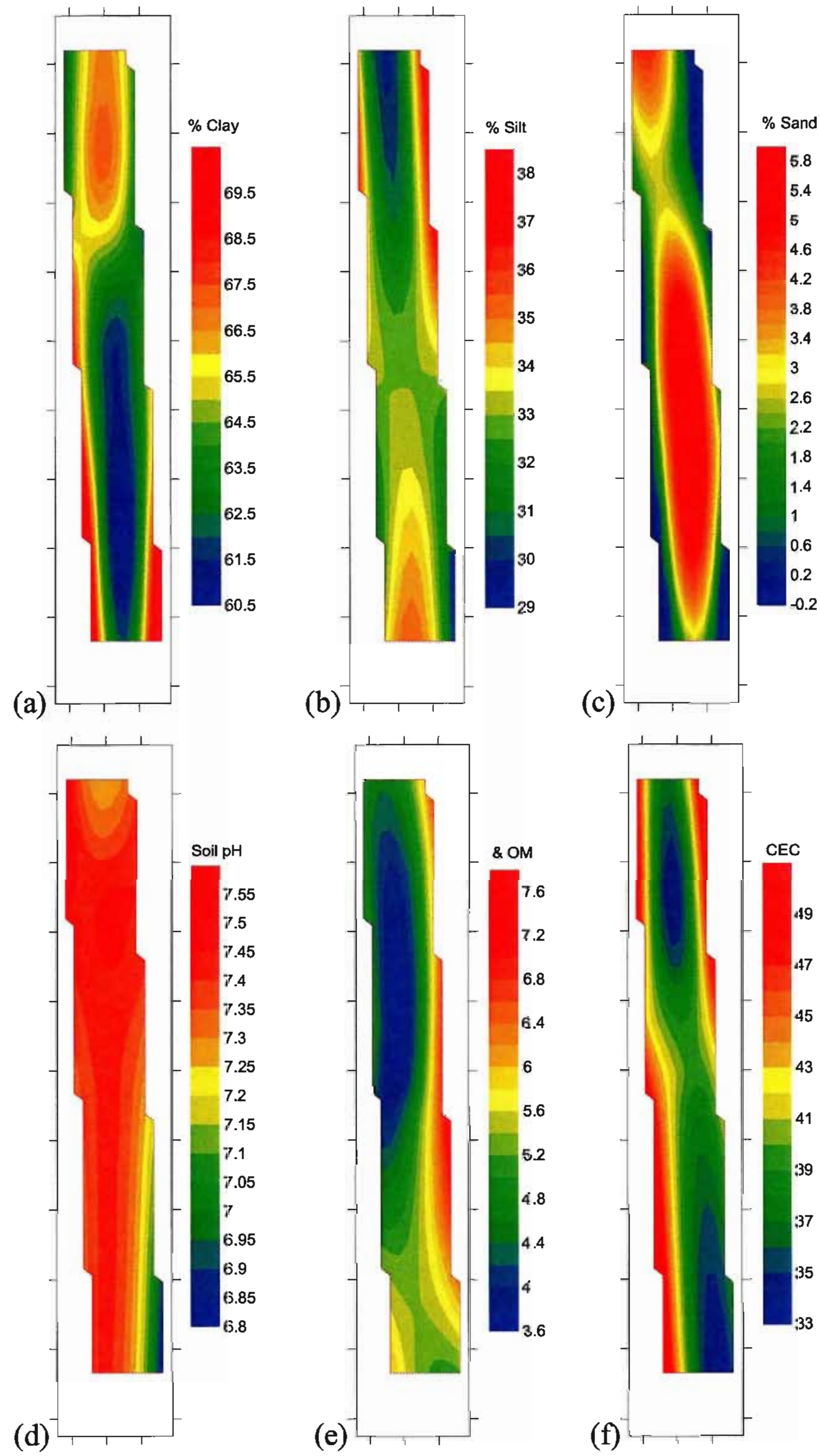
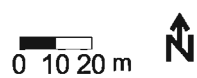


Figure 7-15: Black Paw 2008. Soil variables in a Pinot noir vineyard, St. Davids, ON. (a) % clay; (b) % silt; (c) % sand; (d) soil pH; (e) % organic matter; (f) cation exchange capacity, meq/100g.



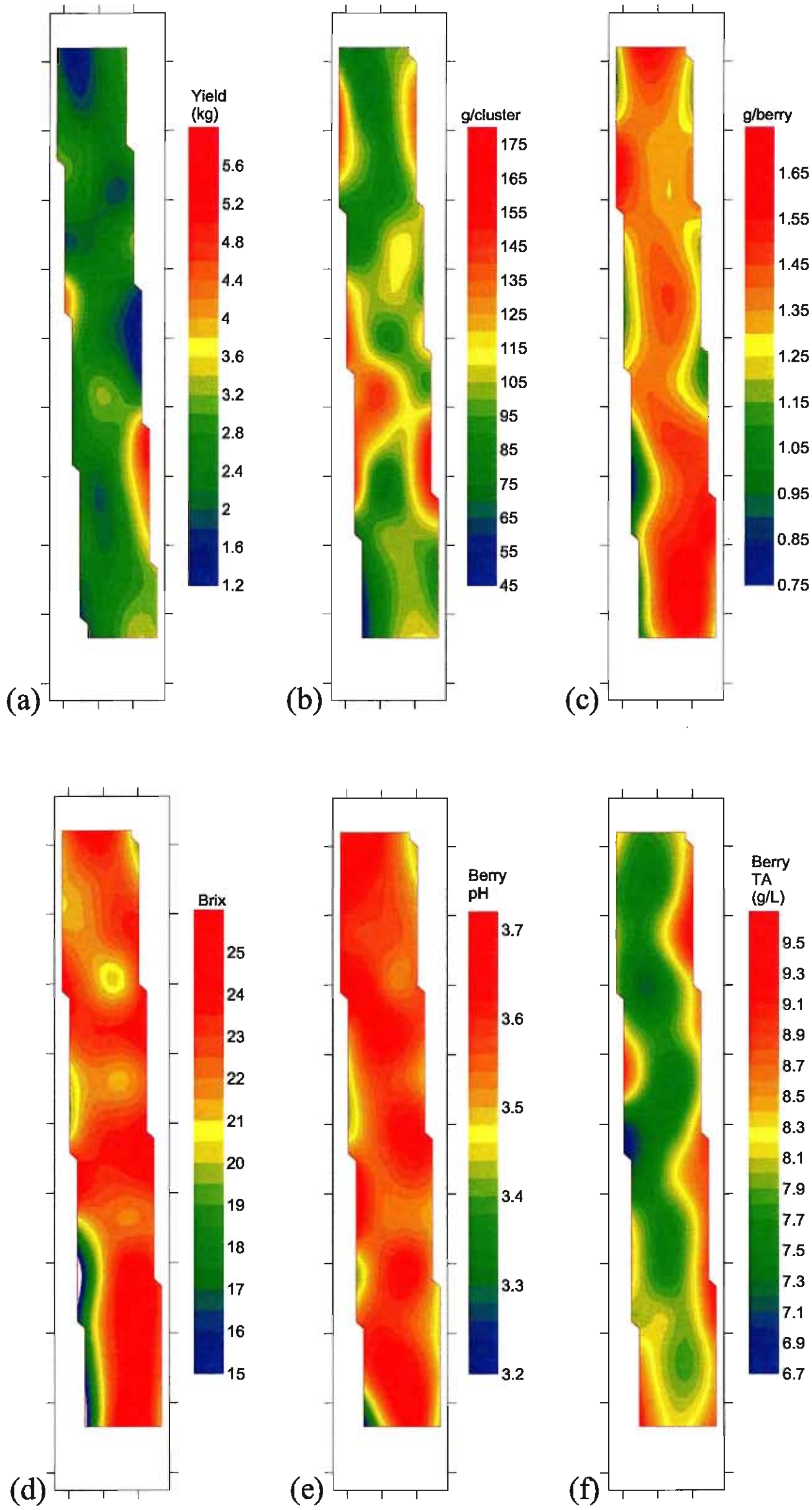
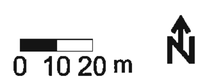


Figure 7-16: Black Paw, 2009 vintage. Yield components and grape composition variables in a Pinot noir vineyard, St. Davids, ON. (a) yield per vine, kg; (b) cluster weight, g; (c) berry weight, g; (d) soluble solids, Brix; (e) berry pH; (f) berry TA, g/L.



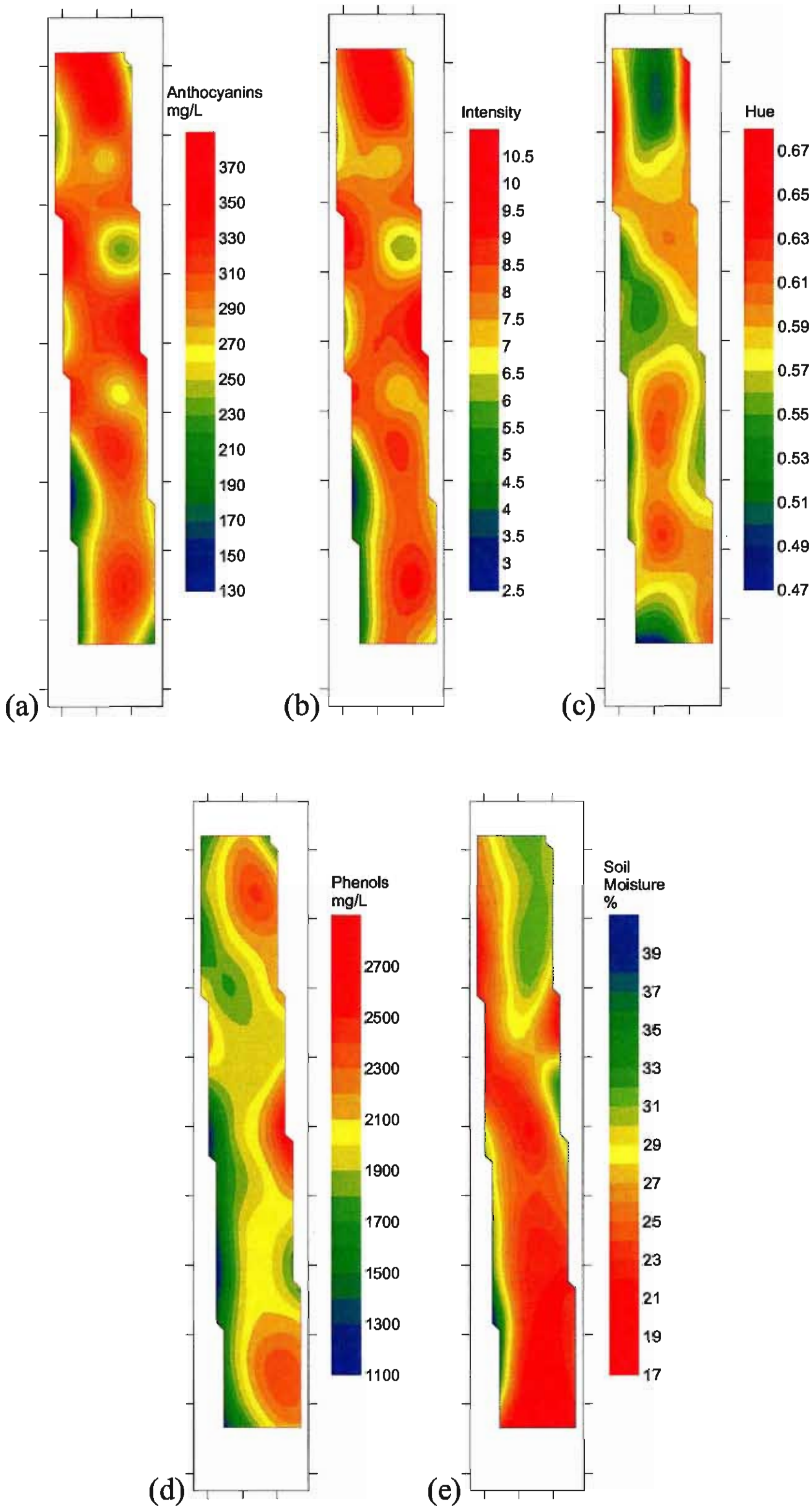
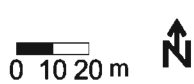


Figure 7-17: Black Paw, 2009 vintage. Grape composition, vine size, and soil moisture in a Pinot noir vineyard, St. Davids, ON. (a) total anthocyanins, mg/L; (b) colour intensity, $A_{420}+A_{520}$; (c) hue, A_{420}/A_{520}; (d) total phenols, mg/L; (e) mean soil moisture, %.



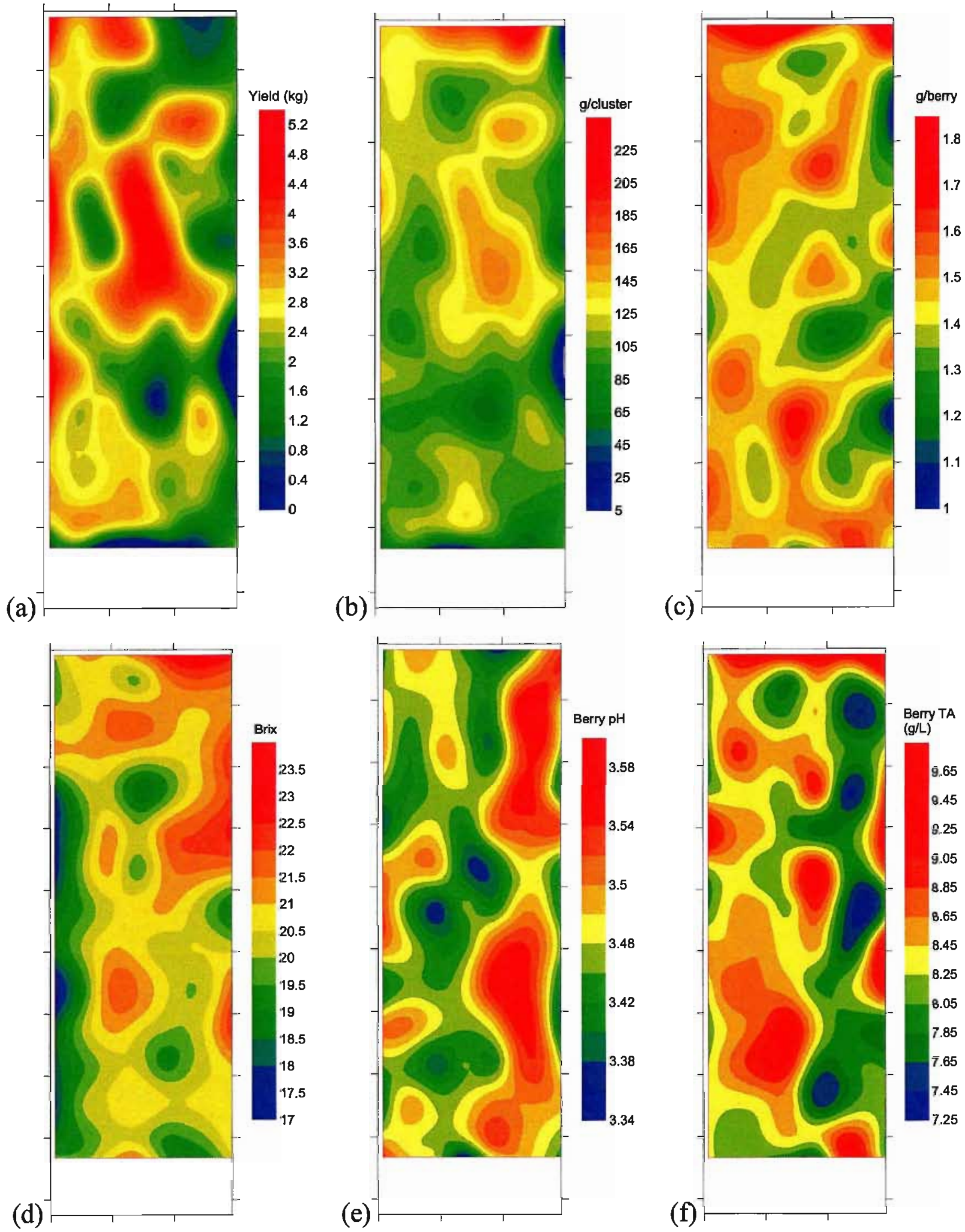
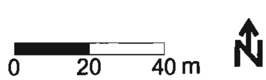


Figure 7-18: Lowrey's, 2008 vintage. Yield components and grape composition variables in a Pinot noir vineyard, St. Davids, ON. (a) yield per vine, kg; (b) cluster weight, g; (c) berry weight, g; (d) soluble solids, Brix; (e) berry pH; (f) berry TA, g/L.



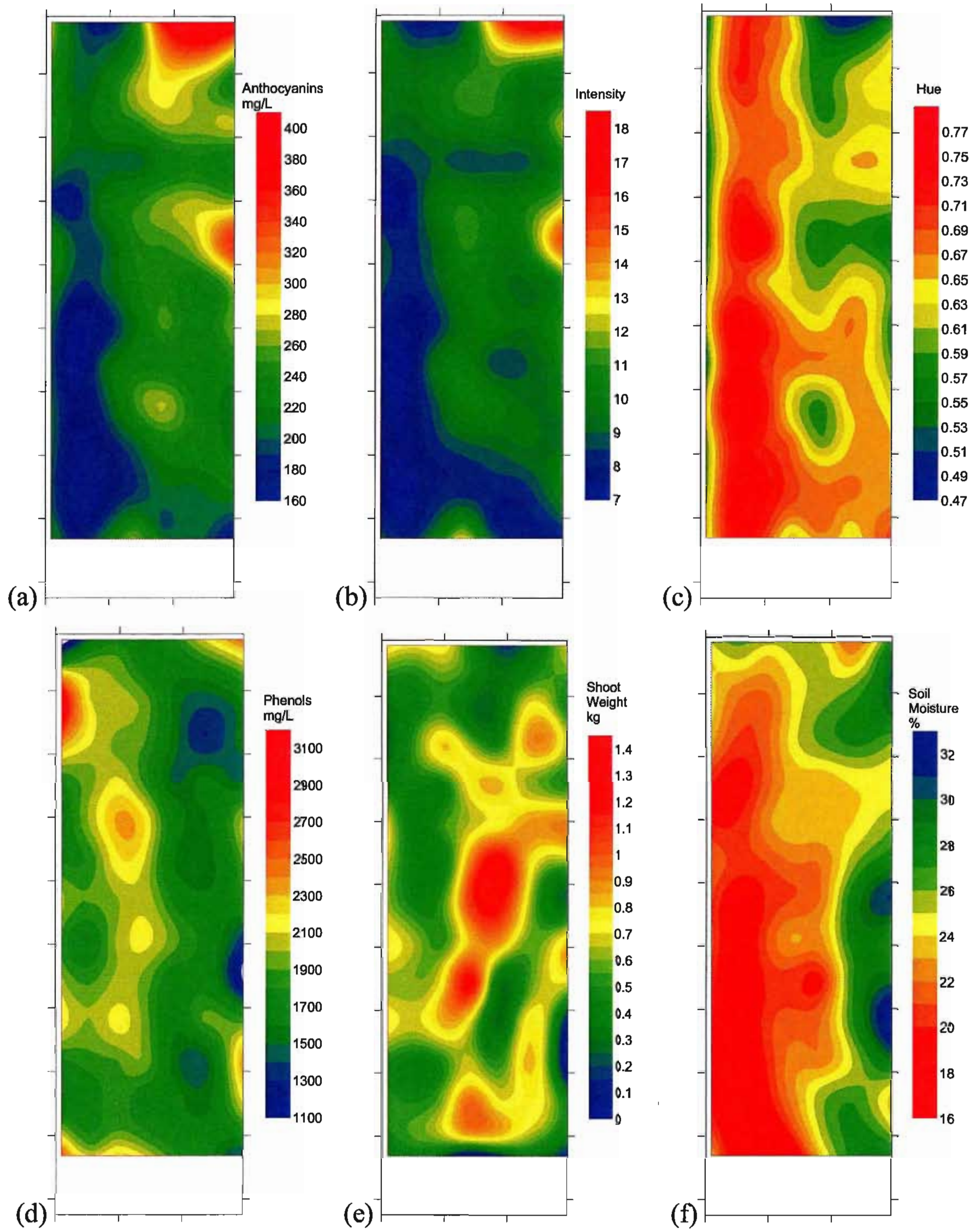


Figure 7-19: Lowrey's, 2008 vintage. Grape composition, vine size, and soil moisture in a Pinot noir vineyard, St. Davids, ON. (a) total anthocyanins, mg/L; (b) colour intensity, $A_{420}+A_{520}$; (c) hue, A_{420}/A_{520}; (d) total phenols, mg/L; (e) weight of cane prunings, kg; (f) mean soil moisture, %.

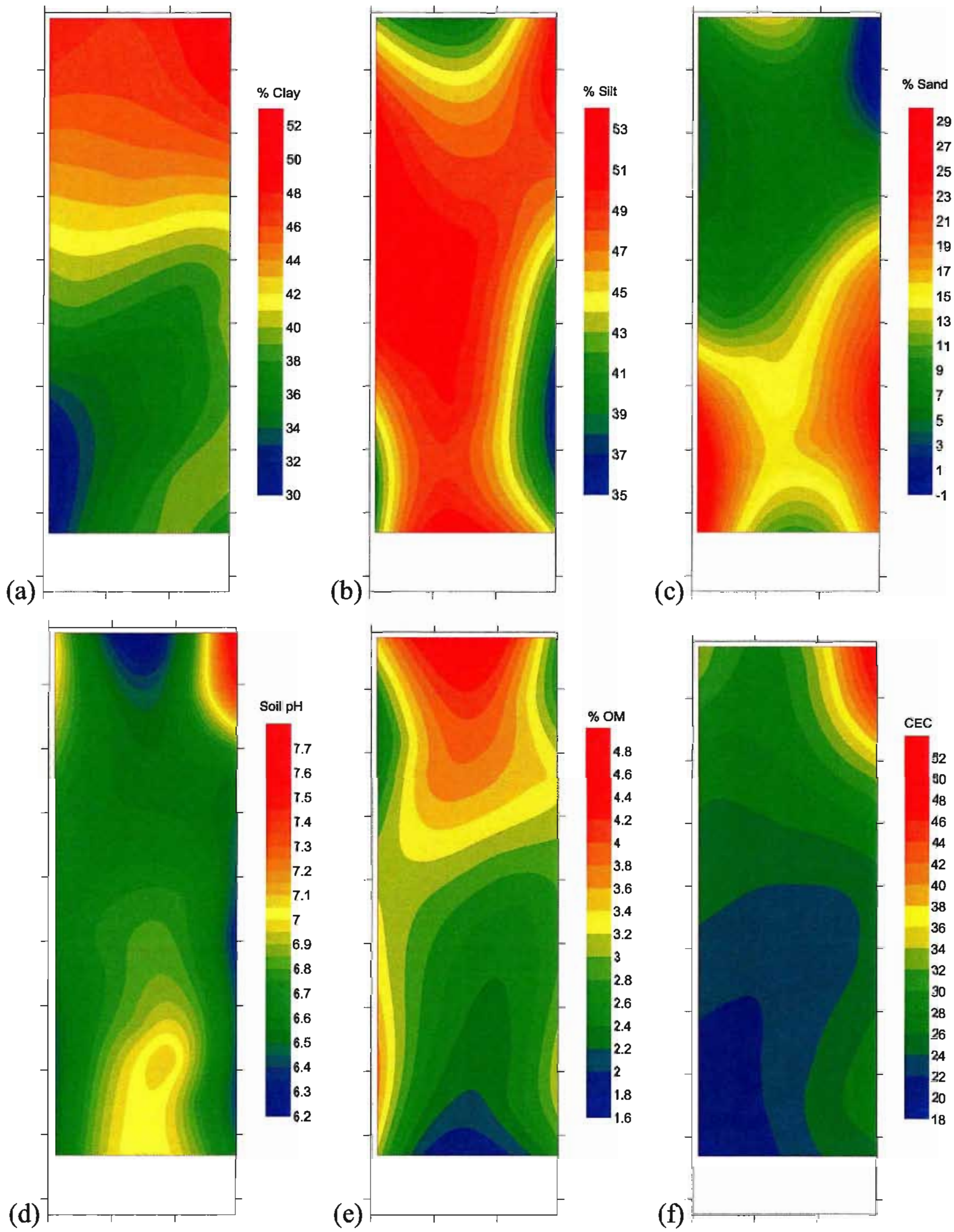


Figure 7-20: Lowrey's 2008. Soil variables in a Pinot noir vineyard, St. Davids, ON. (a) % clay; (b) % silt; (c) % sand; (d) soil pH; (e) % organic matter; (f) cation exchange capacity, meq/100g.

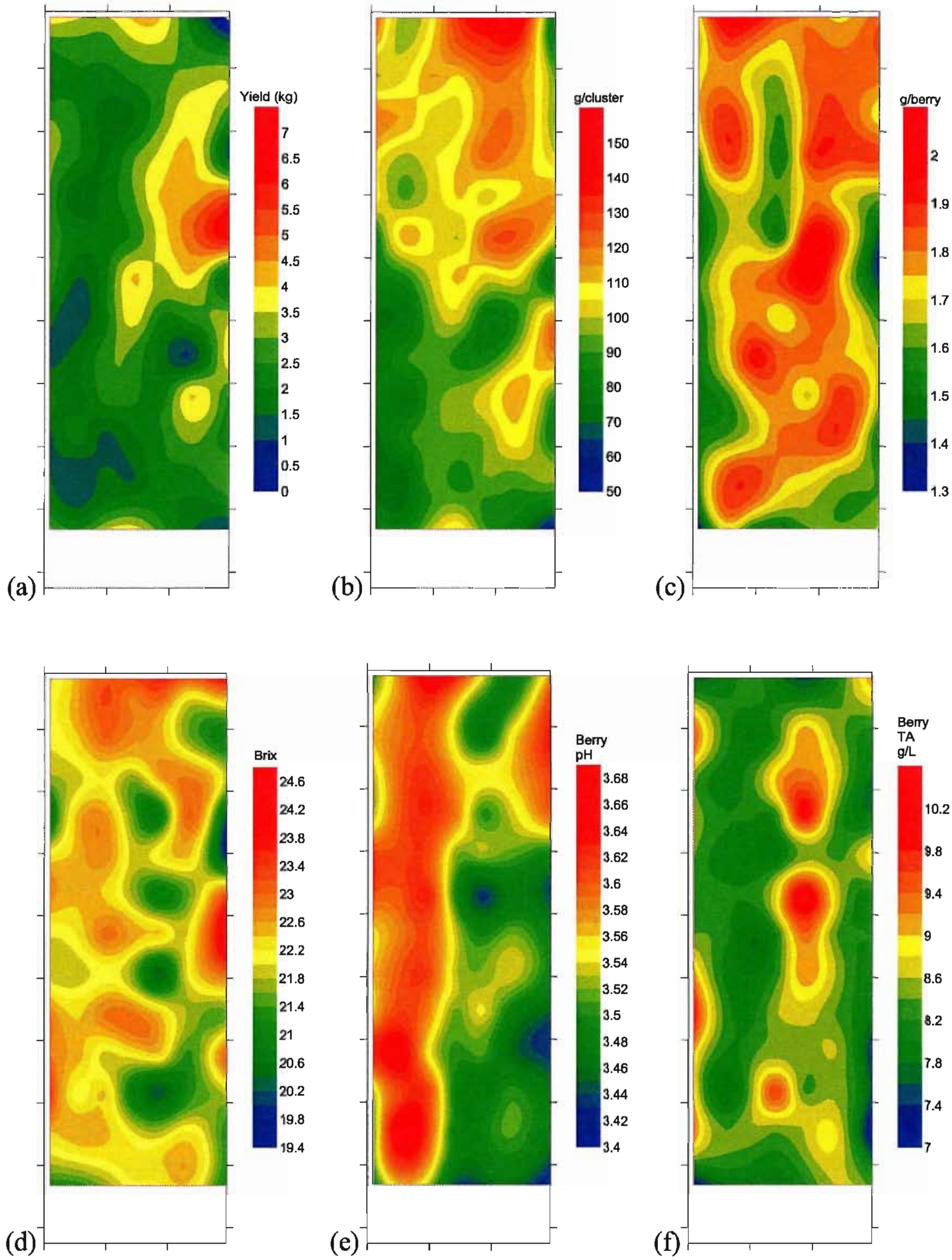


Figure 7-21: Lowrey's, 2009 vintage. Yield components and grape composition variables in a Pinot noir vineyard, St. Davids, ON. (a) Yield per vine, kg; (b) Cluster weight, g/cluster; (c) Berry weight, g/berry; (d) Berry Brix; (e) Berry pH; (f) Berry TA, g/L.

0 20 40 m N

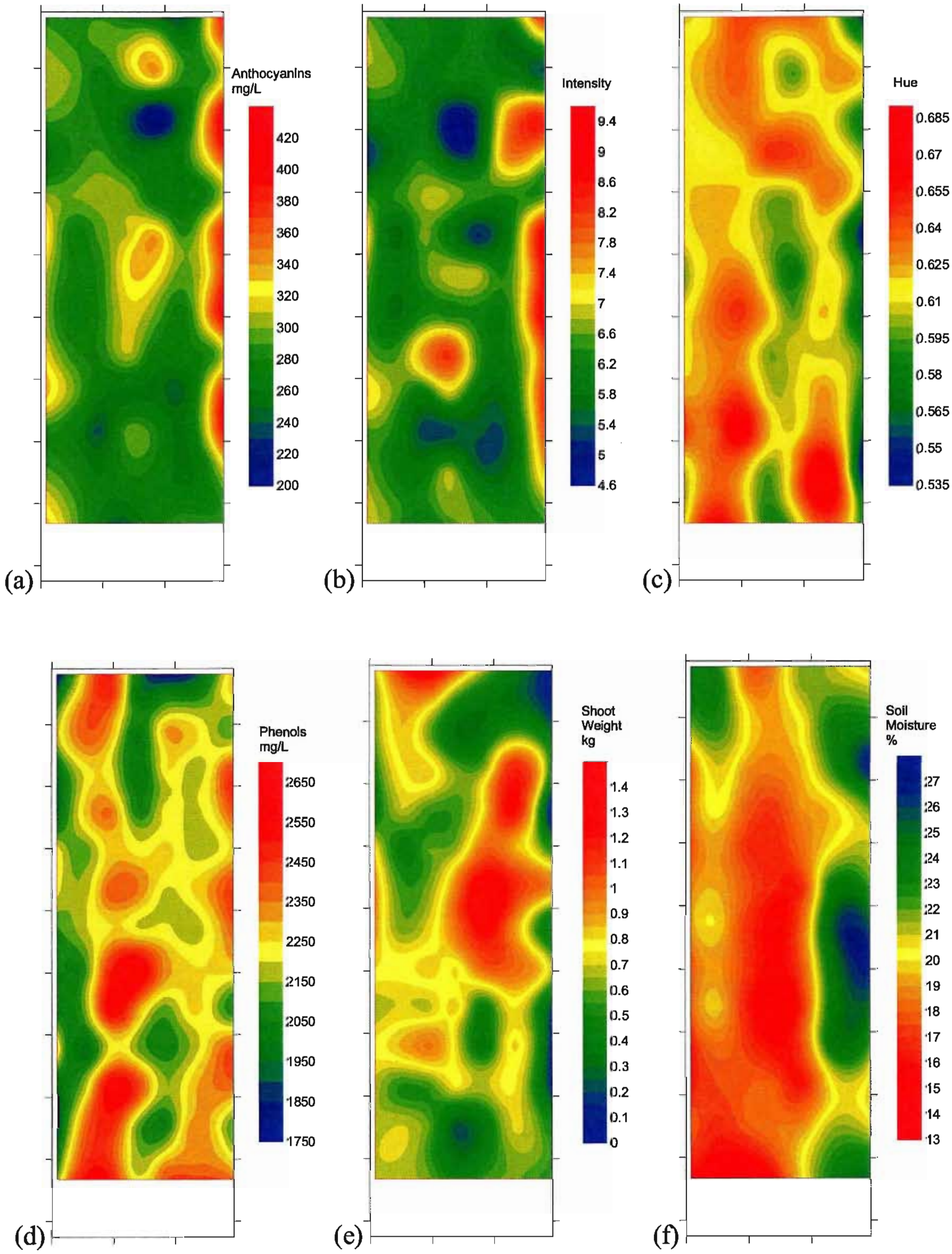


Figure 7-22: Lowrey's, 2009 vintage. Grape composition, vine size, and soil moisture in a Pinot noir vineyard, St. Davids, ON. (a) Total anthocyanins, mg/L; (b) Colour intensity, $A_{420}+A_{520}$; (c) Hue, A_{420}/A_{520}; (d) Total phenols, mg/L; (e) Shoot weight, kg; (f) Mean soil moisture, %.

0 20 40 m N

Table 7-13: F-values and significance[b] of sensory attributes for Red Paw 1 Pinot noir wines, St. Davids, ON from the three-factor ANOVA with interactions.

Red Paw 1: Source of Variation	df	Tart fruit aroma	Sweet fruit aroma	sweet aroma	Pepper spice aroma	Baking spice aroma	Tobacco aroma	Vegetal aroma
Judge	9	54.98***	41.04***	28.13***	18.18***	49.15***	15.06***	10.12***
Wine	5	0.48	1.53	2.64*	1.14	0.69	0.57	0.69
Rep	1	0.51	0.11	0.45	2.76	0.01	0.08	0.79
Judge*wine	45	0.70	2.44**	1.79	1.18	1.43	0.27	0.86
Judge*rep	9	0.63	1.28	1.64	1.90	3.91**	0.36	0.21
Wine*rep	5	1.14	0.36	1.64	0.61	1.26	0.77	1.21
Error[c]	45	2.23	2.50	3.12	4.16	1.63	4.56	4.81

Red Paw 1: Source of Variation	Red fruit flavour	Spices flavour	Vegetal flavour	Earthy flavour	Acidity	Bitterness	Astringency
Judge	58.48***	26.92***	10.76***	24.17***	33.44***	119.30***	82.60***
Wine	1.91	0.29	0.27	1.22	0.30	3.56**	1.32
Rep	0.30	1.18	0.00	0.80	0.98	1.00	0.68
Judge*wine	1.20	1.38	0.95	0.63	0.85	2.27**	1.75*
Judge*rep	1.80	1.84	0.42	0.45	1.24	1.97	2.16*
Wine*rep	0.51	1.92	1.29	0.97	0.44	0.53	0.62
Error	1.94	3.90	4.02	1.92	2.13	0.75	0.76

[b] *, **, ***: significant at $p \leq 0.05, 0.01, 0.001$ respectively

[c] Error value is the mean square (MS) of the error term

Table 7-14: F-values and significance[b] of sensory attributes for Red Paw 2 Pinot noir wines, St. Davids, ON from the three-factor ANOVA with interactions.

Red Paw 2: Source of Variation	df	Tart fruit aroma	Sweet fruit aroma	sweet aroma	Pepper spice aroma	Baking spice aroma	Tobacco aroma	Vegetal aroma
Judge	9	54.63***	24.72***	41.88***	13.78***	49.98***	33.44***	33.77***
Wine	5	0.95	2.62*	1.16	0.58	1.16	0.23	4.54**
Rep	1	2.42	0.83	1.48	0.28	0.25	0.06	17.44***
Judge*wine	44	0.93	1.17	0.80	0.53	0.79	1.00	1.62
Judge*rep	9	1.41	0.56	0.73	0.60	2.24*	1.55	4.02***
Wine*rep	4	1.92	1.42	0.65	1.06	0.22	1.13	1.82
Error[c]	46	2.13	3.71	2.16	4.40	1.62	2.00	2.08

Red Paw 2: Source of Variation	Red fruit flavour	Spices flavour	Vegetal flavour	Earthy flavour	Acidity	Bitterness	Astringency
Judge	31.89***	26.07***	20.91***	58.03***	64.82***	92.16***	47.67***
Wine	1.80	1.03	1.08	0.99	1.83	2.1	1.31
Rep	6.69*	1.95	1.74	3.05	0.58	0.88	0.02
Judge*wine	0.74	0.72	1.10	0.91	1.36	1.05	0.81
Judge*rep	2.71*	2.33*	0.76	0.85	1.61	0.62	3.19
Wine*rep	0.83	1.01	0.80	2.54	0.55	2.17	1.72
Error[c]	2.33	2.95	2.09	1.62	1.25	0.90	1.17

[b] *, **, ***: significant at p≤ 0.05, 0.01, 0.001 respectively

[c] Error value is the Mean Square (MS) of the Error term

Table 7-15: F-values and significance[b] of sensory attributes for Lowrey's Pinot noir wines, St. Davids, ON from the three-factor ANOVA with interactions.

Lowrey's: Source of Variation	df	Tart fruit aroma	Sweet fruit aroma	sweet aroma	Pepper spice aroma	Baking spice aroma	Tobacco aroma	Vegetal aroma
Judge	9	23.18***	11.36***	4.59***	8.40***	20.09***	10.77***	14.89***
Wine	8	1.99	1.65	2.28*	2.02	1.68	0.89	2.91**
Rep	2	0.2	1.91	1.39	3.83	5.30**	0.16	3.86*
Judge*wine	70	0.85	1.66*	1.16	1.27	2.20***	0.79	1.17
Judge*rep	17	1.43	1.62	0.75	1.49	1.71	0.60	1.31
Wine*rep	6	0.82	1.94	0.20	1.67	0.62	0.50	1.89
Error[c]	74	2.76	3.66	4.05	2.41	1.88	2.57	4.42

Lowrey's: Source of Variation	Red fruit flavour	Spices flavour	Vegetal flavour	Earthy flavour	Acidity	Bitterness	Astringency
Judge	23.10***	13.44***	14.68***	31.64***	43.64***	32.77***	25.92***
Wine	0.77	2.11*	1.99	1.1	0.90	0.84	0.83
Rep	1.47	1.24	1.17	0.30	3.55*	2.61	0.45
Judge*wine	1.20	2.21	2.14***	1.31	1.62*	1.49*	1.23
Judge*rep	1.69	1.63	2.23*	0.63	2.19*	0.85	0.71
Wine*rep	1.21	0.34	2.18	1.30	1.54	1.44	2.12
Error[c]	2.06	2.40	2.19	1.76	0.96	1.10	1.05

[b] *, **, ***: significant at $p \leq 0.05, 0.01, 0.001$ respectively
[c] Error value is the mean square (MS) of the error term

Table 7-16: F-values and significance[b] of sensory attributes for Pinot noir wines, St. Davids, ON from the single-factor ANOVA of water status zone for each of three vineyard blocks.

Source of Variation	df	Tart fruit aroma	Sweet fruit aroma	sweet aroma	Pepper spice aroma	Baking spice aroma	Tobacco aroma	Vegetal aroma
Red Paw 1								
Water status zone	1	0.06	0.00	0.05	0.13	0.01	0.35	0.04
Error	118	11.05	11.53	10.96	10.21	8.25	7.80	7.62
Red Paw 2								
Water status zone	1	0.21	0.01	0.02	0.00	0.22	0.03	0.33
Error	118	11.63	10.91	9.10	8.10	8.24	7.41	9.84
Lowrey's								
Water status zone	2	0.58	1.58	3.47*	0.37	0.40	0.54	2.55
Error[c]	187	10.16	10.20	7.75	6.41	7.83	6.77	12.92

Source of Variation	Red fruit flavour	Spices flavour	Vegetal flavour	Earthy flavour	Acidity	Bitterness	Astringency
Red Paw 1							
Water status zone	0.13	0.03	0.61	0.89	0.05	0.47	0.39
Error	10.74	12.49	6.65	9.48	7.23	7.97	5.76
Red Paw 2							
Water status zone	0.03	0.43	1.63	0.10	0.27	0.27	0.08
Error	8.47	9.00	5.50	9.15	7.58	7.67	5.77
Lowrey's							
Water status zone	0.40	0.40	1.23	0.05	0.00	0.09	0.01
Error[c]	8.75	8.67	9.02	10.96	6.96	8.04	5.48

[b] *, **, ***: significant at $p \leq 0.05, 0.01, 0.001$ respectively.
[c] Error value is the mean square (MS) of the error term

Table 7-17: Means of descriptive analysis aroma attributes by wine; 2008 Pinot noir wines from Red Paw 1, Red Paw 2 and Lowrey's vineyards, St. Davids, ON.

Wine	Tart fruit aroma	Sweet fruit aroma	sweet aroma	Pepper spice aroma	Baking spice aroma	Tobacco aroma	Vegetal aroma
Red Paw 1							
High-1	5.70	4.91	1.87b	4.10	2.82	3.79	2.57
High-2	5.73	4.82	3.63a	3.60	2.62	3.17	1.78
High-3	5.44	5.02	3.58a	3.06	3.31	3.09	2.06
Low-1	6.02	5.04	2.98ab	3.93	2.96	3.43	1.81
Low-2	5.87	5.57	2.82ab	4.26	2.92	2.89	2.14
Low-3	5.43	4.21	2.87ab	3.20	2.74	2.83	2.78
Significance[m]	ns	ns	*	ns	ns	ns	ns
Red Paw 2							
High-1	5.77	4.15bc	2.58	3.18	3.15	2.96	3.64a
High-2	5.44	4.32abc	2.82	3.34	2.48	3.47	3.05ab
High-3	5.72	5.09ab	2.46	3.52	2.67	3.30	2.31bc
Low-1	5.13	3.51c	1.98	3.76	2.57	3.37	3.53a
Low-2	5.78	4.78ab	2.60	3.49	2.72	3.27	1.91c
Low-3	5.15	5.47a	3.02	2.74	2.27	3.32	2.58
Significance	ns	*	ns	ns	ns	ns	**
Lowrey's							
High-1	4.72	3.72c	1.48	2.80	2.73	2.60	3.93abc
High-2	5.69	4.49abc	1.92	2.47	2.95	3.14	3.93abc
High-3	5.05	4.74abc	2.13	3.13	2.45	3.11	4.02ab
Medium-1	5.52	4.64abc	3.02	3.40	2.59	3.25	2.65cde
Medium-2	4.43	4.21bc	1.92	2.09	2.21	2.82	4.29a
Medium-3	5.50	4.70abc	2.25	3.18	2.72	2.99	3.61abcd
Low-1	6.09	5.18ab	2.95	2.31	2.40	3.25	2.11e
Low-2	5.39	5.51a	3.07	2.43	3.15	3.78	2.61de
Low-3	5.65	5.21ab	3.50	2.92	3.39	3.17	2.85bcde
Significance	ns	*	ns	ns	ns	ns	**

[d] Mean separation at a=0.05 using the LSD test; *, **, ***, ns: Significant at $p \leq 0.05, 0.01, 0.001$, not significant, respectively.

Table 7-18: Means of descriptive analysis flavour, taste & mouthfeel attributes by wine; 2008 Pinot noir wines from Red Paw 1, Red Paw 2 and Lowrey's vineyards, St. Davids, ON.

Wine	Red fruit flavour	Spices flavour	Vegetal flavour	Earthy flavour	Acidity	Bitterness	Astringency
Red Paw 1							
High-1	6.80	4.50	2.46	4.69	4.30	1.88b	3.28
High-2	6.37	4.92	2.33	4.14	4.37	2.46a	3.37
High-3	6.39	4.25	2.60	4.20	4.30	1.64b	3.42
Low-1	6.56	4.30	2.10	3.28	4.16	1.36b	2.84
Low-2	6.74	4.49	1.97	3.87	4.68	1.82b	3.34
Low-3	5.61	4.57	2.21	4.29	4.48	1.73b	3.07
Significance[m]	ns	ns	ns	ns	ns	**	ns
Red Paw 2							
High-1	5.95	4.24	2.89	4.21	3.98	1.64	3.05
High-2	6.29	4.18	2.59	3.90	4.79	2.34	3.33
High-3	6.83	3.49	2.84	4.01	4.50	2.00	3.21
Low-1	5.67	4.54	2.38	3.86	4.49	1.42	3.16
Low-2	6.35	3.96	2.17	4.22	4.75	2.01	3.05
Low-3	6.76	4.48	2.13	4.57	4.82	1.77	3.76
Significance	ns	ns	ns	ns	ns	ns	ns
Lowrey's							
High-1	6.05	3.53abc	3.68	4.33	4.13	1.44	3.83
High-2	6.56	3.24bc	3.08	3.98	4.62	1.84	3.20
High-3	6.51	3.96ab	2.65	4.46	4.57	1.70	3.53
Medium-1	6.49	3.38abc	3.33	4.48	4.50	1.61	3.80
Medium-2	6.26	2.85c	3.46	3.83	4.33	1.83	3.46
Medium-3	6.51	3.89ab	3.19	3.98	4.49	1.63	3.24
Low-1	6.79	3.32abc	2.20	4.39	4.17	1.80	3.71
Low-2	6.74	4.14ab	2.50	3.70	4.46	2.19	3.40
Low-3	6.92	4.24a	2.82	4.56	4.72	1.58	3.46
Significance	ns	*	ns	ns	ns	ns	ns

[d] Mean separation at a=0.05 using the LSD test; *, **, ***, ns: Significant at p≤ 0.05, 0.01, 0.001, not significant, respectively.

Table 7-19: Pixel values extracted from the rectangle shown in Figure 7-25,derived from Red Paw 2 Pinot noir vineyard site, St. Davids, ON, 2009. The bolded values are the pixels which would be chosen as the seed point for data extraction, based on the highest local NIR band reflectance. The shaded pixels represent those that are most likely to be all vine area. Note that the NIR and NDVI band values are highest at the pixels that are between the two vine rows, and in the case of the row on the left, taking the highest NDVI value as the seed point would also include negative NDVI values when expanded.

	Band	Pixel Value														
(a)	NIR	0.46	0.49	0.42	0.55	**0.70**	0.51	0.72	0.91	0.82	0.65	0.60	**0.66**	0.55	0.38	0.42
(b)	NDVI	-0.13	-0.01	-0.10	0.42	0.37	0.21	0.65	0.69	0.44	0.21	0.32	0.47	0.07	-0.25	-0.20

Table 7-20: Pixel values from the rectangle in Figure 7-26, derived from Red Paw 2 Pinot noir vineyard site, St. Davids, ON, 2009. The NDVI when calculated on a pixel-by-pixel basis is 0.212, and when calculated from the re-sampled NIR and red waveband the NDVI is 0.186; they are not equivalent operations.

NIR					RED					NDVI				
172	191	239	196	178	100	115	75	170	220	0.26	0.25	0.52	0.07	-0.11
185	188	255	198	176	85	132	94	142	255	0.37	0.18	0.46	0.16	-0.18
194	211	245	212	173	95	132	124	118	250	0.34	0.23	0.33	0.28	-0.18
184	192	237	205	182	95	137	91	135	239	0.32	0.17	0.45	0.21	-0.14
192	179	216	216	172	82	110	84	90	255	0.40	0.24	0.44	0.41	-0.19

Table 7-21: Means of NDVI-red extracted from 2008 & 2009 airborne images in four Pinot noir vineyard sites, St. Davids, ON, 2008 and 2009 with vines grouped by vigour status zone. Images were re-sampled at 1x1, 3x3, and 5x5 pixel target areas.

Vigour Status Category	**NDVI-red 1x1pixel**		**NDVI-red 3x3pixel**		**NDVI-red 5x5pixel**	
Red Paw 1	2008	2009[b]	2008	2009	2008	2009
Low	0.24	-	0.12	-	0.05b	-
High	0.26	-	0.13	-	0.07a	-
Significance[a]	ns	-	ns	-	*	-
Red Paw 2						
Low	0.23	-	0.11	-	0.08	-
High	0.25	-	0.11	-	0.08	-
Significance	ns	-	ns	-	ns	-
Black Paw						
Low	0.04a	-	-0.04a	-	-0.04a	-
High	0.01b	-	-0.07b	-	-0.07b	-
Significance	***	-	***	-	**	-
Lowrey's						
Low	0.63	0.34	0.30	0.18	0.16	0.09
High	0.63	0.35	0.32	0.19	0.18	0.10
Significance	ns	ns	ns	ns	ns	ns

[a]Mean separation at $\alpha=0.1$ using the LSD test *, **, ***, ****, ns: Significant at $p\leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively

[b]In 2009, Lowrey's vineyard was the only site where pruning shoot weights were measured

Table 7-22: Means of NDVI-green extracted from 2008 & 2009 airborne images in four Pinot noir vineyard sites, St. Davids, ON, 2008 and 2009 with vines grouped by vigour status zone. Images were re-sampled at 1x1, 3x3, and 5x5 pixel target areas.

Vigour Status Category	NDVI-green 1x1pixel		NDVI-green 3x3pixel		NDVI-green 5x5pixel	
Red Paw 1	2008	2009[b]	2008	2009	2008	2009
Low	0.38	-	0.22	-	0.09	-
High	0.39	-	0.23	-	0.10	-
Significance[a]	ns	-	ns	-	ns	-
Red Paw 2						
Low	0.16	-	0.02	-	0.01	-
High	0.14	-	0.01	-	0.00	-
Significance	ns	-	ns	-	ns	-
Black Paw						
Low	-0.05a	-	-0.11a	-	-0.10	-
High	-0.07b	-	-0.13b	-	-0.11	-
Significance	*	-	**	-	ns	-
Lowrey's						
Low	0.25	0.13b	0.12	0.11	0.13	0.03b
High	0.23	0.17a	0.13	0.12	0.15	0.04a
Significance	ns	**	ns	ns	ns	*

[a]Mean separation at α=0.1 using the LSD test *, **, ***, ****, ns: Significant at $p \leq 0.1$, 0.05, 0.01, 0.001, not significant, respectively

[b]In 2009, Lowrey's vineyard was the only site where pruning shoot weights were measured

Table 7-23: Pearson's correlation coefficients between descriptive analysis attributes, 2008 Pinot noir wines from Red Paw 1, Red Paw 2 and Lowrey's vineyards, St. Davids, ON. Colour coding relates to significance (p-value) where yellow, blue and red represent $p \leq 0.0001$, 0.01, and 0.05 respectively. Descriptors in upper case letters are flavour attributes.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1 - Tart Fruit	1	0.64	0.58	0.49	0.64	0.47	0.35	0.73	0.64	0.40	0.64	0.00	0.42	0.16
2 - Sweet Fruit		1	0.73	0.41	0.64	0.54	0.14	0.64	0.56	0.27	0.53	-0.28	0.20	-0.09
3 - sweet			1	0.39	0.61	0.57	0.12	0.53	0.53	0.21	0.53	-0.22	0.10	-0.13
4 - Pepper Spice				1	0.61	0.47	0.23	0.30	0.67	0.18	0.30	-0.04	0.08	-0.19
5 - Baking Spice					1	0.62	0.21	0.41	0.68	0.19	0.50	-0.13	0.21	-0.10
6 - Tobacco						1	0.19	0.34	0.46	0.23	0.53	-0.42	-0.18	-0.27
7 - Vegetal							1	0.34	0.30	0.70	0.37	0.06	0.31	0.01
8 - RED FRUIT								1	0.47	0.37	0.51	0.00	0.32	0.21
9 - SPICES									1	0.24	0.51	0.07	0.35	0.06
10 - VEGETAL										1	0.51	-0.13	0.26	0.04
11 - EARTHY											1	-0.11	0.35	0.26
12 - Acidity												1	0.48	0.55
13 - Bitterness													1	0.56
14 - Astringency														1

Table 7-24: Pearson correlation coefficient of NDVI-red extracted from airborne images against mean Ψ for 1x1, 3x3, and 5x5 pixel sample sizes centred over sentinel vines in four Pinot noir vineyard sites, St. Davids, ON, 2008 and 2009.

		NDVI-R					
		1x1	3x3	5x5	1x1	3x3	5x5
			r value			Significance	
2008	**29 May**	0.46	0.48	0.46	0.0010	0.0007	0.0012
	1 July	0.34	0.38	0.26	0.0179	0.0085	0.0755
	29 July	0.56	0.08	-0.14	<.0001	0.5384	0.2518
	21 Aug.	0.39	0.08	-0.19	0.0014	0.9104	0.1323
2009	**22 June**	0.26	0.37	0.39	0.0328	0.0020	0.0011
	5 Aug.	-0.13	-0.12	-0.18	0.2899	0.3388	0.1417
	1 Sept.	0.17	0.18	0.18	0.1850	0.1643	0.0003

Table 7-25: Pearson correlation coefficient of NDVI-green extracted from airborne images against mean Ψ for 1x1, 3x3, and 5x5 pixel sample sizes centred over sentinel vines from in four Pinot noir vineyard sites, St. Davids, ON, 2008 and 2009.

		NDVI-G					
		1x1	3x3	5x5	1x1	3x3	5x5
			r value			Significance	
2008	**29 May**	0.44	0.47	0.46	0.0019	0.0008	0.0012
	1 July	0.21	0.41	0.43	0.1510	0.0041	0.0023
	29 July	-0.11	-0.06	0.10	0.3751	0.6408	0.4404
	21 Aug.	0.01	-0.04	-0.14	0.5047	0.7364	0.2662
2009	**22 June**	0.23	0.38	0.39	0.0647	0.0018	0.0011
	5 Aug.	0.04	0.10	-0.01	0.7755	0.4206	0.9446
	1 Sept.	0.39	0.45	0.34	0.0015	0.1565	0.0077

Table 7-26: Pearson correlation coefficient of NDVI-red extracted from airborne images against weight of cane prunings for 1x1, 3x3, and 5x5 pixel sample sizes centred over sentinel vines from in four Pinot noir vineyard sites, St. Davids, ON, 2008 growing season[a].

		NDVI-R					
		1x1	3x3	5x5	1x1	3x3	5x5
			r value			Significance	
2008	29 May	-0.02	0.03	0.04	0.7693	0.6495	0.5046
	1 July	0.12	0.05	-0.06	0.0618	0.4859	0.3706
	29 July	0.35	0.05	-0.13	<.0001	0.4224	0.0236
	21 Aug.	0.29	0.14	-0.04	<.0001	0.0150	0.4878

[a]Following the 2009 growing season, Lowrey's vineyard was the only site where weight of cane prunings were measured.

Table 7-27: Pearson correlation coefficient of NDVI-green extracted from airborne images against weight of cane prunings for 1x1, 3x3, and 5x5 pixel sample sizes centred over sentinel vines in four Pinot noir vineyard sites, St. Davids, ON, 2008 growing season[a].

		NDVI-G					
		1x1	3x3	5x5	1x1	3x3	5x5
			r value			Significance	
2008	29 May	-0.04	0.01	0.03	0.5151	0.9317	0.6977
	1 July	0.17	0.16	0.09	0.0112	0.0139	0.1688
	29 July	-0.24	-0.13	0.04	<.0001	0.0248	0.5310
	21 Aug.	-0.08	-0.10	-0.10	0.1501	0.0892	0.0670

[a]Following the 2009 growing season, Lowrey's vineyard was the only site where weight of cane prunings were measured.

Table 7-28: Pearson correlation coefficient of NDVI-red extracted from airborne images against berry total phenols for 1x1, 3x3, and 5x5 pixel sample sizes centred over sentinel vines in four Pinot noir vineyard sites, St. Davids, ON, 2008 and 2009.

		NDVI-R					
		1x1	3x3	5x5	1x1	3x3	5x5
			r value			Significance	
2008	29 May	-0.54	-0.51	-0.50	<.0001	<.0001	<.0001
	1 July	-0.31	-0.39	-0.38	<.0001	<.0001	<.0001
	29 July	0.02	0.03	0.11	0.7773	0.5538	0.0544
	21 Aug.	0.02	0.03	0.07	0.7102	0.5603	0.1905
2009	22 June	0.16	0.12	0.13	0.0046	0.0328	0.0218
	5 Aug.	0.16	0.06	0.03	0.0045	0.3056	0.5456
	1 Sept.	0.39	0.33	0.25	<.0001	<.0001	<.0001

Table 7-29: Pearson correlation coefficient of NDVI-green extracted from airborne images against berry Total Phenols for 1x1, 3x3, and 5x5 pixel sample sizes centred over sentinel vines in four Pinot noir vineyard sites, St. Davids, ON, 2008 and 2009.

		NDVI-G					
		1x1	3x3	5x5	1x1	3x3	5x5
			r value			Significance	
2008	29 May	-0.52	-0.51	-0.50	<.0001	<.0001	<.0001
	1 July	-0.16	-0.21	-0.30	0.0166	0.0015	<.0001
	29 July	-0.08	0.05	0.21	0.1375	0.3753	0.0002
	21 Aug.	-0.18	-0.15	-0.11	0.0015	0.0081	0.0605
2009	22 June	-0.10	0.09	0.20	0.0694	0.1136	0.0003
	5 Aug.	-0.16	-0.01	0.18	0.0039	0.9079	0.0013
	1 Sept.	0.23	0.24	0.23	<.0001	<.0001	<.0001

Table 7-30: Pearson correlation coefficient of NDVI-red extracted from airborne images against berry Total Anthocyanins for 1x1, 3x3, and 5x5 pixel sample sizes centred over sentinel vines in four Pinot noir vineyard sites, St. Davids, ON, 2008 and 2009.

		NDVI-R					
		1x1	**3x3**	**5x5**	**1x1**	**3x3**	**5x5**
		r value			Significance		
2008	**29 May**	-0.39	-0.45	-0.45	<.0001	<.0001	<.0001
	1 July	-0.54	-0.52	-0.40	<.0001	<.0001	<.0001
	29 July	-0.48	-0.22	0.00	<.0001	0.0002	0.9698
	21 Aug.	-0.40	-0.24	0.01	<.0001	<.0001	0.9272
2009	**22 June**	0.44	0.46	0.45	<.0001	<.0001	<.0001
	5 Aug.	0.36	0.41	0.48	<.0001	<.0001	<.0001
	1 Sept.	0.27	0.34	0.47	<.0001	<.0001	<.0001

Table 7-31: Pearson correlation coefficient of NDVI-green extracted from airborne images against berry total anthocyanins for 1x1, 3x3, and 5x5 pixel sample sizes centred over sentinel vines from in four Pinot noir vineyard sites, St. Davids, ON, 2008 and 2009.

		NDVI-G					
		1x1	**3x3**	**5x5**	**1x1**	**3x3**	**5x5**
		r value			Significance		
2008	**29 May**	-0.34	-0.42	-0.42	<.0001	<.0001	<.0001
	1 July	-0.41	-0.45	-0.47	<.0001	<.0001	<.0001
	29 July	-0.06	-0.06	-0.15	0.3399	0.3572	0.0136
	21 Aug.	-0.20	-0.14	-0.11	0.0009	0.0169	0.0763
2009	**22 June**	0.35	0.45	0.46	<.0001	<.0001	<.0001
	5 Aug.	0.33	0.46	0.55	<.0001	<.0001	<.0001
	1 Sept.	0.16	0.27	0.41	0.0067	<.0001	<.0001

Table 7-32: Pearson correlation coefficients between seasonal mean vegetation indices from airborne images and yield components and berry composition in four Pinot noir vineyard sites, St. Davids, ON, 2008. Colour coding relates to significance (p-value) where yellow, blue and red represent $p \leq 0.0001$, 0.01 and 0.05 respectively.

	Mean NDVI-red			Mean NDVI-green		
	1x1	3x3	5x5	1x1	3x3	5x5
Yield	0.21	0.24	0.21	0.34	0.35	0.29
No. clusters	0.05	0.10	0.13	0.21	0.22	0.15
g/cluster	0.42	0.39	0.27	0.40	0.39	0.39
g/berry	-0.22	-0.11	-0.04	0.22	0.19	0.01
Berry pH	-0.57	-0.48	-0.33	-0.17	-0.21	-0.40
Berry Brix	-0.40	-0.43	-0.35	-0.34	-0.37	-0.43
Berry TA	-0.12	-0.07	-0.11	0.22	0.27	0.11
Shoot wt.	0.51	0.46	0.36	0.14	0.23	0.40
Crop load	-0.17	-0.12	-0.08	0.08	0.04	-0.08
Anthocyanins	-0.63	-0.65	-0.61	-0.53	-0.56	-0.65
Colour	-0.54	-0.58	-0.55	-0.59	-0.60	-0.61
Hue	0.34	0.37	0.39	0.28	0.30	0.36
Phenols	-0.08	-0.12	-0.14	-0.21	-0.17	-0.12
Soil moisture	0.11	-0.06	-0.15	-0.48	-0.43	-0.22
Ψ	0.70	0.65	0.56	0.35	0.45	0.62
NR 1x1	1	0.92	0.79	0.43	0.48	0.76
NR 3x3		1	0.93	0.55	0.63	0.88
NR 5x5			1	0.47	0.57	0.84
NG 1x1				1	0.93	0.76
NG 3x3					1	0.87
NG 5x5						1

Table 7-33: Pearson correlation coefficients between seasonal mean vegetation indices from airborne images and yield components and berry composition in four Pinot noir vineyard sites, St. Davids, ON, 2009. Colour coding relates to significance (p-value) where yellow, blue and red represent $p \leq 0.0001$, 0.01 and 0.05 respectively.

	Mean NDVI-red			Mean NDVI-green		
	1x1	**3x3**	**5x5**	**1x1**	**3x3**	**5x5**
Yield	-0.07	-0.06	-0.07	-0.05	-0.05	-0.07
No. clusters	-0.14	-0.14	-0.16	-0.14	-0.13	-0.14
g/cluster	0.09	0.09	0.11	0.13	0.11	0.09
g/berry	0.16	0.24	0.25	0.37	0.40	0.34
Berry pH	0.05	0.18	0.25	0.33	0.23	0.17
Berry Brix	0.18	0.24	0.30	0.28	0.26	0.24
Berry TA	0.46	0.36	0.27	0.01	0.21	0.31
Anthocyanins	0.44	0.49	0.54	0.37	0.46	0.50
Colour	0.37	0.29	0.26	-0.08	0.08	0.21
Hue	0.18	0.35	0.46	0.63	0.54	0.44
Phenols	0.29	0.20	0.16	-0.04	0.14	0.22
Soil moisture	-0.85	-0.89	-0.89	-0.65	-0.82	-0.88
Ψ	0.14	0.22	0.23	0.29	0.38	0.32
NR 1x1	1	0.94	0.87	0.65	0.83	0.87
NR 3x3		1	0.97	0.77	0.94	0.96
NR 5x5			1	0.82	0.95	0.97
NG 1x1				1	0.87	0.82
NG 3x3					1	0.97
NG 5x5						1

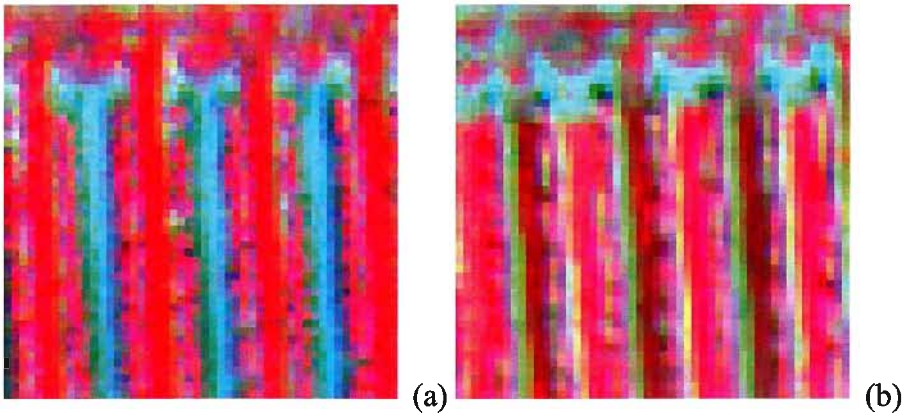


Figure 7-23: CIR image of the same portion of Red Paw 2 Pinot noir vineyard, St. Davids, ON from (a) 22 June 2009 and (b) 5 August 2009. Note that the blue/green of bare soil is replaced with dark red vegetation.

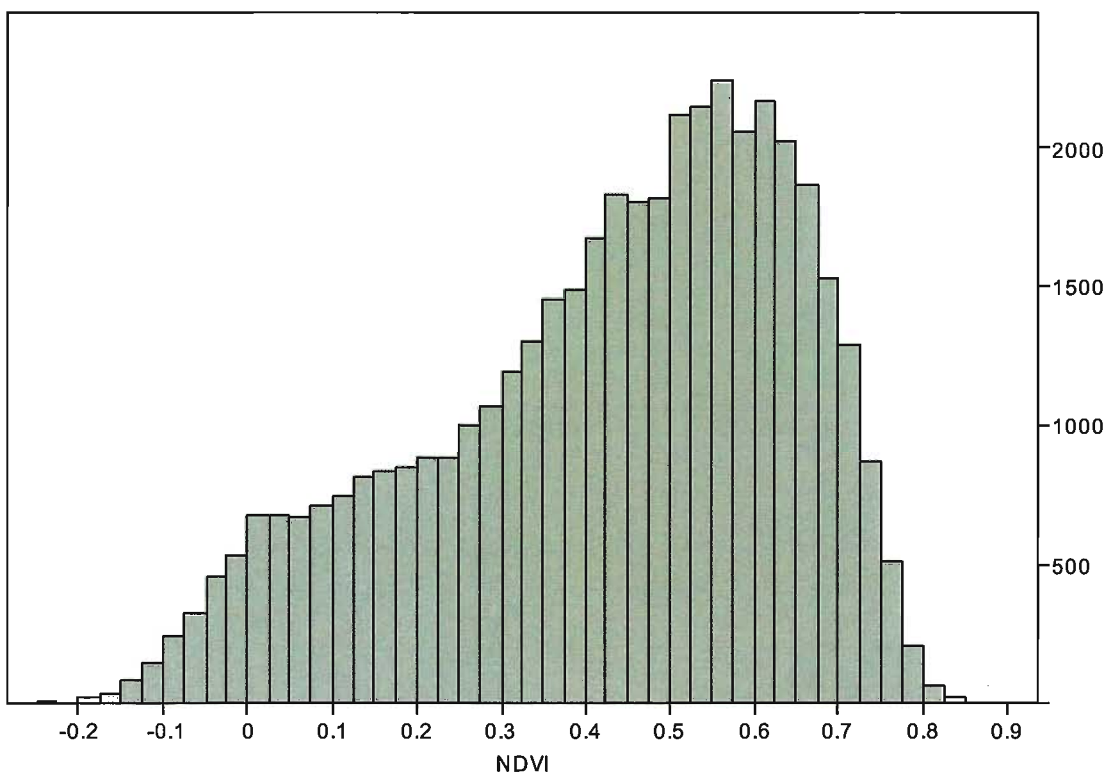


Figure 7-24: Histogram of NDVI values extracted from Red Paw 2 Pinot noir vineyard block, St. Davids, ON, June 22, 2009. The presence of inter-row vegetation means that a threshold value cannot be used to differentiate vines from inter-row spaces, both vines and non-vine vegetation is present at all values of NDVI.

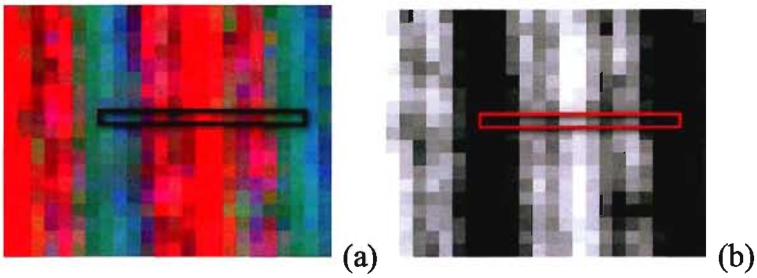


Figure 7-25: (a) CIR and (b) NDVI images from Red Paw 2, Pinot noir vineyard, St. Davids, ON, June 22, 2009. The values of the pixels in the rectangle are given in Table 7-19, and indicate that the highest NIR or NDVI alone cannot be used to identify the representative "vine" pixel for data extraction.

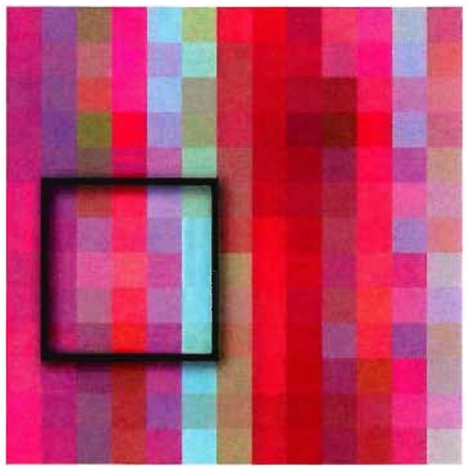


Figure 7-26: CIR image of Red Paw 2 vineyard, 1 September 2009. The values of the pixels in the rectangle are given in Table 7-20, and show that taking the mean NDVI on a pixel-by-pixel basis is not equivalent to re-sampling the individual wavebands and then calculating NDVI.