Delineation of Within-site Terroir Effects using Soil and Vine Water Measurements in Riesling Vineyards within the Niagara Peninsula

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Abstract

The major focus of this dissertation was to explain terroir effects that impact wine varietal character and to elucidate potential determinants of terroir by testing vine water status (VWS) as the major factor of the terroir effect. It was hypothesized that consistent water status zones could be identified within vineyard sites, and, that differences in vine performance, fruit composition and wine sensory attributes could be related to VWS. To test this hypothesis, ten commercial Riesling vineyards representative of each Vintners Quality Alliance sub-appellation were selected. Vineyards were delineated using global positioning systems and 75 to 80 sentinel vines per vineyard were geo-referenced for data collection. During the 2005 to 2007 growing seasons, VWS measurements [midday leaf water potential (ψ)] were collected from a subset of these sentinel vines. Data were collected on soil texture and composition, soil moisture, vine performance (yield components, vine size) and fruit composition. These variables were mapped using global information system (GIS) software and relationships between them were elucidated. Vines were categorized into "low" and "high" water status regions within each vineyard block and replicate wines were made from each. Many geospatial patterns and relationships were spatially and temporally stable within vineyards. Leaf ψ was temporally stable within vineyards despite different weather conditions during each growing season. Generally, spatial relationships between ψ, soil moisture, vine size, berry weight and yield were stable from year to year. Leaf ψ impacted fruit composition in several vineyards. Through sorting tasks and multidimensional scaling, wines of similar VWS had similar sensory properties. Descriptive analysis further indicated that VWS impacted wine sensory profiles, with similar attributes being different for wines from different water status zones. Vineyard designation had an effect on wine profiles, with certain sensory and chemical attributes being associated from different sub-appellations. However, wines were generally grouped in terms of their regional designation ('Lakeshore', 'Bench', 'Plains') within the Niagara Peninsula. Through multivariate analyses, specific sensory attributes, viticulture and chemical variables were associated with wines of different VWS. Vine water status was a major contributor to the terroir effect, as it had a major impact on vine size, berry weight and wine sensory characteristics.

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Chapter 1: Introduction

In contrast to many other types of crops, wine grapes (*Vitis vinifera* L.) can be grown in diverse climates and soils. In its most basic definition, the complex French concept of terroir can be summarized by stating that agricultural commodities such as wine reflect their place of geographical origin. These differences are commonly explained in terms of geology, climatology, and soil. Terroir is of importance because it presumably enables a wine from a particular region to possess unique qualities that differentiate it from other wines of the same variety from other regions or even other vineyards within a region. Thus terroir is an important concept in the wine and food industry because it gives the product a "sense of place" which distinguishes it from other similar products. This has led to an increase of smaller production wines, particularly in the 'New World', and further delimitations and classifications within wine regions worldwide. This rejuvenated interest in terroir in the wine industry worldwide has led to the market identifying a hierarchy in wines such that wine labels, newspapers, magazines and even restaurant menus are using this 'Old World' notion as the single most important criterion for distinction among high-end wines. Thus, the geological and environmental conditions that impart nuances on wine quality and style, giving it specificity have created a demand for a higher price in the market, both domestically and internationally. This is in part due to the fact that terroir-driven wines are largely produced from single vineyard parcels or single wine estates that limit production. Therefore, due to supply and demand, and arguably their quality, the wines can demand a higher price and be quite expensive.

Traditional understanding is that soil is the primary force driving terroir; however, this notion has been controversial in research. Some studies (Noble 1979) have found no consistent trends in sensory profiles of wine from different soil types while others (de Andres-de Prado et al. 2007) indicate that soil effects did influence chemical and sensory properties in wine. Other evidence suggests that water availability and plant water status are the means by which the terroir affects wine style. (Penavayre et al. 1991, Seguin 1983). Yet, the impact of site and plant water status on grape/wine composition and wine sensory properties has not been widely addressed, at least not with important environmental factors and cultural practices kept constant. Precision viticulture techniques, including global positioning systems (GPS) and geographic information systems (GIS), have become powerful tools to study vineyard terroir (Reynolds et al. 2007) and variability (Bramley 2005, Bramley and Hamilton 2004) while keeping key environmental factors constant. Therefore, these were utilized to accomplish our research objectives.

Since the 1970s, there has been a rise in reputable premium wine producing regions in the 'New World'. These represent large areas of grapes planted worldwide and provide a significant amount of wine to domestic and international markets. Contrary to many of the traditional parts of Europe, where vineyards are planted on homogeneous soils and are only a few acres in size, 'New World' vineyard blocks tend to be quite large, with variable soils. The Niagara Peninsula in Ontario, Canada, is known for its diverse soils, macroclimates and topographical features that further complicate the terroir effect. The soils of the Niagara Peninsula have complex compositions due to several glacial and interglacial events. It is surrounded by two major bodies of water, Lake Ontario and Lake Erie, which impact the climate of the region on many levels. Furthermore, many of the vineyards are located on or below the Niagara Escarpment (a prominent 100 m uplift) which results in more complex topographies and mesoclimates. Consequently, there are many distinct terroirs in the region with the potential to produce a variety of cultivars with high quality wines. Some studies have indicated that wines from different geographical locations within the Niagara Peninsula have different sensory profiles; Riesling (Douglas et al. 2001), Chardonnay (Schlosser et al. 2005) and Bordeaux-style (Kontkanen et al. 2005). In recent years, the Vintners Quality Alliance of Ontario (VQAO) who regulate standards for Ontario wine, created sub-appellations within the Niagara Peninsula based on physical characteristics of soil, climate and topographical differences (Shaw 2004). Therefore, there is a need for research to gain more insight into the influence of terroir on wine quality in the Niagara Peninsula.

1.2. Hypotheses and Objectives. Little research has been done to determine whether Niagara's unique terroir influences wine varietal character. Some studies performed in Niagara have indicated that vine size and soil texture can have some effects on fruit composition and sensory characteristics of wines but the findings were not consistent from year to year (Reynolds et al. 2007). Furthermore, it was found that vintage and wine aging had a more profound impact on the wine sensory profiles than any measured terroir effect. Therefore, this dissertation attempted to further evaluate the basis of terroir in the Niagara Peninsula by using Riesling vineyards representative of each VQAO sub-appellation. The specific primary objectives of this research were: (i) to test the influences of soil texture, soil water content, and vine water status on vine and fruit development within vineyard blocks and to delineate these terroir effects using GPS and GIS; and (ii) to elucidate the relationships between soil and vine water status and wine sensory properties. It was hypothesized that (i) consistent water status zones can be identified within vineyard blocks and, ii) vine water status will play a major role in fruit composition and sensory characteristics of Riesling wine, whereas soil will play a role through its water holding capacity and water supply to the vine. A secondary objective was to validate the VQAO sub-appellations in terms of fruit composition and wine sensory attributes. The criterion used to create these sub-regions included soil and climate data but did not include any chemical analysis of grapes/wine or sensory analysis of wine. Therefore, this research was conducted to validate these new sub-appellations using chemical parameters and sensory characteristics, and to relate sensory profiles of the wines to various soil and vineyard features within the Niagara Peninsula. Furthermore, with over 32 grape varieties planted in the Niagara Peninsula there is need for more focus on specific varieties that are best suited to these regions/appellations, not only for sustainability purposes but also for the production of higher quality wines.

This project had two distinct phases; the first phase was the geospatial aspect of the project where spatial relationships of soil characteristics, vine performance (yield, vine size), plant water status, and fruit composition (including aroma compounds) were delineated using GPS and GIS technology. The second phase consisted of the sensory characterization of wines produced from regions of different water status delineated through GIS, as well as the ten VQAO sub-appellations through multiple sensory evaluation tasks. Finally, multivariate statistics were used to help elucidate relationships between terroir effects and wine sensory properties with the ultimate goal to create a model for the basis of terroir in Niagara Riesling vineyards.

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Chapter 2: Literature Review

2.1. ***Terroir.*** The concept of terroir is quite complicated since it integrates many environmental, biological and human factors. Human factors need to be mentioned because no wine is created without some form of human intervention. These include, but are not exclusive to, aspects such as winemaking regimes, cultural practices and cultivar/rootstock clonal selection. However, the major focus of this review will be on the environmental and biological factors of terroir. Terroir can be defined as a spatial and temporal entity that is characterized as an interactive ecosystem, including soil, climate and the vine (van Leeuwen and Seguin 2006). There are a multitude of factors that can highly impact vine and fruit development as well as wine sensory attributes. Therefore, the combination of these factors and the relationships among them is known as the terroir effect. Due to its complexity, terroir-related studies over the last 30 years have mostly focused on associating grape and wine quality to a few environmental factors such as soil or climate. However, in some studies researchers (Carbonneau 1992, Carbonneau and Casteran 1987, van Leeuwen et al. 2004) have included the interaction of these attributes with other factors. Centuries of relationships observed between wine quality and terroir were used for creation of the Appellation d'Origine Contrôlée (AOC) in France, but the terroir concept was first published in scientific literature by Seguin (Seguin 1970, Seguin 1975, Seguin 1983, 1986) who initiated studies in the region of Bordeaux in the 1970s. Many of the initial papers concerning terroir in the literature originated from 'Old World' wine growing regions that had existing appellations. Thus, studies have been performed in France including the Loire (Asselin et al. 1983, Bodin and Morlat 2003, Jourjon et al. 1991, Morlat 1992) and Rhone Valleys (Coipel et al. 2006, Vaudour et al. 1998), Bordeaux (Carbonneau and Casteran 1987, Seguin 1970, van Leeuwen et al. 2004), Languedoc (Carbonneau et al. 1978), Alsace (Lebon 1993), and Champagne (Dolédec 1995) but also regions of Italy (Falcetti and Scienza 1991), Spain (de Andres-de Prado et al. 2007), and Germany (Fischer and Bauer 2006). More recently, studies have emerged from 'New World' regions that have attempted to understand their terroir such as South Africa (Carey et al. 2008b, Conradie et al. 2002), Canada (Reynolds et al. 2007b), and New Zealand (Tesic et al. 2002) as well as other wine regions. Understanding the terroir effect from a scientific standpoint is a daunting task as it needs to take into consideration a wide range of factors and their interactions. Therefore, some authors have considered a single environmental parameter of the terroir effect including climate (Winkler et al. 1962) and soil (Seguin 1975) but also biological factors such as cultivar or rootstock (Rankine et al. 1971).

Climate. Climate can encompass all aspects including macroclimate, mesoclimate and microclimate and their interaction with the vine (van Leeuwen and Seguin 2006). Climate has a major influence on the vegetative and reproductive development of grapevines through, but not exclusively, the effects of temperature, precipitation, solar radiation, and evapotranspiration on physiological processes. Macroclimate differences between cool and warm climate regions can have a profound impact on the ripening of grape varieties (Jackson and Lombard 1993). Malic acid has been shown to decrease as temperature increases whereas soluble solids increase in a curvilinear fashion (Coombe 1986). However, there is an upper limit where warm temperatures will reduce ripening due to a reduction in physiological functions such as photosynthesis. For example, Kliewer (1973) found that photosynthesis is most efficient in temperatures between 18°C and 33°C.

Climatic factors have a major influence on vine development and are critical for dormancy and bud break of grapevines but not exclusive to these two events. Vine phenology has been modelled through the sum of metabolically active temperatures (Winkler et al. 1974). The most important phenological events for wine grapes are bud break, flowering, fruit set, veraison, harvest, and leaf fall. The rate of development between these phenological events varies greatly with each grapevine variety, the climate, and its geographical location (Nemani et al. 2001). Tesic et al. (2001) attempted to characterize viticulture environments and phenology with Cabernet Sauvignon in New Zealand. They found the largest differences between sites were in indices of precocity and that they correlated best with vegetative growth and canopy indices. Climate differences in seasons resulted in a large variation in budburst, flowering and veraison in all sites. Date and duration of veraison varied greatly with site and season. Climate research has indicated that high wine quality is generally associated with early, even budburst, flowering and development as a result of warm springs; optimal fruit maturation with low diurnal fluctuations in temperature near harvest; and low frost damage as a result of mild winters (Gladstones 1992, Jones and Davis 2000). It can be summarized that the most suitable cultivar(s) for a region should match the length of the growing season so that fruit maturation will occur during the cool portion of the season but with enough warmth to continue accumulation of sugars and flavour development in the berries (Jackson and Lombard 1993). Furthermore, some studies have stated that grape cultivars should ideally mature in cool conditions at the end of the growing season in order to obtain terroir expression (van Leeuwen and Seguin 2006).

Mesoclimate differences can be due to variations in altitude, aspect or slope within a region and therefore contribute to the terroir effect (Falcetti 1994). These factors have more of an impact in marginal cool climate regions as in the case of steep, south-facing slopes in the Mosel Valley in Germany. Many of the best wines are produced by choosing mesoclimates created by sun-facing slopes. According to Jackson and Lombard (1993) and Becker (1977), slope can influence a number of factors and their interactions may include reducing incidence of late spring and early autumn frost; higher heat accumulation and thus warmer temperatures; extended growing seasons; and more air movement/drainage. However, there is no single ideal climate parameter (temperature, rainfall, solar radiation) to define high quality wines since fine wines are grown in many diverse climates. Some studies have tried to address this issue. Morlat (1992) and Jorjon (1991) have both integrated soil and mesoclimate (precipitation, heat accumulation) differences within the Loire Valley and their relationship to wine quality and typicity. It has been demonstrated that viticulture climate (temperature, light, water balance) as shown in the works of Tonietto (1999) and Tonietto & Carbonneau (2000, 2004) are important environmental criteria to relate the typicity of wines to different wine-making zones.

Microclimate variation refers to the temperatures within the fruit zone of the grape vine canopy, thus impacting terroir within a specific location or site. Soil influences and canopy management have been shown to have the greatest impacts on these microclimate differences. Soils can impact microclimate in a number of ways including anthropomorphic heat retention and light reflecting capacity. Soil reflectance is derived from the combination of mineral, organic and fluid matter. Soil colour, temperature, structure, depth and water status determine the amount of solar radiation or soil reflection

(Muller and Decamps 2001, Post et al. 2000). Soil colour can also impact heat retention and temperature of the soil. For example, darker soils absorb more solar radiation as opposed to lighter soils which reflect more. Quality and quantity of reflected light have been shown to impact sugar concentrations and colour of grapes (Robin et al. 2000). In terms of texture, dry gravelly soils warm up quickly, retain more heat and reflect more light into the canopy. Sabon (2002) found that sites in which the soils were warmer had higher concentrations of certain varietal aroma compounds in Grenache than other soils. The grapes also had lower acidity. Canopy microclimate can be impacted either by more light exposure within the canopy or less due to shading based on the soil's inherent nature to influence vine growth.

Canopy management techniques have been shown in many studies (Reynolds and Wardle 1989b, Reynolds et al. 1994, Reynolds et al. 1996b, Smart et al. 1982, Smart et al. 1990) to improve the microclimate in the fruiting zone. These include training systems (Reynolds and Vanden Heuvel 2009), leaf removal (Percival et al. 1994, Reynolds et al. 1995), hedging (Reynolds and Wardle 1989a), and pruning strategies (Smart et al. 1982), among others.

Excessive water through rainfall or irrigation is synonymous with reduced fruit and wine quality (Sala et al. 2005, Smart et al. 1985). Rainfall post veraison can cause berries to become diluted or to split, which predisposes them to diseases such as botrytis, or bunch rot. Excessive water can also lead to a delay in fruit maturation as well as excessive vegetative growth (Smart and Coombe 1983). This can be due largely to the relationship between excess vigour, poor reproductive development and improper vine balance. Large vigorous canopies can lead to shaded, poorly exposed fruit, resulting in unripe, vegetative flavours (de Boubee et al. 2000, Smart 1974). Vintage effects occur due to variations in yearly climatic conditions. Variations in fruit ripening, vine performance, and quality caused by vintage effects are a consequence of climate since soil and cultivar are considered a constant (van Leeuwen et al. 2004). Therefore, it can be said that the best terroirs are considered those that limit climatic extremes which may occur from year to year.

Soil. Soil has traditionally been presumed the main constituent of terroir, particularly in the 'Old World' regions, and has therefore been the dominant focus throughout the literature. This is probably the case since soil is a stable variable over time, unlike climate or other terroir effects. Nonetheless, as with the case of climate effects, it is difficult to define the best soil in terms of texture, soil depth, or mineral content since high quality wines are grown on a diversity of soils worldwide. The effect of soil on vine behaviour and grape composition is complex. The influence of soil is problematic to quantify since soil has a multitude of effects on growth and fruit composition of grapevines. Some influences may include: plant water and nutrient availability, root growth and rooting depth, and microclimate and temperature in the rooting zone (Jackson and Lombard 1993, Seguin 1986, van Leeuwen and Seguin 2006).

Depending on the location, it may not be possible to relate high quality wines in terms of soil texture, soil type or mineral composition (Seguin 1983). In California, Noble (1979) evaluated sensory differences of Chardonnay wines from various sites with different soil compositions. No consistent trends in wine from different soil types were observed; however, soil, must, and wine compositions varied among locations. In Italy, Constantini et al. (1996) found that the most fertile soils in many of the vineyard sites studied in Vino Nobile di Montepulciano resulted in overproduction, leading to poorer grape ripening and wine quality. The best results were reported from moderately fertile soils with some pedological limitations. The authors noted that the poorest soils produced variable results and were highly dependent on climatic conditions (Costantini et al. 1996). However, Winkler et al. (1974) stated that good to excellent quality grapes have been produced for many varieties on all soil types except very heavy soils, in California.

Vineyard sites can impact grape phenology, vegetative growth and yields through relationships attributable to soil differences and soil moisture (Tesic et al. 2001). The authors found that sites earlier in phenological stages were excessively drained, stony gravels and well drained sandy soil. Later sites were sandy loams with high water table and very deep silty loams (Tesic et al. 2001). In the Loire valley, Barbeau et al. (1998) found that the later sites often had soil water problems (for example poor drainage, water perching) regardless of soil substrates. Therefore, water logged soils stay cooler longer and delay bud break.

van Leeuwen et al. (2004) studied the impact of different soil textures and grape maturation of Bordeaux varieties in France. Gravely soils were found to stop shoot growth earlier in the growing season and sugar, total acidities were low, anthocyanins high, and berry size small. Sandy soils had large berries, with low sugars and anthocyanins but high acidity. The authors also found that clay soils resulted in berries with the highest sugars, anthocyanins and phenolics and that these soil effects were related to vine water status. It was concluded that mineral nutrient uptake by the vine or availability in the soil did not have a significant impact on fruit quality (van Leeuwen et al. 2004).

Bader and Wahl (1996) moved soils from different regions around Germany to one vineyard site to eliminate any climatic influences. The authors found the soil effects on wine flavour to be very small and they concluded that although climate was more important than soil on wine sensory characteristics in a cool climate region, yield differences were found among different soil types. In another study that kept mesoclimate constant, Reynolds et al. (2007) found that there were no consistent soil texture or vine size effects on berry, must and wine composition or wine sensory attributes but there were correlations between soil texture and composition on berry weight and potentially-volatile terpene content. Soil effects were recently shown to influence chemical and sensory properties in Grenache wines from Spain (de Andres-de Prado et al. 2007). Fertile soils, with greater water holding capacity, produced wines with lower colour intensity and lower total phenols.

Most plant processes are affected, either directly or indirectly, by water availability usually derived from rainfall. Plants require soil water reserves that accommodate an intermittent supply and continuous demand (Winkler et al. 1962). Many areas where grapevines are grown have strong seasonal variations in moisture availability, frequently with hot, dry summers; therefore, the capacity of soil to store water is important (Winkler et al. 1962). Soils vary not only in their water holding capacity, but also in the amount and composition of mineral nutrients for root uptake (Chone et al. 2006, Keller 2005). The water holding capacity and nutrient accessibility are influenced by soil texture (van Leeuwen and Seguin 2006), rooting depth (Seguin 1986) and organic matter content, but nutrient availability is modified by soil moisture and pH (Keller 2005).

Nitrogen is the nutrient that has the largest impact on vine vigour (Peyrot des Gachons et al. 2005, Spayd et al. 1993). There have been some studies investigating soils of varying nitrogen status (Choné et al. 2001, Peyrot des Gachons et al. 2005). High amounts of nitrogen in the soil or through application have been found to increase vine growth and generally reduce some parameters of fruit quality (Spayd et al. 1994, Spayd et al. 1993). High nitrogen status has been shown to decrease fruit quality through reduced soluble solids (Spayd et al. 1994), higher acidity, and a decrease in desirable aroma compounds (Chone et al. 2006, Peyrot des Gachons et al. 2005). Since excess nitrogen can increase vine vigour, there are some indirect relationships that can occur in grapes and wine. Many studies have found that wine from vigorous grapevines has higher levels of undesirable flavour compounds such as methoxypyrazines (Morrison and Noble 1990, Sala et al. 2005). On the other hand, Hoenicke et al. (2002a) found that low nitrogen status coupled with water stress led to off flavour compounds in Riesling wines. The authors have described these flavours as Untypical Aging (UTA) or Atypical Aging (ATA) (Hoenicke et al. 2002b). Mild nitrogen deficits have been shown to be the most beneficial in terms of grape and wine quality. Moderate deficits of nitrogen maximized aroma potential in Sauvignon blanc through an increase in volatile thiol precursors (Peyrot des Gachons et al. 2005).

Potassium has been correlated with some must and wine parameters, particularly pH. Excessive potassium can lead to juice or wine with unacceptably high pH and high malic acid (Morris et al. 1983, Morris et al. 1987). This can impact wine quality through the effects of pH on colour, taste and microbial stability. High soil potassium can also lead to a decrease in magnesium content in many organs of the vine (Morris et al. 1983) due to competition in soil particle cation absorption sites and differential uptake of K/Mg into the plant (Hovland and Caldwell 1960).

The classic studies of Seguin (1970, 1975) tried to scientifically define the terroir effect by investigating chemical properties of soils in Bordeaux and its famous Chateaux. The author found that soil chemical composition did not have a direct, specific influence on wine quality, however the soil physical properties that regulated water supply to the vine did. Soil texture and rooting depth were noted as the most important soil factors. The best soils were those that were free draining, avoided water logging in the rooting zone, but limited water availability later in the season. This was further supported by Asselin et al. (1983) where the authors demonstrated some relationships between soil and wine sensory profiles using soil types from different sites within the Loire Valley. Hancock and Price (1990) studied the pure chalk soils in Champagne and other regions in France with limestone mixed with clays or other soil types. The authors noted that high porosity and high permeability of the chalk provided both good water holding capacity during drought, and easy drainage following heavy rains (Hancock and Price 1990).

One of the most important aspects of soil is its influence on vine vigour. Vigour has been shown to be directly related to texture, structure and soil water content. Soil texture (type) is usually classified by percentage sand, silt and clay content. The effect of soil texture seems to have an indirect effect in viticulture. Soil texture influences water holding capacity, cation exchange capacity, root penetration, temperature in the root zone and drainage. Typically, soils containing high levels of clay tend to have poor drainage, high nutrient content and high water holding capacity (Keller 2005). This tends to cause less vigorous growth in comparison to coarser textures, as shown in the work of Carey et al. (2008a) and Conradie et al. (2002). This may, in part, be due to better drainage (Seguin 1986) found in coarser soils and the ease of the vine roots to explore greater volumes of soil to access water and nutrients (Seguin 1970). Water is the carrier of essential nutrients from the soil because plant-available nutrient ions are dissolved in the soil solution and nutrient uptake depends on water uptake through the vine (Keller 2005, Menzel et al. 1986). Hence, water and nutrients exist together in close association. Growth reduction induced by water deficit decreases vine nutrient requirements and vice versa (Keller 2005). Therefore, the particular stress on the vine and its response depends on developmental status (Hardie and Considine 1976, Smart et al. 1974). Soils that limit yield or vine vigour through limited water or nitrogen supply are considered to be ideal for wine grape quality.

Soil water holding capacity and fertility directly influence vine size (Tesic et al. 2001, 2002). Many of the effects of soil on vine behaviour are mediated through changing water content and the subsequent effects on vine water status (Klepper 1968, Seguin 1983, 1986, van Leeuwen and Seguin 1994). Some studies indicate that plant water status is the means by which the terroir affects wine style and quality (Choné et al. 2001, Koundouras et al. 1999). Hence, soil water content and availability are now considered important criteria of terroir. In the Loire Valley in France, free-draining sandstone soils that provided water stress during maturation were associated with intense varietal character in Cabernet Franc wines (Penavayre et al. 1991). Vine water supply was also noted as a major factor in the terroir effect due to its impact on early budburst potential and potential vine vigour (Morlat et al. 2001). van Leeuwen et al. (2004) studied soil, climate, and cultivar simultaneously and found that climate and soil had a greater impact than that of cultivar. They also concluded that soil and climate effects were mediated through vine water status.

Many studies have examined the effect of water supply on vine performance and grape quality. Choné et al. (2001) explored the effect of soil variation on vine vigour, berry composition, and wine quality on a single estate in Bordeaux. The authors found that the highest quality wines were from sites with low nitrogen status throughout the season, but without water deficit and from a medium nitrogen status site coupled with mild water status. The authors also found that low nitrogen status reduced vigour more than mild water deficit. Low nitrogen status also decreased berry weight, increased anthocyanins and tannins in the skins, and reduced yield (Choné et al. 2001). In Greece, Koundouras et al. (2006) found that differences in vine water status between sites were correlated with the earliness of shoot growth cessation and veraison. In the same study, water deficit accelerated sugar accumulation and malic acid breakdown and early water deficit had a positive influence on the concentration of berry anthocyanins and phenolics in the fruit and wines. Limited water availability also increased glycoconjugates of aroma compounds and increased wine quality (Koundouras et al. 2006). One can conclude that mild water deficits have shown to be a major factor in the terroir effect (Koundouras et al. 1999, Seguin 1983) and grapes cultivated under mild water stress can have improved berry composition (Matthews and Anderson 1988, Smart 1985).

2.2. Water deficit. Plant water potential has been widely accepted as a fundamental measurement of water status in grapevines. Water potential represents a simple, reliable method for evaluating the physiological condition of a plant; cell growth, photosynthesis and crop productivity are all strongly influenced by water potential and its components (Repellin et al. 1997). During moisture stress, water in the xylem vessels increases in tension, and hence water potential becomes increasingly more negative (Klepper 1968, Scholander et al. 1965). This increase in negativity is measured using excised leaves in a pressure chamber, which has become an invaluable tool for measuring vine water status in the vineyard. The method was pioneered by Dixon (1894) at the beginning of the twentieth century and has become the widespread method for measuring plant water status since Scholander et al. (1965) improved the chamber design and demonstrated its practical use under field conditions (Jones 1990).

The influence of water supply on grapevine development and physiology has been widely addressed in the literature (Lakso 1984, Nagarajah 1989, Schultz and Matthews 1993). Grapes are commonly grown in areas with low water supply (Grimes and Williams 1990), where most vineyards are not irrigated and vines are subjected to some degree of water stress during the growing season. Generally, the water used by grapevines depends on the soil water table and rainfall.

The main driving force for vine water use (transpiration) is net radiation (Klepper 1968). Other environmental factors include wind speed and ambient vapour pressure deficit. Studies have also shown that vine size and trellis system can have a significant effect on vine water use (Carbonneau and Costanza 2004, Rosier et al. 1995). Rosier et al. (1995) found that physio-chemical soil differences and differences in leaf surface area among trellis system were responsible for differences in grapevine water consumption. van Zyl and van Huyssteen (1980) noted that consumptive water use was not affected by the amount of roots, but by the microclimate of the vine above ground. Furthermore, contrary to the authors' expectation, the bush vines had a higher water consumption rate than the largest trellising system. This was attributed to higher ambient air temperature, more air movement, and less shading of the soil surface surrounding the vines (van Zyl and van Huyssteen 1980). In simplest terms, vines with more leaf area will use more water. Thus, vine water use varies throughout the growing season as the canopy dynamics change. At the beginning of the season, a vine has little canopy surface area but as the season progresses there is a large increase in leaf area. Therefore evaporative demand increases in a linear fashion until water use is relatively constant at full canopy (Williams 2000). Also it is common in many viticultural regions that soil water content diminishes as the growing season advances, exacerbating vine water demand.

The availability of water to grapevines is one of the most important factors of terroir and wine quality (Deloire et al. 2005, Seguin 1986, van Leeuwen and Seguin 1994). Fruit quality may be directly affected by vine water status via changes in turgor, or indirectly via the effects of canopy sink competition (Smart et al. 1990) and light penetration in the cluster zone (Smart 1985). A vine suffering from some degree of water stress may have less shoot growth and therefore have better leaf and fruit exposure to sunlight than a vine growing with abundant water, which would tend to have large canopies and poor fruit exposure. Grapevines respond significantly to water status during their entire growth cycle (Hardie and Considine 1976, Matthews and Anderson 1988). There is strong competition for water and carbohydrates between different parts of the vine. Bunches are weak sinks until ripening begins, at which point they become stronger sinks. This is due to dramatic changes in water relations of the grape berry at the transition to ripening (Greenspan et al. 1994, Greenspan et al. 1996). Berry growth is most affected by water deficit during Stage 1 of fruit development, at which time it can decrease both cell division and elongation in the berry (Williams 2000).

Many papers (Choné et al. 2001, Grimes and Williams 1990, Hardie and Considine 1976, Kennedy et al. 2002a, Matthews and Anderson 1989, Smart 1974) report the influence of water deficits on vine development, yield and fruit composition. Generally, water deficits have a greater impact on vegetative growth than reproductive growth (Williams 2000). Water deficits in vines have been shown to first reduce shoot growth (Kliewer et al. 1983, Reynolds et al. 2006, Schultz and Matthews 1988) and canopy density (Smart 1974, Smart et al. 1990). Berry size is affected by water deficit from anthesis to maturity, but final berry weight is more influenced by deficits between flowering and veraison (Becker and Zimmermann 1984, Ojeda et al. 2001, Poni et al. 1994). Ojeda (2001) found vine water status more important than leaf area in regards to determining final berry size. Berry growth and development are affected by modification of the carbohydrate supply to the berry. Rapid shoot growth during ripening may also slow sugar accumulation in the berry. Modifications in leaf area can impact berry composition. Water availability to the plant is important in organ enlargement but also closely interacts with photosynthesis and berry carbohydrates supply.

Some studies indicate that vine water stress can advance maturity (McCarthy and Coombe 1985) and increase sugar levels (Kliewer et al. 1983). These increases in sugar can be due to a concentration effect resulting from water loss; lower yields (Smart 1974) from an early water deficit which reduces the number of carbohydrate sinks in the vine; and better fruit exposure due to less vegetative growth (Smart 1974, Smart 1985, Smart et al. 1990). Conversely, other studies indicate that water stress can also have many negative consequences including reduced yields (Smart 1974), reduced fruit set (Hardie and Considine 1976), and delayed maturity (Hardie and Considine 1976) . Generally, fruit quality in white grapes is reduced by severe water stress (Hardie and Considine 1976, Peyrot des Gachons et al. 2005, Reynolds and Naylor 1994). Water deprived vines have produced smaller berries (Roby et al. 2004) with lower sugar (Peyrot des Gachons et al. 2005), titratable acidity (Peyrot des Gachons et al. 2005), and low pH (Smart and Coombe 1983). The decrease in photosynthesis and sugar export from leaves during water stress could lead to this reduction in berry sugar accumulation (Quick et al. 1992, Rogiers et al. 2004).

The influence of water stress on the concentration of specific flavour compounds is controversial. McCarthy and Coombe (1985) found that reducing irrigation led to increased concentration of monoterpenes, but Reynolds and Wardle (1997) indicated that irrigation deficits could reduce these flavour compounds in berries. In subsequent studies, Reynolds et al. (2006) found that decreasing the duration of water stress increased free volatile terpenes (FVT) and potentially-volatile terpenes (PVT) in Gewurztraminer at harvest. Vine water stress has been shown to be associated with increased concentration of glycosylated aroma compounds in grapes (Bravdo and Shoseyov 1997) which are released into wines during fermentation and/or aging. More recently, Qian et al. (2009) found an increase in norisoprenoids (vitisparine; β-damascenone) and volatile phenols in Merlot wines of different water status but no effect on the concentrations of other aroma compounds. In Sauvignon blanc, volatile thiol precursors were highest in vines under mild water deficit, whereas severe water deficit seemed to limit aroma potential (Peyrot des Gachons et al. 2005). It has also been reported that irrigated vines have significantly higher 3-akyl-2-methoxypyrazine levels than non-irrigated vines (Sala et al. 2005). Most importantly, consensus among research findings indicates that neither severe water stress nor lack of water stress is optimal for the desired balance of yield and wine quality.

Grapevines with an abundant water supply produce a dense, shaded canopy that reduces wine grape quality (Reynolds and Naylor 1994, Smart 1974, Smart et al. 1974). On the other hand, severe stress responses include reduced cell division and expansion, reduced photosynthesis, and even cell desiccation and death (Hardie and Considine 1976, Naor and Wample 1994, Schultz and Matthews 1988). Therefore, it appears that water stress can be both a positive or negative determinant of terroir depending on its severity and timing of onset.

2.3. Precision Viticulture. Modern advances in technology are now being utilized to study terroir, particularly in the 'New World' wine regions. Beginning in the mid-1970s, variability within fields was recognized, allowing one to manage zones within fields as opposed to whole fields. Precision viticulture looks at spatial and temporal variations and is accomplished through the measurement of environment factors [soil, topography (slope, aspect), climate variables] that impact grape yields and quality and then applying appropriate management practices (fertilization, irrigation, harvest, etc.) to adjust for this variability and maximize quality (Lamb and Bramley 2001). Precision viticulture uses technologies such as GPS, GIS, environmental sensors, high resolution soil surveys, and airborne remote sensing to study variability and spatial relationships.

GIS has been used in many applications for terroir related studies and zoning. One of its most common uses is for suitability analysis of a potential viticultural region. In general, site selection for specific regions focuses on climate, topography and edaphic factors. Site suitability studies have been undertaken to understand a new region's potential (Boyer and Wolf 2000) or to predict new areas to plant in existing regions. The research by Jones et al. (2004) modelled the potential of the Umpqua and Rogue valley wine regions in Oregon. Spatial variation of environmental and biological factors within vineyards can impact grapevine health and growth which in turn affect grape and wine quality.

GPS allows for all soil and vine measurements to be associated to specific locations within the vineyard. The geo-referenced information can then be used in conjunction with computer GIS software, such as ArcGIS to analyze and map spatial relationships between targeted variables, and make decisions based on the layered data.

Precision viticulture techniques have typically been used in vineyards to study yield variation using yield monitoring technology fixed to mechanical grape harvesters equipped with GPS technology. For example, these techniques were used to relate yields and soluble solids of Concord grapes in Washington, USA using yield monitors (Davenport et al. 2001). In Australia, yields were found to be highly variable within vineyards, but in patterns that were stable over a three year period (Bramley and Hamilton 2004). Ortega et al. (2003) found that Chilean vineyards varied spatially in yield and quality. The same group also found that soils varied significantly in chemical and physical properties. The combined use of GPS and GIS has become a fundamental tool to study terroir, and is becoming more common in terroir related studies, creating a greater focus on targeted variables (or terroir effects). Reynolds and de Savigny (2001) used GPS and GIS technology to study the basis of terroir in the Niagara Peninsula, Canada, focusing on the impacts of soil texture and vine size. The authors concluded that there were no consistent vine size or soil texture effects on grape, must or wine composition, and that sensory differences were related more to vintage and wine age (Reynolds et al. 2007b). Cortell et al. (2007) studied different vigour zones within vineyards and found that vine vigour impacted berry weight, Brix, titratable acidity and some anthocyanins. They attributed variation between vigour zones to soil depth and water holding capacity. In a number of studies, soil water status has been shown to be spatially variable due to the heterogeneity of soil physical properties in the vineyard site (Tisseyre et al. 2005, Wendroth et al. 1999). Variability of soil moisture has frequently been analyzed and trends have been shown to be stable both temporally and spatially (Vinnikov et al. 1996). As with soil moisture, vine water status has been shown to be quite variable in a number of studies. van Leeuwen et al. (2006) found there were intra-block variations of vine water status. The variability in vine water status was particularly evident at the end of the summer months when significant water restriction occurred. A whole field may induce high variability in vine water status since soils can vary in water holding capacity due to textures and depth (Tisseyre et al. 2005). Consequently vine water status and vine water stress variability can be attributed to spatial variations in water table movement during the growing season (Guix-Hébrard et al. 2007). Specifically, the authors suggested that water table depths throughout the entire cropping season and the initial soil water storage were the main factors in the variability of vine water status in the vineyards studied.

Remote sensing. Remote sensing uses aerial imagery, typically consisting of a combination of near infra-red and visible wavebands. Remote sensing has a tremendous ability to study the grapevine shape, size and vigour within vineyards. Viticulture practices have been improved using the known relationships between canopy characteristics, yield and grape/wine quality and remote-sensing imagery (Hall et al. 2003). The most common purpose for using remote-sensing imagery in a vineyard is to map and monitor vineyard canopy density (Hall et al. 2002, Johnson et al. 1996). Canopy density contributes significantly to grape quality and yield. Vineyards are variable in terms of canopy density due to a wide range of factors. Delineating variability is very difficult over a large area using only ground measurements on individual vines. The normalized difference vegetation index (NDVI) can show variations in vegetation patterns with respect to vigour when applied to remote-sensing imagery of the vineyard. NDVI is the most widely used indicator of plant vigour or relative biomass (vine size) (Hall et al. 2002) and photosynthetic activity (photosynthetically active biomass). NDVI has been correlated with leaf area index (LAI) of individual plants through a linear relationship and it also correlated well with vine surface area and biomass (Lamb et al. 2004).

LAI is a key variable controlling water loss, photosynthesis and radiation penetration through the canopy. LAI and related index maps can be combined with other spatial datasets to derive assessments such as shoot balance (Smart 2001) and vineyard water relations (Nemani et al. 2001). Observations during canopy expansion can detect problems related to water and nutrient stress (Lamb 1999), while later-season imagery can support harvest management (Johnson et al. 2001). Fruit ripening rate (Winkler et al. 1974), infestation and disease (Lobitz et al. 1997), water status (Smart and Coombe 1983), yield (Dry 2000), fruit composition and wine quality (Jackson and Lombard 1993, Smart 1985) are all related to vineyard canopy density.

Since vigour is strongly related to soil water availability, NDVI can provide useful information in terms of water restrictions (Tisseyre et al. 2007). Remote sensing can be used to investigate stress in a vineyard by revealing areas of reduced vegetative growth. In the 1990's, phylloxera infestations in California vineyards were recognized using remote sensing by annually identifying areas of reduced canopy density within vineyards (Lobitz et al. 1997). Vegetation indices have been used to delineate spatial differences in canopy conditions and to divide vineyards into zones of uniform canopy vigour (Johnson et al. 1996). Greenspan and O'Donnell (2001) investigated the spatial variability within two vineyard blocks (Cabernet Sauvignon on a horizontally-divided canopy and Zinfandel on a vertical shoot positioned canopy) to investigate correlations between NDVI and some viticultural properties. They were able to distinguish between high and low vigour zones and found that these "management zones" had significantly different means of yield, Brix, and water status. Segmentation has been shown to increase the quality of wines through differential harvesting. Remotely sensed vegetation index imagery was used to establish sub–block management zones in a 3-ha commercial vineyard of Chardonnay wine–grapes. Subsequent ground–based measurements revealed a clear differentiation between low– and high–vigour zones with respect to biomass (primarily shoot vigour), vine water status, and most importantly, fruit and wine character (Johnson et al. 2001).

Remote sensing is also useful to study soil characteristics and their variability within a vineyard. For example, Bramley (2001) used electromagnetic induction (EM) survey techniques in Coonawarra, Australia vineyards and found that soil electrical conductivity, which varied by a factor of two, was highly correlated with soil depth. The author found in subsequent studies that high and low yielding vines were stable over time (Bramley and Hamilton 2004). They concluded that soil, topography and microclimate had a large impact on the spatial variability within vineyards, suggesting that there is great potential in the use of precision viticulture techniques to study the soil component of terroir while keeping mesoclimate constant.

2.4. Classification of Wines by Geographical Origin. Appellations have been an integral part of 'Old World' wine grape growing regions for centuries. These geographical boundaries are mainly based on meteorological, pedological, and geological factors and they have governing bodies that regulate viticulture and winemaking practices in these regions. Geographical origin has been widely used as an attribute that defines wine quality. Differences in sensory characteristics of wines between appellations can supposedly be related to the nature of the terroir. The combined importance of these pedoclimatic conditions, vine components and viticulture techniques has led researchers to try to categorize wines based on these additional parameters according to geographical origin. Studies have attempted to classify wines of origin by means of volatile composition (Arrhenius et al. 1996, Marais et al. 1981, Sabon et al. 2002), trace elements (Coetzee et al. 2005, Taylor et al. 2003), isotopes (Martin et al. 1999), phenolics (Rastija et al. 2009), anthocyanins (Arozarena et al. 2000), organic and amino acids (Etievant et al. 1988, Seeber et al. 1991), proteins (González-Lara et al. 1989), and the electronic nose (Berna et al. 2009).

In the Rhone Valley, Sabon et al. (2002) found that factors such as region and vintage influenced the level of volatile compounds in Grenache wines. Kallithraka et al. (2001) found that Greek red wines could be classified according to anthocyanins, whereas minerals and phenols did not allow any clustering of wine. White wines however, could not be classified by region. Croatian wines of different origins were able to be classified according to patterns of flavonols and trans-resveratrol (Rastija et al. 2009). On the contrary, South African red wines could not be differentiated according to geographical location by using multivariate analysis based on chemical constituents (Minnaar and Booyse 2004). In a study characterizing Italian red wines from different locations using nuclear magnetic resonance (NMR) and other analytical methods, heavy metals and amino acids were found to be most responsible for discriminating among the wines (Brescia et al. 2002). In California Chardonnay wines, Arrhenius et al. (1996) found that concentrations of volatiles were correlated with sensory data and that these were associated with regional distinctness. Reynolds et al. (1996a) found some differences in monoterpene content and sensory properties in Gewürztraminer wines from different British Columbia vineyard sites that could be attributed to climatic differences. Wines from the warmest site had the highest monoterpene concentrations and the most floral, fruity and cedar aromas and flavours. Cliff et al. (2002) characterized icewines from Canada and Germany using different chemical and sensory parameters. Icewines were shown to differ in their sensory profiles as well as chemical constituents, with Germany/Canada and BC/Ontario separating well presumably for climatic reasons (Cliff et al. 2002).

2.5. Sub-appellations in the Niagara Peninsula. The Niagara Peninsula of Ontario is the main region of wine production in Canada with over 5260 ha planted to wine grapes. The Niagara Region is situated near 43°N latitude, has an average of 1400 growing degree days (10°C) (Shaw 2005) and a Jackson and Cherry (1988) latitude-temperature index (LTI) of 362 (Shaw 2005) making the region suitable for growing cool climate grape varieties. Most importantly, the semi-continental climate of the Niagara Peninsula is dominated by the moderating effect of the Great Lakes (mainly Lakes Ontario and Erie). The main wine growing region is below and to the north of a100 m uplift, the Niagara Escarpment. The circulation of cooler air from Lake Ontario to the North and warmer air from the southern portion of the region adjacent to the escarpment impacts the seasonal temperatures (Wiebe and Anderson 1977). In contrast to 'Old World' viticulture, pedological descriptors in the 'New World' are often restricted to soil texture (Haynes 2000). The soils of the Niagara Peninsula are complex due to several glacial and interglacial events. Therefore, the soils are quite heterogeneous since they were derived mainly by direct organic and weathering breakdown of glacial, lacustrine, fluvial and alluvial sediments (Haynes 2000). The variations of topography, soil composition and drainage have led to the creation of appellations within the Niagara Peninsula. Three appellations have been traditionally defined by mesoclimate differences influenced by the proximity to Lake Ontario and the Niagara Escarpment by using infra-red aerial photography (Wiebe and Anderson 1977), as well as soil drainage and topography (Sayed 1992). These vineyard designations include 'Bench', 'Lake Plains' and 'Lakeshore' due to the individual vineyard proximity to the escarpment, lakeshore plain, and the shoreline of Lake Ontario, respectively.

Sites adjacent to the shoreline of Lake Ontario are greatly influenced by its year-round moderating effect, resulting in cooler days, warmer nights and typically a longer growing season than more inland sites (Shaw 2005). Soils are typically lighter and sandier than other appellations within the Niagara Peninsula. There is a wide variety of lacustrine sandy, silty and clay loam soils as well as alluvial deposits present in close proximity to

Lake Ontario (Haynes 2000). Drainage classification ranges from well drained to imperfectly drained soils with sandy soils draining rapidly but loam and clay soils impeding water drainage. Soil water holding capacity also varies based on these same criteria.

Vineyard sites located along the north face of the Niagara Escarpment are sheltered from the prevailing winter south-west winds but benefit from the breezes from Lake Ontario which cool in the hot summer months (Shaw 2005). Furthermore, the escarpment face traps warm air from the unfrozen lake surface in the cooler months. The soils are highly variable on these 'bench' sites. They are clay till alluvial deposits as well as glaciolacustrine clays and silty clays. The steeper escarpment slopes have good surface drainage as well as groundwater drainage on the silty clay soils.

Sites in the Lake plain appellations have the least amount of climatic moderation because of their flat, less complex topography and their location equidistant from Lake Ontario and the Escarpment. This appellation has greater heat unit accumulation but also is characterized by greater diurnal ranges throughout the year. The soils are mainly heavy clay till soils on a relatively flat lake plain.

Studies have found sensory differences in Riesling (Douglas et al. 2001), Chardonnay (Schlosser et al. 2005) and Bordeaux-style (Kontkanen et al. 2005) wines originating from these appellations. Haynes (2000) first considered more sub-appellations within the Niagara Peninsula based on climatic models, geological differences, detailed soil and climatic data from wineries, as well as anecdotal wine profiles. In recent years, the VQAO that regulates standards for Ontario wine, created sub-appellations within the Niagara Peninsula based on soil, climatic and topographical differences (Shaw 2004). "Lakeshore" appellations were further separated into Niagara Lakeshore and Lincoln Lakeshore sub-appellations. The "Lake Plains" appellation was divided into three sub-appellations named Niagara River, Creek Shores and the largest being Four Mile Creek. The "Bench" or Escarpment appellation was separated into four distinct sub-appellations including St. David's Bench, Short Hills Bench, Twenty Mile Bench and Beamsville Bench. Finally, the Vinemount Ridge sub-appellation encompasses the area south and above the escarpment.

2.6. Multivariate Statistical Analysis. There is an increase in the use of multivariate statistical methods across all disciplines of research to help understand complex data sets. Multivariate analyses include a range of techniques that can be used to examine patterns of relationships between and among variables simultaneously. These methods can be used to: i) test hypotheses; ii) to develop a system of classification of the data set as well as; iii) being useful to group data or items (products, wines etc.) to generate further hypotheses. Many multivariate techniques are prevalent in grape and wine related studies. Much of the present data collected cannot be directly used to interpret aroma profiles or patterns of a given food system (Lee and Noble 2006). Therefore, multivariate statistical methods are widely used to determine which variables best model the system (i.e., which volatiles best model the sensory profiles).

Some commonly used methods include principal component analysis (PCA), canonical variate or factor analysis, discriminant analysis, multidimensional scaling and partial least squares regression (PLS). PCA is a multivariate statistical method used to extract the most important information by reducing the number of dimensions in the data set in order to interpret and visualize differences among groups of products. Therefore, PCA is a very useful way to show the relationship of wines based on their chemical and sensory characteristics. PCA, in combination with descriptive analysis, was able to show differences among Spanish red wines from different appellations of origin using flavonoids, anthocyanins, and colour variables (Gomez-Cordoves et al. 1995). Multivariate analysis was used to discriminate among Chardonnay must and wines of different vintages and regions within the Trentino region, Italy (Seeber et al. 1991). Pinot noir wines, from different regions of California, were discriminated by their sensory profiles through PCA (Guinard and Cliff 1987) as was the case with Chardonnay and Pinot noir wines produced from different districts of the Okanagan Valley in British Columbia (Cliff and Dever 1996). A study investigating red wines from four regions of France based on their sensory and chemical data achieved better differentiation of the wines from the chemical data set as opposed to the sensory data set although the sensory methodology was not ideal (Sivertsen et al. 1999). Heymann and Noble (1989) compared sensory descriptive analysis data of Cabernet Sauvignon from four different regions and

Chardonnay from three vintages and found that the data sets were similar if they used canonical variate analysis or PCA.

PLS is a widely used multivariate technique to investigate relationships between response variables (chemical, viticultural) and explanatory variables (sensory). PLS is a regression model that allows for the identification of underlying factors, which are a combination of the explanatory variables (Talbot 1997). It has fewer restrictions than other multivariate analyses such as PCA or discriminant analysis. Thus, it is a very powerful technique to relate analytical data to sensory information. Its most common application in wine related research has been to investigate the relationships between sensory and gas chromatography (GC) data sets (Aznar et al. 2003, Noble and Ebeler 2002, Fischer 1996). Lee and Noble (2006) attempted to characterize California Chardonnays using odour active compounds and sensory data. Through PLS regression the authors created a model that enabled them to associate various groups of odour active aroma compounds with specific groups of sensory characteristics (Lee and Noble 2006). Initially, studies attempted to classify wines by geographical origin solely based on chemistry using expensive analytical techniques. Multivariate techniques are becoming more commonly used since wines can be classified according to chemical and sensory data. In a study by Liu et al. (2006), Tempranillo wines from Australia and Spain were classified according to geographical origin through spectroscopy coupled with multivariate analyses (i.e., PCA, PLS-DA, LDA). Multivariate analyses are now one of the fundamental methods to study the terroir effect, because many variables can be interpreted at once and the most important factors can be determined from the large data sets required to study terroir.

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Chapter 3: Variation in Soil, Vine Water Status and Vine Performance within Riesling vineyards in the Niagara Peninsula

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Abstract

The major focus of this research study was to explain terroir effects that impact wine varietal character. We choose vine water status as a major factor of the terroir effect. Our hypotheses were that a) consistent water status zones identified within vineyard sites would play a major role in vine performance and yield components (yield/vine; berry weight; cluster weight) and b) soil texture would play an indirect role through its water holding capacity. To test this hypothesis, ten commercial Riesling vineyards representative of each VQAO sub-appellation were selected in the Niagara Peninsula. Using global positioning systems (GPS), 75 to 80 sentinel vines were georeferenced within a sampling grid for data collection in each vineyard. During the 2005 to 2007 growing seasons, vine water status measurements [midday leaf water potential (ψ)] were collected bi-weekly from a subset of these sentinel vines. Data were collected on soil texture and composition, soil moisture, vine performance and yield components. These variables were mapped using global information system (GIS) software and relationships between them were discussed. Vineyards were variable in terms of soil texture and composition. However, in general, few consistent relationships with soil variables were found. As hypothesized, consistent water status zones were identified within vineyards in three distinct vintages, some of which were found to be spatially and temporally stable within vineyards. In many cases, the spatial distribution of vine water status was temporally stable within vineyards despite different weather conditions during each growing season. Spatial trends within vineyards for soil moisture and vine leaf water potential were found to be temporally stable over a 3 year period for eight vineyards. Generally, spatial relationships between vine water status, soil moisture, vine size, berry weight and yield were also stable from year to year. Some inconsistencies in the spatial distribution of variables were attributable to winter injury.

Keywords: Terroir, precision viticulture, vine water status, spatial and temporal variability

Introduction

Vine growth, yield and fruit composition are highly influenced by water supply from the soil. Many differences in grape and wine quality can be attributed to soil-related differences. Traditional understanding is that terroir is primarily influenced by soil; however, this notion has been controversial in research. Some studies (Noble 1979) have found no consistent trends in sensory profiles of wine from different soil types, while others (de Andres-de Prado et al. 2007) indicate that soil effects did influence chemical and sensory properties in wine. The main influence of soil on wine quality seems to be due to its physical properties, its water holding capacity, and its drainage characteristics. It is difficult to define the best soil in terms of texture, soil depth or mineral content, because high quality wines are grown on a diversity of soils worldwide. Depending on the location it is not possible to relate high quality wines in terms of soil texture, soil type or minerals (Seguin 1983). In California, Noble (1979) evaluated sensory differences of Chardonnay wines from various sites with different soil compositions. No consistent trends in wine from different soil types were observed; however, soil, must, and wine compositions varied among locations. In France, van Leeuwen et al. (2004) studied the impact of different soil textures and grape maturation of Bordeaux varieties. Gravely soils were found to stop shoot growth earlier in the growing season and sugar, total acidity were low, anthocyanins high and berry size small. Sandy soils had large berries, with low sugars and anthocyanins but high acidity. The authors also found that clay soils resulted in berries with the highest sugars, anthocyanins and phenolics and that these soil effects were strongly influenced by vine water status. Bader and Wahl (1996) moved soils from different regions around Germany to one vineyard site to eliminate any climatic influences. The authors found the soil effects on wine flavour to be very small and they concluded that climate was more important than soil for wine sensory characteristics in a cool climate region although yield differences were found among different soil types. In another study that kept mesoclimate constant, Reynolds et al. (2007) found that there were no consistent soil texture or vine size effects on berry, must and wine composition or wine sensory attributes, but there were correlations between soil texture and composition and berry weight and potentially-volatile terpene content. Soil effects were shown to influence chemical and sensory properties in Grenache wines from Spain (de Andres-de Prado et al. 2007). Fertile soils, with larger water holding capacity, produced wines with lower colour intensity and lower total phenols.

Soil texture seems to have an indirect effect in viticulture. Variation of soil characteristics such as water holding capacity, drainage, and root penetration can have a pronounced impact on vine-to-vine variation within a vineyard. Variation in vine vigour and yield has been shown to be closely associated with variation in plant available water (Cortell et al. 2005, Hall et al. 2002, Lamb et al. 2004). Seguin (1970, 1975) first tried to scientifically define the terroir effect through investigating chemical properties of soils in Bordeaux and its famous Chateaux. The author found that soil chemical composition did not have a specific influence on wine quality; instead it was the soil anthropomorphic physical properties that regulated water supply to the vine that did. Soil texture and rooting depth were noted as the most important soil factors, and the best soils were those that were free draining which avoided water logging in the rooting zone but did limit water availability later in the season. This was further supported by Asselin et al. (1983) where the authors were able to demonstrate some relationships between soil and wine sensory profiles using soil types from different sites within the Loire Valley. Many of the soil effects on vine behavior were mediated through water content levels and therefore vine water status (Klepper 1968; Seguin 1983, 1986; van Leeuwen and Seguin 1994). Some studies indicated that plant water status was the means by which the terroir affected wine style and quality (Choné et al. 2001, Koundouras et al. 1999). In the Loire Valley in France, free-draining sandstone soils that resulted in water stress during maturation were associated with intense varietal character in Cabernet Franc wines (Penavayre et al. 1991). Vine water supply was noted as a major factor in the terroir effect due to its impact on early budburst and potential vine vigour (Morlat et al. 2001). Soil, climate, and cultivar were studied simultaneously and the authors' found that climate and soil had a greater impact than that of cultivar (van Leeuwen et al. 2004). They concluded that soil and climate effects were mediated through their influence on vine water status.

Vineyards have been shown to vary spatially in terms of soil, vine nutrition (Davenport and Bramley 2007), vegetative growth (Baldy et al. 1996), yield, and fruit composition (Reynolds et al. 2007). Precision viticulture (PV) techniques including global positioning systems (GPS) and geographic information systems (GIS) have become powerful tools to study vineyard terroir (Reynolds et al. 2007) and variability (Bramley 2005, Bramley and Hamilton 2004), while keeping key environmental factors constant. There have been studies that have utilized PV to explain interactions between soil characteristics and vine growth and/or fruit composition. Bramley (2001) found that soil texture had an impact on yield in Australian vineyards. Areas within the vineyard that had a higher clay percentage were found to have lower yielding vines. Strong spatial and temporal distribution patterns were found within vineyards for many nutrients in various tissue types of vines in Coonawarra vineyards (Davenport and Bramley 2007).

Little research has been conducted to determine how Niagara's unique terroir influences wine varietal character. Some studies performed in Niagara have indicated that vine size and soil texture can have some effects on fruit composition and sensory characteristics of wines, but the findings were not consistent from year to year (Reynolds et al. 2007). Furthermore, it was found that vintage and wine aging had a more profound impact on the wine sensory profiles than any measured terroir effect. Therefore, this study attempted to further understand the basis of terroir in the Niagara Peninsula. The specific objectives of this research study were to demonstrate the influences of soil texture, soil water content, and vine water status on vine performance and yield components within vineyard blocks and to delineate these terroir effects using GPS and GIS; and to elucidate the relationships between soil and vine water status and vine performance.

Materials and Methods

Site selection. In April 2005, ten Riesling vineyard sites were selected throughout the Niagara Peninsula. These sites were non-irrigated, commercial vineyards and the vineyard blocks had heterogeneous soil textures. Each site was also representative of each

VQAO sub-appellation. Details concerning soil and vineyard characteristics and vineyard management can be found in Table 3.1a and 3.1b. All recorded vines were balance pruned prior to each growing season. In each vineyard block, a grid-style sampling pattern was established with a "sentinel vine" at each grid intersection point. These sentinel vines (72 to 80 per vineyard block) were flagged for identification to be used for data collection. A Raven Invicta 115 GPS receiver (Raven Industries, Sioux Falls, SD) with a built in differential global positioning system (DGPS) correction receiver giving positions with a root mean squared (RMS) accuracy of 1-1.4 m was used in May 2005 to georeference each sentinel vine and to delineate the shape and size of each vineyard block.

Soil analysis. Detailed soil mapping was carried out on a site-by-site basis at the onset of this study. Soil sampling was performed in June 2005 with no additional sampling dates as the soil data was presumed to be consistent for the duration of this study. Soil samples (ca. 200 g) were collected using a soil probe at a subset of sentinel vines (every 4th vine in a serpentine pattern; ~ 20 vines/site) in June 2005. Soil analyses including pH, organic matter concentration (OM), elemental concentration, cation exchange capacity (CEC), and base saturation (BS) were performed on each soil sample. All soil analyses were carried out at Agri-Food Laboratories, Guelph, ON. Proportions of sand, silt, and clay were also determined and geospatial maps of each vineyard block were subsequently constructed from this information.

Soil water content and vine water status. At each vineyard, volumetric soil water content and vine water status measurements were taken bi-weekly (every 10 to 14 days) from sentinel vines between the end of June and early September (beginning of fruit set to pre-harvest). Soil moisture was measured using a portable time domain reflectometer (TDR) (Spectrum Technologies, Plainfield, IL) at a depth of 20 cm. On the same day, vine water status was determined on a subset of sentinel vines (≈18 vines) by midday leaf water potential (ψ) using a Scholander-type pressure chamber (Soil Moisture, Santa Barbara, CA). Measurements were taken between 1100 and 1400 hours under full sun conditions according to methods of Scholander (1965).

Viticultural data collection. For each sentinel vine, data were collected annually at vine dormancy for weight of cane prunings as an estimate of vine vigour ("vine size"). Yield components (yield per vine; clusters per vine; cluster weight; berries per cluster; berry weight) were either measured directly or calculated from measured variables during harvest each season. Fruit was sorted based on vine water status and retained for winemaking. Clusters were counted from each sentinel vine and samples of 100 berries were taken for determination of berry weight. A large database was compiled annually on these sentinel vines for all vine performance and yield component variables.

Geographic information systems (GIS). The delineated vineyards and data layers were incorporated into a MapInfo Professional 8.0 GIS database with Vertical Mapper 3.1 (Northwood GeoScience, Ottawa, ON). Inverse distance weighting (IDW) was used to construct grid files. This interpolation method was chosen due to uneven nature of vineyards. Unlike interpolation techniques such as Kriging, IDW does not make assumptions about spatial relationships except the basic assumption that nearby points are more closely related than distant points to the value at the interpolate location (Naoum and Tsani 2004). Spatial maps were generated for all soil and viticulture variables to depict the spatial distribution of each variable within each vineyard.

Statistical analysis. SPSS (Chicago, IL) was used for correlation analyses. Pearson correlation coefficients were determined between soil composition, soil texture, vine water status, soil water content, vine performance and yield components for all vintages. Through the use of XLSTAT, principal component analyses were conducted to elucidate relationships among soil, water status, yield, and vine performance variables. Soil variables were used as supplementary variables for PCA. MapInfo and Vertical Mapper (Northwood GeoScience, Ottawa, ON) were used to construct geospatial maps of all variables. These maps, correlation analyses and PCA were used to examine spatial variation for selected variables in each season, and to compare spatial relationships between correlated variables.

Results

General comments. All results shown are from the 2005-2007 growing seasons. Meteorological data depicting temperature and rainfall events for each growing season are depicted in Figure 3.1. The growing seasons of 2005, 2006 and 2007 were quite typical for the Niagara Peninsula and ideal for studying terroir effects, particularly vine water status. All vintages had some dry periods during summer months but 2005 and 2007 had prolonged drought periods during most of the growing season. Through the use of GPS and GIS technologies, the data collected from each vintage were depicted spatially and analysed to examine spatial trends and relationships. Examples of such maps from representative vineyard blocks are depicted in Figures 3.2a through 3.4c. Interpretation of the entire data set was accomplished through correlation tables (Tables 3.1 through 3.3) and PCA biplots (Figures 3.5 to 3.7) but the results section is further divided in sections (A-G) detailing the within-site findings from Riesling vineyards used for this study that had three complete years of data collected. Each of these sections is subdivided into geospatial maps depicting spatial relationships of soil and viticulture variables for each site followed by PCA results. Tables of point correlations for each vineyard are also included. All of the within-site tables and figures can be found under Supplementary Tables and figures at the conclusion of this chapter. Some vineyards (Lambert, Vailmont) in the study were dramatically impacted by winter injury in 2004/2005 and were not included.

Within-site results. Section A. Myers Vineyard (Lincoln Lakeshore sub-appellation), Vineland, ON, 2005-2007.

Consistent water status zones were identified within vineyard sites in 2005-07. Spatial relationships in vine water status were temporally stable during each of the growing seasons. Furthermore, Figures 3.2a to 3.4a indicate that many variables and spatial relationships were temporally stable with many highly significant correlations between years (Supplemental Table 3.1a and Supplemental Figures 3.1a to 3.8a). Vine water status (Suppl. Figure 3.1a), soil moisture (Suppl. Figure 3.2a), vine size (Suppl. Figure. 3.3a) and berry weight (Suppl. Figure 3.5a) were all temporally stable and strong relationships were found between these variables (Fig.3.2a to 3.4a). Vine water status was spatially correlated with vine size in all three vintages (r= 0.64; 2005, r= 0.76; 2006, r = 0.72; 2007) and berry weight (r= 0.83, 2005; r= 0.60, 2006; r = 0.77, 2007). Higher yields were associated with areas of high water status and more soil moisture (Fig. 3.2a to 3.4a). Yield varied spatially but trends were temporally stable only from 2006-07.

Grapevine winter injury had a major impact on the spatial variation in yield in 2005, hence the difference in spatial relationships compared to the other vintages. As shown in Figures 3.2a to 3.4a, excellent spatial relationships between vine size and vine water status were correlated in 2005 (Suppl. Table 3.1a). In all three growing seasons, vine water status had excellent spatial relationships with berry weight. Soil texture (Suppl. Figure 3.6a), physical properties and elemental composition (Suppl. Figures 3.7 to 3.8a) varied spatially within the vineyard block. Soil analyses, correlation analysis and spatial maps indicated that sand and clay were inversely correlated, as expected. Organic matter (OM) and cation exchange capacity (CEC) also had high variation (Suppl. Figure 3.8a).

Through principal component analysis (PCA) (Suppl. Figure 3.9a), vine water status, vine size, berry weight, soil moisture, CEC and Ca were all positively correlated with each other in all three growing seasons, but were inversely correlated with sand in the drier 2005 and 2007 vintages. These relationships were also found with respect to yield in 2006 but not in the other two vintages. OM, potassium (K), phosphorus (P), and calcium (Ca) concentrations plus base saturation (BS) were all positively correlated (Suppl. Table 3.9a). Soil Ca was also correlated with soil pH and magnesium (Mg). CEC and Mg were also positively correlated. Other significant correlations included both OM and Ca with yield and vine size ($p<0.05$; Suppl. Table 3.1a). In 2006, soil moisture, clay, soil pH, and Ca were all correlated with berry weight at $p<0.05$ (Suppl. Table 3.1a). As in 2005, OM was correlated with vine size ($p<0.01$). In 2007, vine water status was correlated ($p<0.01$) with berry weight. Percentage sand ($p<0.05$), OM ($p<0.01$) and P ($p<0.05$) were correlated with vine size.

Section B. Glenlake Vineyards (Niagara Lakeshore sub-appellation), Niagara-on-the-lake, ON, 2005-2007.

Consistent zones of vine water status (Suppl. Figure 3.1b) and soil moisture (Suppl. Figure 3.2b) were found in 2005, 2006, and 2007 despite different weather conditions and different absolute ψ values in each season. For example, soil moisture content was twice as high in 2006 and very few vines had leaf ψ readings < – 10 bars, whereas in 2005 all vines had readings below that value. Trends in vine size (Suppl. Figure 3.3b) were temporally stable during the course of this study. Strong relationships were found between vine water status, vine size, and soil moisture (Figures 3.2 to 3.4b). Yield varied spatially (Supp. fig. 3.4b) and trends in yield were temporally stable from 2006-07. Yield varied substantially between 2005 and 2006/07 and this can be attributed to winter injury and crop loss caused by the severe winter of 2004/05. However, vine water status had some spatial relationships with yield. Spatial trends in berry weight were inconsistent across vintages (Suppl. Figure 3.5b) but there were some relationships with vine water status (Figures 3.2b to 3.4b). There was some variation in soil texture (Suppl. Figure 3.6b) within the vineyard but not to the same extent as other vineyards in this study. This vineyard also varied in terms of soil physical properties and elemental composition (Suppl. Figures 3.7 to 3.8b). Soil pH was correlated with Ca content as well as BS of the soil. OM and Mg were also correlated and spatially related (Suppl. Figures 3.7 to 3.8b).

Through PCA some relationships were observed (Suppl. Figure 3.9b). In 2005, vine water status and soil moisture, and vine size, berry weight and CEC were correlated. In 2006, soil moisture and vine water status were not correlated however, water status, vine size, Ca, and CEC were correlated. Soil moisture was highly correlated with yield and clay soils whereas berry weight was correlated with higher sand percentage. In 2007, soil moisture, vine size, berry weight and percent sand were all highly correlated and inversely correlated with yield.

Supplemental Table 3.1b shows that soil moisture was correlated with vine size ($p<0.05$) in 2005 but was not correlated in 2006 and 2007. Soil P was negatively correlated with cluster numbers in both 2005 ($p<0.05$) and 2006 ($p<0.01$). In 2007, yield was negatively correlated with soil pH ($p<0.05$) and Ca ($p<0.01$). Soil Ca was also negatively correlated with number of clusters/vine ($p<0.05$).

Section C. Chateau des Charmes (St. David's Bench sub-appellation), Niagara-on-the-Lake, ON, 2005-2007.

This vineyard was very consistent from year to year and spatial trends in many of the variables were temporally stable over the 3 yr period of this study (Figures 3.2 to 3.4c, Suppl. Figures 3.1 to 3.5c). Very clear spatial trends in water status were observed (Suppl. Figure 3.1c). Spatial trends in soil moisture were temporally consistent from 2006-07 with some differences observed in 2005 (Suppl. Figure 3.2c). Very clear spatial trends in vine water status and vine size were observed during the course of this study (Figures 3.2 to 3.4c). Vine water status and vine size were spatially related with areas of higher water status having more vine vigour. No clear relationship was found between leaf ψ and soil moisture as shown in Figures 3.2 to 3.4c. This may be due to limitations in our methodology for measuring soil moisture. Firstly, there was a lot of tillage of the soil that could have interfered with proper contact of instrument probes with the soil. Furthermore, this was an older, established vineyard and an accurate measurement of water available to the plant may not be accurately measured close to the surface because of its expansive rooting system. There were some consistent trends in terms of yield (Suppl. Figure 3.4c) and berry weight (Suppl. Figure 3.5c). In general, areas of lower water status had lighter berry weights and lower yield (Figures 3.2 to 3.4c). No spatial maps of yield were presented from 2006 due to inaccurate spatial trends because of extensive fruit removal in sections of the vineyard due to sour rot infections. The soils of this vineyard block were quite variable in terms of texture, physical properties and composition (Suppl. Figures 3.6c to 3.8c). As shown in Supplemental Figure 3.8c, K and P varied tremendously spatially and both were very low in the northern section of the vineyard.

In 2005 soil moisture was correlated with yield at $p<0.05$ (Suppl. Table 3.1c). Vine water status was correlated with vine size ($p<0.05$) and OM was correlated with yield ($p<0.05$). Vine water status was negatively correlated with yield in 2006 ($p<0.05$). In 2007, soil moisture was correlated with berry weight ($p<0.05$) and vine water status was negatively correlated with number of clusters/vine ($p<0.05$). There were many significant correlations concerning vine size. Vine size was positively correlated with vine water status and percent sand and negatively correlated with soil moisture and percent clay at $p<0.05$ in all cases (Suppl. Table 3.1c).

Many of these findings can be further explained through results of PCA (Suppl. Figure 3.9c). In all three vintages vine water status was highly positively-correlated with berry weight. Vine size demonstrated positive correlations with OM as did yield in all vintages. Soil pH was correlated with Ca, CEC, and BS of the soil. OM was positively correlated with P, K while being negatively correlated with Ca and BS. Soil Ca was negatively correlated with P and Mg while being positively correlated with CEC and base saturation. Soil K and P were positively correlated.

Section D. Cave Spring Cellars (Beamsville Bench sub-appellation), Beamsville, ON, 2005-2007.

Contrary to other vineyards, this site did not show temporal stability for many of the variables studied (Suppl. Figures 3.1 to 3.5d). In part this may be due to different weather conditions experienced. Some variation in temporal stability could be a result of additional drainage tiling being installed prior to the 2006 growing season. This could have impacted the drainage, damaged roots and caused disturbances in the rooting zone, all of which would impact water availability and uptake. However, some regions were stable in terms of soil moisture (Suppl. Figure 3.2d) and vine water status. There were also some relationships between these two variables. Trends in vine size (Suppl. Figure 3.3d) were temporally stable and consistent from 2005-07. Variability in yield (Suppl. Figure 3.4d) was fairly consistent as well over the three year period. There were also some relationships that were observed between soil water content, vine water status and berry weight (Suppl. Figure 3.6d). Soils differed spatially within this vineyard including texture, physical properties, and nutrients, especially Ca content (Suppl. Figures 3.6 to 3.8d).

Some relationships were depicted through PCA (Suppl. Figure 3.9d). In 2005, water status was highly correlated with clay content, CEC, and Ca while being non-correlated with soil moisture. Leaf ψ was also inversely correlated with yield, berry weight, and vine size. Soil moisture, however, was highly correlated with sand content, vine size, yield, and P. In 2006, ψ and soil moisture were both highly correlated as well as yield, vine size, yield, OM, and K. Vine water status, vine size, and berry weight were highly correlated but inversely related to yield in 2007. From Supplemental Table 3.1d, in 2005, soil moisture was correlated with berry weight at $p<0.05$ however in 2006 it was non-correlated. Berry weight was also correlated with OM and P at $p<0.01$). In 2007, soil moisture was negatively correlated ($p<0.05$) with yield and number of clusters/vine. Soil Mg was negatively correlated with yield ($p<0.05$). Correlation analysis indicated that percent clay content was correlated with OM ($r = 0.748$; $p<0.01$). Clay content was also correlated with K, Ca at $p<0.05$ and CEC at $p<0.01$. OM was correlated with K ($r = 0.692$; $p<0.01$) and negatively correlated with Ca ($r = -0.571$; $p<0.05$).

Section E. Flat Rock Cellars (Twenty Mile Bench sub-appellation), Jordan, ON, 2005-2007.

Results from geospatial maps show that many variables under study appear to be temporally stable from year to year despite different weather conditions experienced in each growing season (Supp. Figures 3.1 to 3.5e). Vine water status (Supp. Figure 3.1e) appears to be temporally stable for the most part with consistent water status zones demonstrated in each year. Spatial trends in soil moisture (Supp. Figure 3.2e) were also temporally stable and good relationships with vine water status were observed. Vine size (Supp. Figure. 3.3e) was the most temporally stable variable. Within-site variations in yield (Suppl. Figure 3.4e) were observed but they were not consistent and appeared to be related to elevation and crop reductions due to winter injury in the lower cold pockets of the vineyard more than anything else. Other variables were consistent between some vintages but were quite different from another year. Berry weight spatial trends were temporally stable from 2006-07 (Supp. Figure 3.5e). Good relationships between berry weight, soil moisture and vine water status were found. Differences in berry weight spatial trends in 2005 can be associated with winter injury and secondary clusters observed during that particular growing season. Soil texture and other soil variables (Suppl. Figures 3.6 to 3.8e) varied within the vineyard site.

From Supplemental Table 3.1e, soil moisture was correlated with yield and vine water status was correlated with vine size in 2005 at $p<0.05$. Leaf ψ was negatively correlated ($p<0.05$) with yield in 2006. Through PCA (Suppl. Figure 3.9e) it was found that soil moisture and vine water status were not correlated in 2005. However, vine water status was positively correlated with K, and sandy soils. In 2006 and 2007, vine water status and soil moisture were closely related showing a higher positive correlation. Vine size was correlated with soil moisture in 2005-2006 but not correlated in 2007. From PCA factor loadings, vine water status was negatively correlated with yield. Soil moisture on the other hand was better correlated with yield. In 2005 and 2006 berry weight was correlated with clay soils. This makes sense given the fact that in a dry year, such as

2005, vine water status would be more negative in sandy soils due to less water holding capacity but in a wetter year more water would be available in a more sandy soil. Through PCA (Suppl. Figure 3.9e) soil texture was also correlated with OM and K. Sand content was positively correlated with OM and K. OM was also correlated with P and K and negatively with base saturation. Soil pH was positively correlated with Ca, CEC and BS but negatively correlated with K and Mg. Soil Mg and Ca were inversely correlated. From Suppl. Table 3.1e, OM was negatively correlated ($p<0.05$) with yield in 2005 and in 2007, P was correlated ($p<0.05$) with yield.

Section F. Henry of Pelham (Short Hills Bench sub-appellation), St. Catharines, ON, 2005-2007.

Through geospatial mapping, some areas of temporal stability were observed in terms of leaf ψ (Suppl. Figure 3.1f). This was also the case in terms of soil moisture (Suppl. Figure 3.2f). No vine size data were collected in 2005, but some areas of temporal stability were found in 2006-07 (Suppl. Figure 3.3f). Some good spatial relationships were observed between soil moisture, vine water status and vine size (Suppl. Figures 3.1 to 3.3f) in 2006-07) where vine size was smaller in areas of lower water status. Yields (Suppl. Figure 3.4f) varied spatially and some areas of temporal stability were observed. Some spatial relationships could also be found with vine size and leaf ψ. Yield was found be inversely related whereas vine size was positively related to water status. Therefore, less vegetative growth was observed in vines with lower water status. In many other vineyards the opposite affect was found, where larger vines with more evaporative demand were lower in water status. Spatial trends in berry weight (Suppl. Figure 3.5f) were consistent from 2005-07 and some relationships were observed with soil moisture and vine water status. Areas of higher water status and more moisture were associated with areas of larger berry weights. This vineyard was quite variable in terms of soil texture and other soil variables (Suppl. Figures. 3.6 to 3.8f).

No correlations were found between vine water status or soil moisture and yield components in 2005 or 2006 (Table 3.2f). In 2007, soil moisture was positively correlated with yield ($p<0.05$), berry weight ($p<0.01$), and vine size ($p<0.05$). Vine water status was also positively correlated with berry weight ($p<0.01$). Through PCA (Suppl.

Figure 3.9f), no clear positive correlations were found between soil moisture and vine water status. Vine water status was positively correlated with berry weight in 2005 and 2006 but not correlated in 2007. Yield was correlated with soil moisture in 2005 and CEC and Ca in 2005 and 2006. Vine size was correlated with OM in 2006 and 2007 and with sand content in the wetter 2006 vintages and with clay content in the drier 2007 vintage. Positive correlations ($p<0.01$) were found between soil pH, CEC and BS (data not shown).

Section G. Paragon Vineyards (Creek Shores sub-appellation), Jordan, ON, 2005-2007.

There were some consistent spatial trends in vine water status (Suppl. Figure 3.1g) but no consistent relationship was observed between vine water status and soil moisture. For the most part, there were spatial trends in soil moisture (Suppl. Figure 3.2g) that were temporally stable from year to year. Vine size and vine water status had some good relationships and spatial trends in vine size (Suppl. Figure 3.3g) were consistent with the exception of 2005 where vine size was impacted by winter injury. Yield (Suppl. Figure 3.4g) also showed consistent spatial trends within this vineyard site and could be associated with vine size and vine water status in many instances. Similar to vine size, spatial variability was affected in 2005 by crop loss due to winter damage. Some consistent spatial trends in berry weight (Suppl. Figure 3.5g) were observed in some areas with some association with vine water status. The vineyard was variable in terms of soil texture and composition. Relationships were found between soil texture (clay or sand content) and Mg, Ca and CEC (Suppl. Figures 3.6 to 3.8g). From Supplemental Figures 3.1g and 3.6g, sand-dominated areas of the vineyard were spatially correlated with zones of lower water status while the opposite effect was found in clay-dominated areas. Furthermore, there were also some excellent relationships between OM and soil elemental concentrations and vine water status (Suppl. Figures 3.1g, 3.7 to 3.8g).

Positive correlations ($p<0.01$) were found between these variables and clay content and for sand. Soil pH, Mg, Ca and CEC were all positively correlated ($p<0.01$). OM, P and K were also correlated with each other at $p<0.01$. As shown in Supplemental Table 3.1g, vine water status was correlated with vine cluster numbers in 2005 and berry weight in 2006 and 2007 at $p<0.05$. A number of soil variables were correlated with berry weight. Soil P was negatively correlated ($p<0.05$) with vine size and soil K was negatively correlated ($p<0.05$) with berry weight in 2005. OM was negatively correlated with berry weight in 2005 and 2006 at $p<0.01$. In 2006, sand content and P were correlated as well with berry weight at $p<0.05$.

Many relationships were found through PCA (Suppl. Figures 3.9g). In 2005, soil moisture and vine water status were positively correlated with clay content, OM and yield, whereas berry weight, vine size and sand content were negatively correlated. In 2006 and 2007 vine water status was positively correlated with vine size, berry weight and negatively correlated with OM, P and K.

Correlation analysis (2005-2007). (Tables 3.2 to 3.4). Through correlation analysis of the entire data set including all vineyards, many relationships were elucidated. In 2005, leaf water potential (ψ) was correlated with berry weight ($p<0.001$) and soil K ($p<0.05$) and inversely correlated with vine size ($p<0.001$). Leaf ψ was highly correlated with vine size and yield in 2006 and 2007 as well as berry weight in 2007. Soil moisture was correlated with vine size in 2005 and 2007 and correlated with yield and berry weight in 2006 and 2007 but inversely correlated with berry weight in 2005. Leaf ψ was correlated with soil moisture in both 2006 and 2007. In all years, leaf ψ was correlated with soil moisture, percent sand ($p<0.05$) and soil P ($p<0.001$) and was inversely correlated with percent clay ($p<0.05$), soil pH ($p<0.01$), soil Mg ($p<0.05$), Ca ($p<0.001$) and CEC ($p<0.01$). Soil moisture was correlated with percent clay and inversely correlated with sand percentage in 2006 and 2007. Soil moisture was correlated with OM in both 2006 and 2007. Vine size, berry weight and yield were highly correlated in all three vintages.

Clay and sand percentage were inversely correlated. Sand percent was inversely correlated with soil moisture in all vintages whereas the opposite relationship was found with clay percentage. In 2006 and 2007, percent sand was highly correlated with vine size, yield and leaf ψ but no correlations were found in 2005. Percent sand was inversely correlated with soil pH, OM, K, Mg, Ca, CEC and BS. Clay percentage was correlated with soil Mg, Ca, CEC, BS and inversely correlated with soil P.

Principal component analysis (2005-2007). See Figures 3.5 to 3.7. Principal component analysis was used to help interpret the full data set from all of the vineyard sites to elucidate relationships between soil, vine water status, vine size and yield components. Many of the correlations and spatial analyses of the individual vineyards were demonstrated through PCA. Vine water status was correlated with soil moisture, berry weight, yield and vine size in all three vintages with the exception of 2005 where it was only correlated with berry weight. Sand percentage was correlated with vine size, ψ, berry weight, and yield in most vintages. Soil P and K were correlated with vine size and many of the yield variables.

Discussion

Soil and vine water status (2005-2007). The values of soil moisture varied based on the climatic conditions experienced throughout each of the three growing seasons. Since the sites were not irrigated, the percentage of moisture in the soil was reflective of rainfall and the physical properties of the soil. Soil moisture values within sites were highest in 2006 followed by 2007 and were lowest in 2005. These trends were similar in terms of vine water status. Vine water status varied within all of the vineyards studied. Vine water status was lowest in 2005 and highest in 2006. In each vintage there were areas within vineyards that had ψ values < -10 bars indicating some water stress was evident (Bogart 2000). Consistent areas of vine water status could be identified as hypothesized. In every vineyard studied, distinct regions were delineated that could be categorized as "high" and "low" water status. This is in agreement with the findings of Acevedo-Opazo et al. (2008) who found that it was possible to assess spatial variability of vine water status within vineyards, even those small in size (<1 ha). In many cases, particularly in the hot and dry vintages, the "low" water status regions consisted of vines suffering moderate to high water stress. Soil moisture varied spatially within all vineyard sites examined. Spatial trends within vineyards for vine leaf ψ (vine water status) were temporally stable over a 3 year period for eight vineyards (Myers, Flat Rock, Glenlake, Henry of Pelham, Lambert, Paragon, Reif, Vailmont, Chateau des Charmes; Suppl. Figures 3.1a, b, c, e, f, g). Spatial trends in soil moisture were not found to be as temporally stable as ψ but were still evident in many areas of these same eight vineyards (Suppl. Figures 3.1a, b, c, e, f, g). Variation in soil moisture was site specific and was not only due to annual rainfall but also evaporation, water holding capacity, differences in the effective root zone and drainage unique to each site. Furthermore, some of the annual inconsistencies of soil moisture measurements could possibly be related to shading of the root zone by the heavy canopy and human disturbances of the soil (i.e., tilling and grape hoeing) leading to poor TDR instrument contact with the soil.

Vine size and yield components (2005-2007). ***Vine size.*** Vine size (vigour) was measured to determine the vegetative growth during the growing season. There was spatial variation in vine size within vineyards and between many of the vineyards. This supports many other studies that have demonstrated that vineyards vary in terms of vine vigour (Bramley 2001, Cortell et al. 2007, Cortell et al. 2008, Zerihun et al. 2010) including Riesling vineyards within the Niagara Peninsula (Reynolds et al. 2007). Spatial trends for vine size were also found to be stable within eight vineyard sites (Myers, Chateau des Charmes, Cave spring, Flat Rock, Glenlake, Henry of Pelham, Lambert, Vailmont); Suppl. Figures 3.3a, b, c, e, f, g). Vine size values were much larger in 2006 than in 2007 or 2005. This is reflective of the 2006 growing season where there was more rainfall during canopy development resulting in more available water from higher moisture levels. Water availability influences shoot growth. As soil moisture increases, vigour is stimulated and this can lead to larger vine sizes (Smart and Coombe 1983). Not only was there more vigour in vineyards in years characterized by more rainfall, but in all vintages, many areas within vineyards with more soil moisture had larger vines. This is similar to findings of Cortell et al. (2005) who found a strong association between soil depth and soil water-holding capacity and vine vigour. Some of the strongest relationships (Figures 3.2a to 3.4c) were between vine water status (Suppl. Figures. 3.1a-g) and vine vigour (Suppl. Figures. 3.3a-g). Research has generally found that vine water status has a large impact on the vegetative growth of the vine (Reynolds et al. 2006, Schultz and Matthews 1988). Soil texture was found to have some influence on vine size. Sand content was correlated with larger vines in some vintages (Suppl. Table 3.2a, 3.2d) and associated with each other and yields in many cases through PCA (Figures 3.5 to 3.7). This is in agreement with the results of Reynolds et al. (2007) who found that soils higher in sand content had larger yield components (clusters/vine, yields).

Berry weight. Many of the same vineyard sites that demonstrated temporal stability for vine size and vine water status also had annually consistent spatial trends in regards to berry weight (Chateau des Charmes, Cave Spring, Flat Rock, Henry of Pelham, Myers, Paragon, Reif, Vailmont; Suppl. Figures 3.5a, c, d, e, f, g). Leaf ψ and berry weights were lower in the hotter and drier vintages of 2005 and 2007. Soil moisture was also closely associated with berry weights in a number of vineyards. Generally, regions with lower water status were found to have smaller vine sizes and berry weights (Fig. 3.2a to 3.4a, Figures 3.6 and 3.7) whereas areas of high water status had higher berry weights. This supports findings by Cortell et al. (2008) where the authors found that berry weights generally increased with vigour. Furthermore, these research findings are in agreement with other studies (Ojeda et al. 2001, Roby et al. 2004) that indicate the impact of vine water status on berry weight. Mild to moderate water stress has been shown to lower berry size especially if it occurs during the first phase of rapid berry expansion (Dry et al. 2001, Williams 2000). However, any plant water deficit almost always limits berry size (Matthews and Anderson 1988, Roby et al. 2004). Low water status results in reduced photosynthesis and less water and photosynthate being translocated to the berries (Carbonneau et al. 1983). Lower vine water status can help improve fruit quality since small berry size is considered an important indication of grape and wine quality (Walker et al. 2005).

Yield. Yields varied within vineyards both spatially and temporally. Many precision viticulture studies have shown that within-vineyard yield can vary tremendously, but with some temporally stability (Bramley and Hamilton 2004, 2003). In this study, spatial trends in yield were not as stable as water status, vine size, or berry weight but some stable trends were still found in several sites (Cave Spring, Glenlake, Henry of Pelham, Myers, Paragon; Suppl. Figures 3.4a, b, d, f, g). This inconsistency in yield was similar to findings in other precision viticulture work in the Niagara Peninsula where the authors found that yield spatial distribution changed substantially over four vintages in a Riesling vineyard (Reynolds et al. 2007). In Australia, yields were found to be highly variable within vineyards, but with patterns being temporally stable over a three year period (Bramley and Hamilton 2004). However, the lack of temporally stability of yield in Niagara vineyards can be explained by individual vine variation in fruit set and health. Unlike warmer areas such as Australia, bud and/or vine cold injury can result due to cold winters experienced during the dormant season. This can lead to vines having similar growth but different crop loads. The variation in yield could also be due to increased climate variability during growing seasons in Ontario compared to Australia. Therefore, yield estimations using precision viticulture techniques may not be appropriate for marginal grape production areas due to this yearly variation.

Areas within vineyards with higher yields were often associated with vines of higher water status and more soil moisture. Vineyards varied in yield also due to vintage differences. Yields were highest in 2006 and lower in 2007. Yields in 2005 were the lowest. This can be attributed to differences in seasonal weather patterns including light, temperature, rainfall and humidity. Some inconsistencies in terms of yields can be related to winter injury suffered during the winter of 2004/2005. Some of the yield variation within some vineyard sites in 2005 was directly related to widespread primary bud or woody tissue damage that occurred across Ontario resulting in low or non-existent yields. In 2005, grape tonnage across the Niagara Peninsula was reduced to 1/3 of an average harvest (Grape Growers of Ontario). In every vintage most of the variation in yield were probably attributed to vine to vine differences in cluster as opposed to berry weight differences (Keller 2010). However, there were still some good relationships found between vine water status, soil moisture, vine size and yield. Particularly, larger vines on moister soils were associated with higher leaf water potentials and yields in many vineyards. Sandy soils often also had higher yields which has been shown in other studies (e.g., Reynolds et al. 2007).

Soil texture and composition. Soil texture varied in all of the vineyard sites (Figures Suppl. Figures 3.6a to g). The degree to which they varied in sand or clay percentage ranged (9-19%) but due to the geological history of the Niagara Peninsula, this is not a surprise finding. The soils of the region are very diverse and complex due to the history of several interglacial and glacial events and are therefore quite heterogeneous (Haynes 2000). This variation in soil is similar to the findings of Ortega et al. (2003) who found that Chilean vineyards varied significantly in terms of chemical and physical properties. As expected, in all vineyards, sand and clay content were inversely correlated. Soils higher in sand content were found to be also higher in OM at a number of sites (Cave Spring, Flat Rock, Vailmont).

Similar to the findings of texture, soil composition varied as well within vineyard sites (Supplemental Figures 3.8a to g). Again, some vineyards were more variable than others especially in terms of soil pH, OM, and certain macronutrients including P, K, and Ca. Within-site differences in terms of OM ranged from 0.8-1.9%. Soils higher in OM were generally found to have higher concentrations of P and K and less Ca content. Differences in pH within vineyards ranged from 0.5-1.5 indicating spatial variation. Soil Ca had a positive impact on the pH of the soil in most of the vineyards. This is not surprising as calcareous soils that contain free Ca carbonate may be quite strongly alkaline.

There were also strong relationships between Ca, CEC, and BS (Figures 3.5 to 3.7, Suppl. Figures 3.7a to 3.8g). Soil pH and BS were positively correlated but the relationship was not always linear as suggested by Wolf (2008). Soil Mg and Ca were negatively related in most vineyards. Soil K was also negatively correlated with Mg. Soils with higher CEC have greater plant mineral nutrient-holding potential. In limestone based soils the Ca and Mg can out compete K in exchange sites. This can lead to K deficiency due to this antagonistic effect. Some sites varied little spatially in K (Suppl. Figure 3.8b) whereas other vineyards had an almost six-fold difference (Suppl. Figure 3.8c). This was also found with K with some vineyards showing small variations while others had large spatial variations.

The other macronutrients measured in this study also varied within sites and to different extents. These findings indicate that there may be a need for site-specific nutrient management in Niagara Peninsula vineyards. Within vineyards, some areas were below adequate levels for general grapevine nutritional requirements, where other regions were excessive. Supplemental Figures 3.3c and 3.8c show that low vine size was found in the areas deficient in K. In other vineyards, lower yields were found in such areas as shown in Suppl. Figure 3.7f. Cellular K is important in plant biochemical processes, including carbohydrate production, protein synthesis, solute transport, and maintenance of plant water status. Lack of K can reduce shoot growth, vine vigour, berry set and crop yields (Keller 2010).

While the vineyards exhibited within-site variation for many soil composition variables, no clear trends were found as to their impact on vine performance or yield. No consistent relationships were observed for any soil variable on vine performance over three vintages for any vineyard. While Ca and P had an influence on vine size in a few vineyards and vintages, OM and texture were found to have an influence on more occasions but not consistently. The same observation was found with the impact of these soil factors on yield components such as berry weight and yield/vine. The exception was when an area of a vineyard displayed low concentrations of certain macronutrients then vine vigour and yield suffered in those instances. Perhaps petiole analysis indicating the nutrient status of the vine would have given clearer explanation of the impact of soil composition on vine performance or yield components but other studies such as Reynolds et al. (2007) claimed it is difficult to make conclusions about the impact of soil nutrients on the terroir effect. Therefore, while vineyards do vary in terms of chemical composition, as long as no deficiencies are present, the soil mineral composition does not clearly impact vine performance or yield components in this study.

In general, soil texture was related to soil moisture with areas of higher clay content having higher water content as expected. For the most part, these areas often had vines of higher water status (lower leaf ψ) but there may have been other interactive factors that possibly influenced vine water status other than just soil texture. Some inconsistencies between the different vineyards studied may have been a result in differences in rooting depth, soil depth, and gravel content as seen through soil pits (no data available) or differences in drainage. Therefore, these factors cannot be ignored when looking at relationships between soil moisture and vine water status.

Principal component analysis (2005-2007). Principal component analysis (PCA) was used to help interpret the large data sets collected annually for each vineyard site. While some relationships were site-specific for each vineyard, some general conclusions can be made through multivariate statistical analyses, such as PCA. Many of the spatial relationships associated with many of the variables were further supported through PCA. In general, the most consistent findings through PCA were the relationships concerning vine water status, vine size, and berry weight. In many of the vineyards, across all vintages, vine water status, vine size and berry weight were found in close association with each other. Through PCA of the entire data set, water potential, soil moisture, vine size and berry weight were closely associated in every vintage (Figures 3.5 to 3.7). Less negative leaf ψ was associated with larger vine size, particularly in the drier 2005 and 2007 vintages. In the literature, it is often stated that a reduction in vegetative (shoot) growth is the most common consequence of water deficits (Kliewer et al. 1983, Reynolds et al. 2006, Schultz and Matthews 1988, Williams 2000). In 2005, vine size and leaf ψ were negatively correlated but highly correlated with soil moisture and yield (Figure 3.5). This may be indicative of vine health and crop level as a result of winter injury. Small vines with no crop would respond differently to water stress than larger vines with higher crops. The larger vines with crop would have a larger water demand than the vines recovering from winter injury. As shown in Figures 3.5 through 3.7, berry weight was highly correlated with leaf ψ in all vintages. The sensitivity to water deficits depends on the developmental stage of the vine so it is possible that some inconsistencies between vineyards or vintages could be related to the timing of deficit. For example, limited water supply during berry cell expansion can restrict berry size (Roby et al. 2004). Soil moisture was associated vine size and berry weight in some vineyards across the vintages but vine water status had a closer association with these variables. This indicates that plant-based measurements are a better measurement of how water is impacting vine and reproductive growth rather than prediction solely through soil-based measurements, the most commonly used method to monitor irrigation timing in horticulture crops.

Aside from common soil associations (i.e., Ca content, soil pH), soil composition variables did not have any consistent relationships with vine size, berry weight or yield. In most vineyards and vintages, there were expected findings such as soil texture being associated with soil moisture content. Generally, more moisture was associated with clay-dominated areas of the vineyard with less in sand-dominated areas. Soil texture was found to be associated vine water status in some instances and the association was usually dictated by the vintage through natural precipitation events. Texture of the soil and OM did have some associations with vine vigour and yields, with higher sand content usually being correlated with larger vines and yields. OM can impact vigour and yields as it serves many functions in the soil such as water retention and increased nutrient holding capacity. Coarse textured soils can result in large vine growth due to water availability and excellent root penetration (Carey et al. 2008, Seguin 1970). Variation in soil moisture due to water-holding capacity has been shown to strongly influence vine performance within vineyards (Cortell et al. 2005, Hall et al. 2002). In Germany, Wahl (1988) found that soil type did not impact many factors but yields varied between soils. This is in agreement with this study where sandier soils generally had larger yields than soils with higher clay content. This was consistent with the results of Reynolds et al. (2007) who found that soils higher in sand content had larger yield components.

In general, vineyards within the Niagara Peninsula were shown to be variable in terms of soil texture, composition, nutrition and moisture. Furthermore, many viticulture variables such vine water status, vine vigour, berry weight and yield were spatially variable. There was some temporal stability of these variables despite different growing seasons. These findings are quite remarkable since previous studies performed in Niagara did not find many spatial data to be temporally stable. Temporal stability is required for many practical applications of GPS and GIS to be initiated in Niagara vineyards, but it is also of importance to future research endeavors for this project as well as others.

Conclusions

As hypothesized, consistent water status zones were identified within vineyards in three distinct vintages. Many geospatial patterns and relationships were determined and found to be temporally stable. The strongest relationships were those concerning vine water status, soil moisture, vine size, and berry weight. No consistent relationships were found concerning soil composition. The most consistent quality of soil that impacted vine performance and yield components was texture. Therefore, soil did have some indirect effects but vine water status was found to be a major contributor to the terroir effect as it had a major impact on vine size, berry weight and yield in many vineyards across multiple vintages.

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Table 3.3. Overall correlations of soil, water status and vine performance variables for all vineyard sites, Niagara Peninsula, ON. 2006.

Table 3.4. Overall correlations of soil, water status and vine performance variables for all vineyard sites, Niagara Peninsula, ON. 2007.

Table 3.1a. General features of Niagara Peninsula Riesling vineyards used for elucidation of terroir studies, 2005- 2007.

Variable	**Sites**				
	Chateau des Charmes	**Reif Estate Winery**	**Lambert Farms**	**Glenlake Vineyards (Lakelodge)**	**Henry of Pelham**
Location	St Davids	Virgil	Virgil	NOTL	West St Catharines
VQA Sub-appellation	St David's Bench	Niagara River	Four Mile Creek	Niagara Lakeshore	Short Hills Bench
Area of vineyard block (ha)	1.68 ha	1.71 ha	0.81 ha	3.39 ha	1.57 ha
Number of sentinel vines	75	74	75	74	80
Soil series	TLD7; B>B	VLD 6; B=B	CGU19: B=B	TVK 15; c >B	BVY 8; c=B
Parent materials	Mainly lacustrine silty clay	Mainly reddish-hued lacustrine fine sandy loam & very fine sandy loam 40-100cm reddish-hued loamy textures over clay loam till	Mainly reddish-hued clay loam till	40-100cm reddish-hued loamy textures over clay loam till	Mainly lacustrine silty clay
Soil drainage	Imperfect to poor	Imperfect	Imperfect to poor	Imperfect	Imperfect to poor
Clone	R239	R239	R239	R239	R49 Colmar
Rootstock	SO4	SO4	SO4	SO4	C3309
Vine age at initiation of trial (yr planted)	22 yrs (1983)	22 yrs (1983)	5 yrs (2000)	9 yrs (1996)	7 yrs (1998)
Vine spacing (m; row X vine)	2.5 X 0.9	3.0 X 1.3	2.74 X 1.22	2.5 X 1.5	2.5 X 1.2
Number of rows; vines per row	47 rows; 7520 vines 160 vines/row	14 rows; 4104 vines 12 @ 298 v/r, 2@ 264 v/r	15 rows; 2400 vines 160 vines/row	58 rows; 10,940 vines 42 @ 198v/r, 16 @ 164v/r	27 rows; 5000 vines 21 @ 188v/r; 6 @ 165 v/r
Training system	Double Guyot	4-arm Kniffin	Scott Henry	Scott Henry	Pendelbogen
Floor management	Clean cultivation	Alternate Sod	Alternate Sod	Clean cultivation	Alternate Sod

Table 3.1b. General features of Niagara Peninsula Riesling vineyards used for elucidation of terroir studies, 2005-2007.

Variable	**Sites**				
	Paragon Estate Vineyards	**Flat Rock Cellars (Nadja's Vineyard)**	**Cave Spring (Home Block)**	**Myers Vineyard**	**Vailmont Vineyards (Vieni Estate)**
Location	West St Catharines	Jordan	Vineland	Vineland	Beamsville
VQA Sub-appellation	Creek Shore	Twenty Mile Bench	Beamsville Bench	Lincoln Lakeshore	Vinemount Ridge
Area of vineyard block (ha)	1.55 ha	0.92 ha	2.22 ha	1.26 ha	1.26 ha
Number of sentinel vines	74	72	75	72	74
Soil series	MAT 1;B	CGU11;C>B	CGU14; c>B	JDD 1; B	JDD 1;B
Parent materials	40-100 cm lacustrine silty clay over clay till loam	No.1: Mainly clay loam till No.2: 40-100 cm lacustrine silty clay over clay loam till	No.1: 15-40 cm loamy textures over clay loam No.2: Mainly clay loam till	Mainly clay loam till	Mainly clay loam till
Soil drainage	Poor	Imperfect to Poor	Imperfect to Poor	Poor	Imperfect to Poor
Clone	R21B Weis	R21B Weis	R21B Weis	R21B Weis	R21B Weis
Rootstock	SO4	SO4	SO4	SO4	SO4
Vine age at initiation of trial (yr planted)	7 yrs (1998)	5 years (2000)	27 yrs (1978)	18 yrs (1987)	7 yrs (1998)
Vine spacing (m; row X vine)	2.3 X 1.2	2.3 X 1.2	2.5 X 1.5	3.0 X 1.5	2.5 X 1.2
Number of rows; vines per row	43 rows; 5800 vines 145 vines/row	46 rows; vines/row varies	45 rows; 6120 136 vines/row	17 rows; 2890 vines 170 vines/row	29 rows; 3828 vines 132 vines/row
Training system	Double Guyot	Double Guyot	Pendelbogen	Pendelbogen	Halbbogen
Floor management	Alternate Sod	Alternate Sod	Alternate Sod	Alternate Sod	Alternate Sod

Table 3.2. Overall correlations of soil, vine water status and vine performance variables for all vineyard sites, Niagara Peninsula, ON. 2005.

Variables	Water Potential	Yield	vine size	Berry wt	Soil Moisture	%Sand	%Clay	Soil pH	OM	P	K	Mg	Ca	CEC	BS
Water Potential	1	-0.044	**-0.27**	**0.452**	0.046	0.141	-0.15	0.027	-0.124	0.021	**-0.184**	-0.099	-0.088	-0.147	0.074
Yield		1	**0.148**	**0.135**	-0.015	0.05	-0.078	-0.081	**-0.204**	**-0.181**	**-0.249**	-0.133	-0.072	-0.111	0.01
vine size	***	***	1	**-0.679**	**0.522**	0.113	-0.148	**-0.22**	0.162	0.08	0.161	0.066	-0.091	-0.067	-0.127
Berry wt	***	**	***	1	**-0.364**	0.142	-0.155	0.06	-0.124	0.094	**-0.244**	**-0.287**	-0.112	-0.136	0.007
Soil Moisture			***	**	1	**-0.171**	0.085	**0.338**	0.101	0.146	0.065	0.051	**0.314**	**0.288**	**0.31**
%Sand				***	*	1	**-0.881**	**-0.397**	**-0.239**	0.113	**-0.173**	**-0.495**	**-0.631**	**-0.632**	**-0.307**
%Clay						***	1	**0.297**	0.092	**-0.207**	0.09	**0.556**	**0.57**	**0.584**	**0.237**
Soil pH			**		***	***	***	1	0.004	0.082	0.002	0.096	**0.799**	**0.662**	**0.833**
OM		*				**			1	**0.497**	**0.692**	**0.19**	0.073	0.151	-0.019
P		*					**		***	1	**0.556**	**-0.189**	-0.003	0.068	0.072
K	*	**		**		*			***	***	1	-0.01	0.071	**0.17**	-0.023
Mg				**		***	*		*	*		1	0.114	**0.162**	-0.05
Ca					***	***	***	***					1	**0.92**	**0.688**
CEC					***	***	***	***			*	*	***	1	**-0.302**
BS					***	***	**	***					***	***	1

Bold are significant.

*, **, ***: Significant r values at $p<0.05$, 0.01, 0.001, respectively.

Table 3.3. Overall correlations of soil, vine water status and vine performance variables for all vineyard sites, Niagara Peninsula, ON. 2006.

Variables	**Water potential**	**Yield**	**vine size**	**Berry wt**	**Soil Moisture**	**%Sand**	**%Clay**	**soil pH**	**OM**	**P**	**K**	**Mg**	**Ca**	**CEC**	**BS**
Water potential	**1**	**0.347**	**0.183**	0.132	**0.256**	**0.167**	**-0.198**	**-0.233**	0.067	**0.269**	-0.004	**-0.189**	**-0.289**	**-0.25**	-0.079
Yield	*	**1**	**0.395**	-0.011	**0.337**	**0.353**	**0.285**	**-0.419**	**0.158**	0.142	**0.201**	-0.086	**-0.421**	**-0.311**	**-0.176**
Vine size	***	***	**1**	**0.134**	0.037	**0.434**	**-0.459**	**-0.294**	0.112	**0.354**	0.067	**-0.381**	**-0.343**	**-0.188**	-0.135
Berry wt			**	**1**	**0.101**	-0.048	-0.008	-0.019	0.075	**0.159**	0.119	-0.008	-0.063	-0.079	0.098
Soil Moisture	**	***		**	**1**	**-0.23**	**0.222**	**-0.175**	**0.448**	**0.157**	**0.331**	**0.371**	-0.095	-0.125	-0.046
%Sand	*	***	***		**	**1**	**-0.881**	**-0.397**	**-0.239**	0.113	**-0.173**	**-0.495**	**-0.631**	**-0.632**	**-0.307**
%Clay	*	***	***		**	***	**1**	**0.297**	0.092	**-0.207**	0.09	**0.556**	**0.57**	**0.584**	**0.237**
soil pH	**	***	***		*	***	***	**1**	0.004	0.082	0.002	0.096	**0.799**	**0.662**	**0.833**
OM		*			***	**			**1**	**0.497**	**0.692**	**0.19**	0.073	0.151	-0.019
P	***			*	*		**		***	**1**	**0.556**	**-0.189**	-0.003	0.068	0.072
K		**			***	*			***	***	**1**	-0.01	0.071	**0.17**	-0.023
Mg	*		***		***	***	*		*	*		**1**	0.114	**0.162**	-0.05
Ca	***	***	***			***	***	***					**1**	**0.92**	**0.688**
CEC	**	***	*			***	***	***			*	*	***	**1**	**-0.302**
BS		*				***	**	***					***	***	**1**

Bold are significant.

*, **, ***: Significant r values at $p<0.05$, 0.01, 0.001, respectively.

Table 3.4. Overall correlations of soil, vine water status and vine performance variables for all vineyard sites, Niagara Peninsula, ON. 2007.

Variables	Water potential	Yield	Vine Size	Berry wt	Soil moisture	%Sand	%Clay	soil pH	OM	P	K	Mg	Ca	CEC	BS
Water potential	**1**	**0.416**	**0.497**	**0.646**	**0.172**	**0.497**	**-0.416**	**-0.226**	-0.057	**0.267**	-0.009	**-0.324**	**-0.341**	**-0.322**	**-0.175**
Yield	***	**1**	**0.56**	**0.328**	**0.2**	**0.501**	**-0.483**	**-0.39**	**0.176**	**0.468**	**0.273**	**-0.334**	**-0.438**	**-0.388**	**-0.304**
Vine Size	***	***	**1**	**0.551**	**0.202**	**0.362**	**-0.377**	**-0.242**	0.111	**0.322**	0.088	**-0.347**	**-0.294**	**-0.22**	**-0.19**
Berry wt	***	***	***	**1**	**0.269**	**0.337**	**-0.353**	-0.131	0.037	**0.371**	0.023	**-0.301**	**-0.25**	**-0.21**	-0.063
Soil moisture	*	***	***	***	**1**	**-0.226**	**0.234**	**0.246**	**0.259**	**0.375**	**0.305**	0.136	**0.269**	**0.303**	**0.223**
%Sand	***	***	***	***	**	**1**	**-0.881**	**-0.397**	**-0.239**	0.113	**-0.173**	**-0.495**	**-0.631**	**-0.632**	**-0.307**
%Clay	***	***	***	***	**	***	**1**	**0.297**	0.092	**-0.207**	0.09	**0.556**	**0.57**	**0.584**	**0.237**
soil pH	**	***	***		**	***	***	**1**	0.004	0.082	0.002	0.096	**0.799**	**0.662**	**0.833**
OM		*			***	**			**1**	**0.497**	**0.692**	**0.19**	0.073	0.151	-0.019
P	***	***	***	***	***		**		***	**1**	**0.556**	**-0.189**	-0.003	0.068	0.072
K		***			***	*			***	***	**1**	-0.01	0.071	**0.17**	-0.023
Mg	***	***	***	***		***	*		*	*		**1**	0.114	**0.162**	-0.05
Ca	***	***	***	**	***	***	***	***					**1**	**0.92**	**0.688**
CEC	***	***	**	**	***	***	***	***			*	*	***	**1**	**-0.302**
BS	*	***	**		**	***	**	***					***	***	**1**

Bold are significant.

*, **, ***: Significant r values at $p<0.05$, 0.01, 0.001, respectively.

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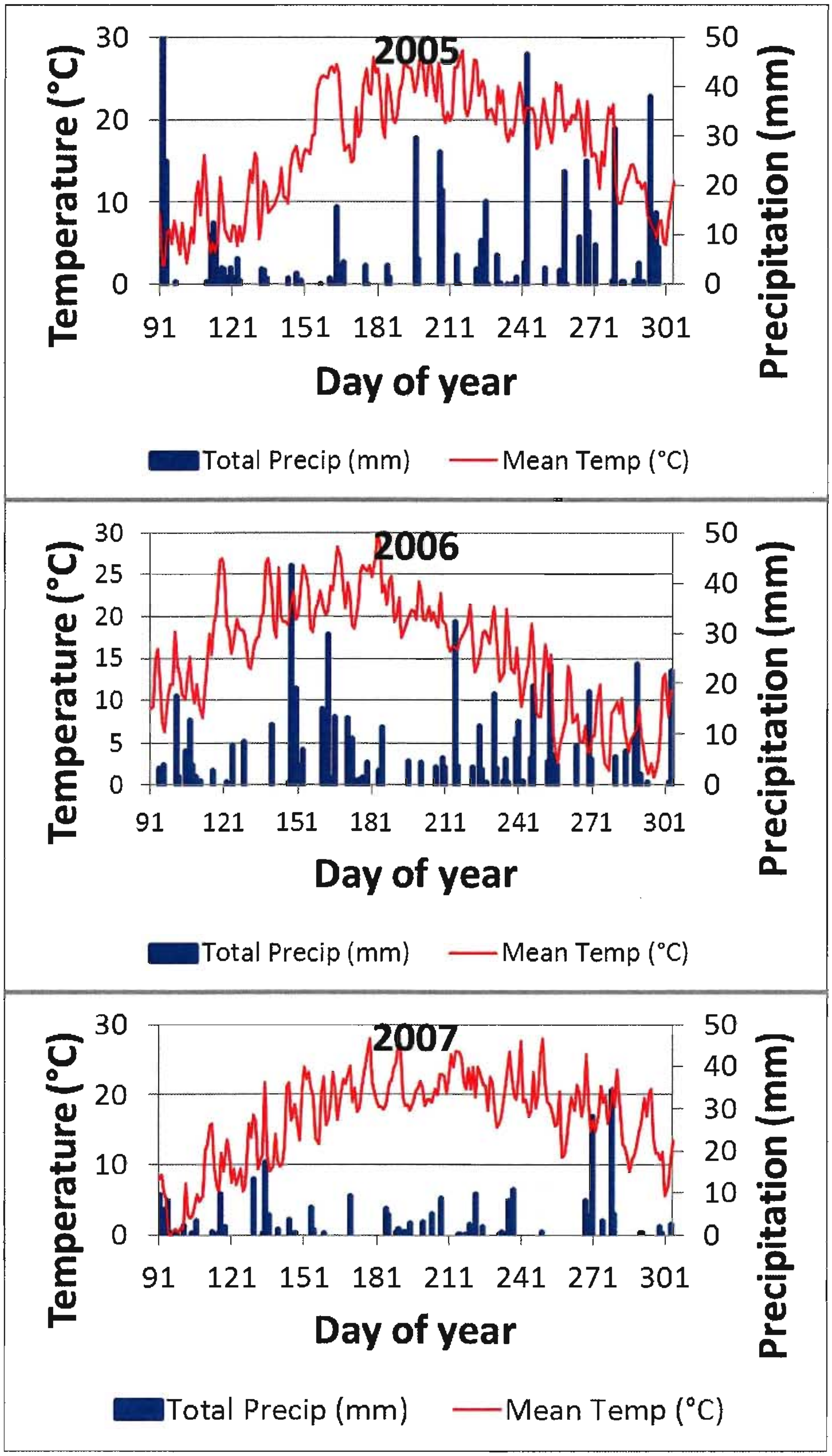

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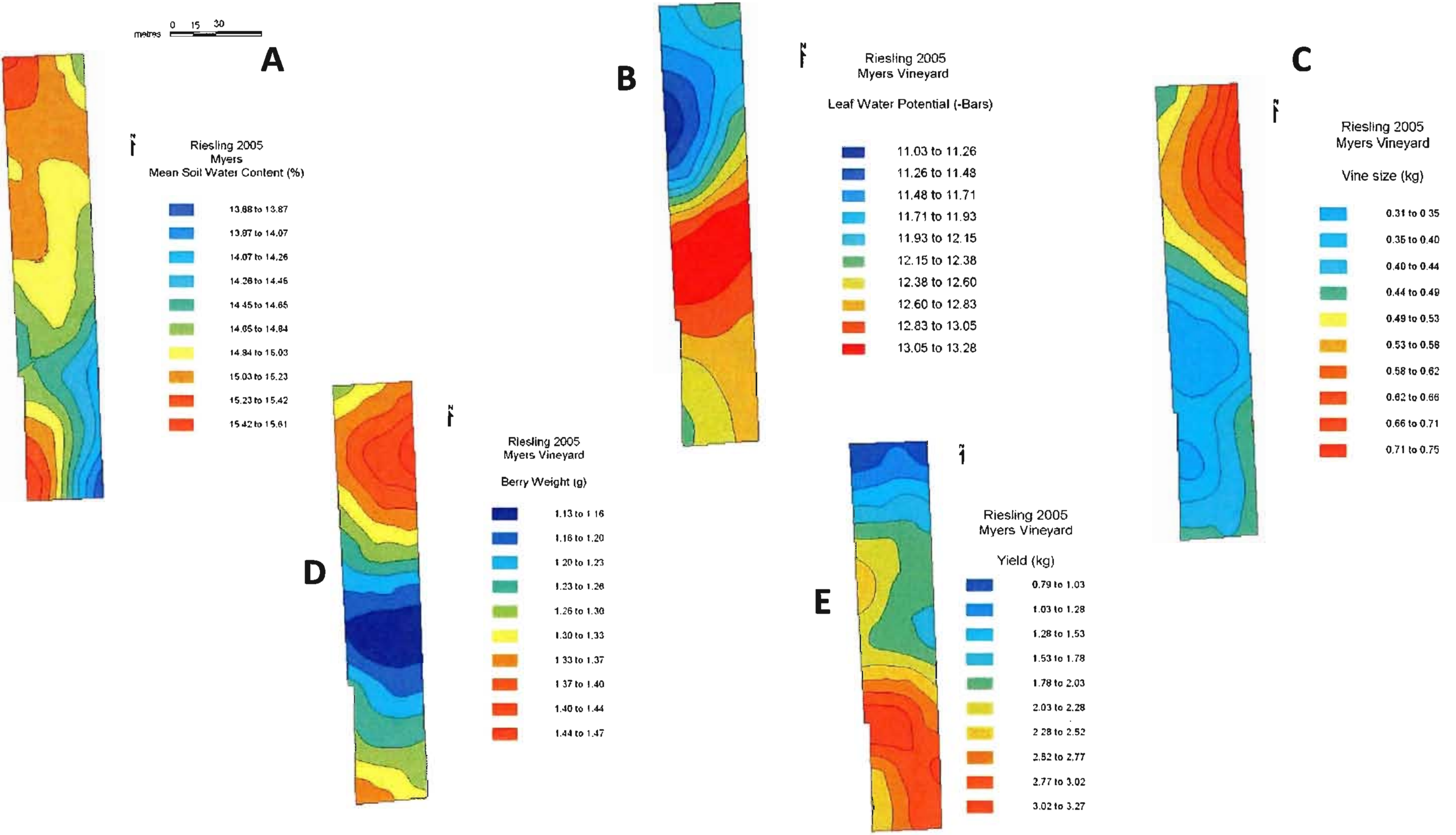

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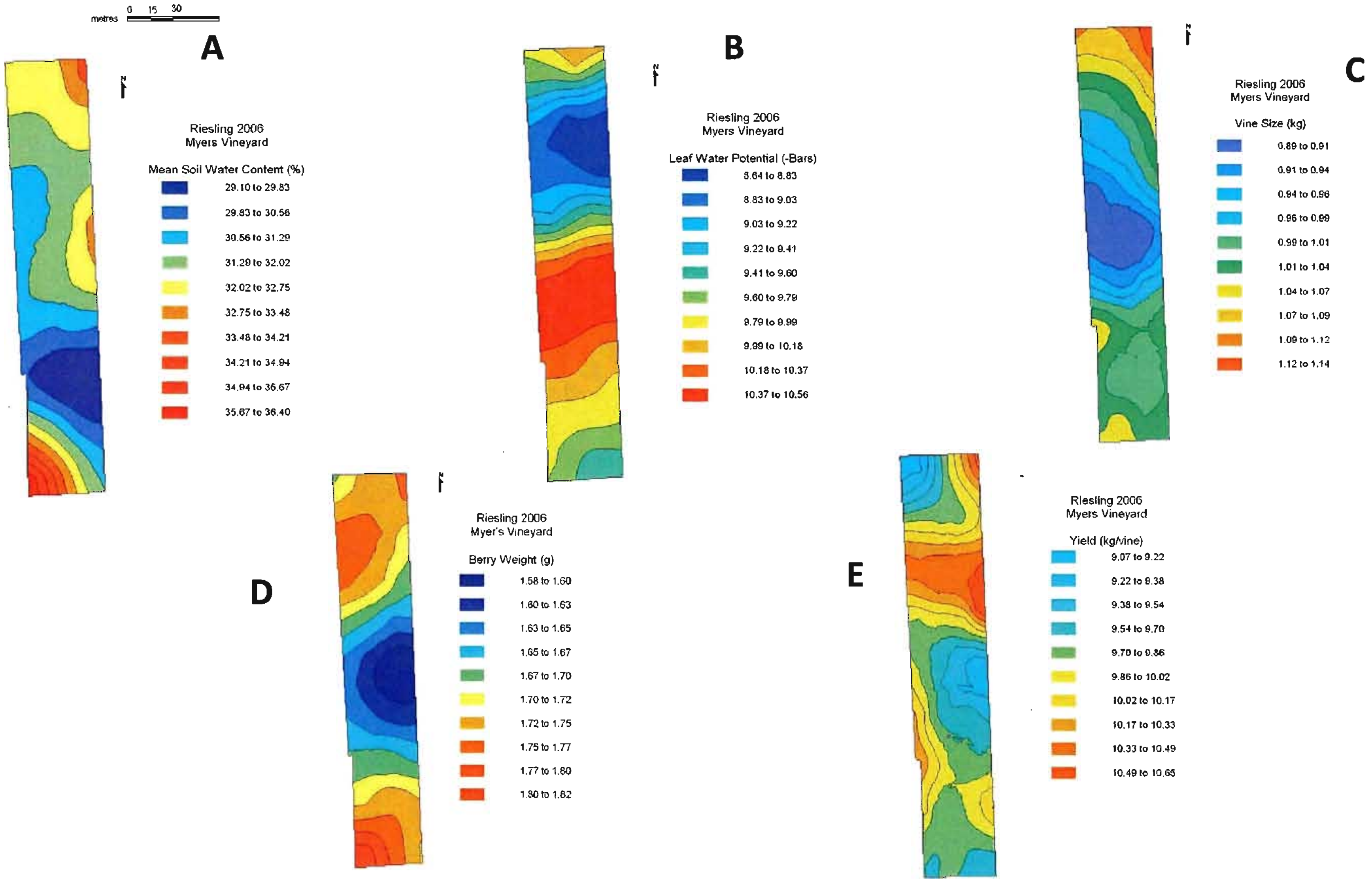

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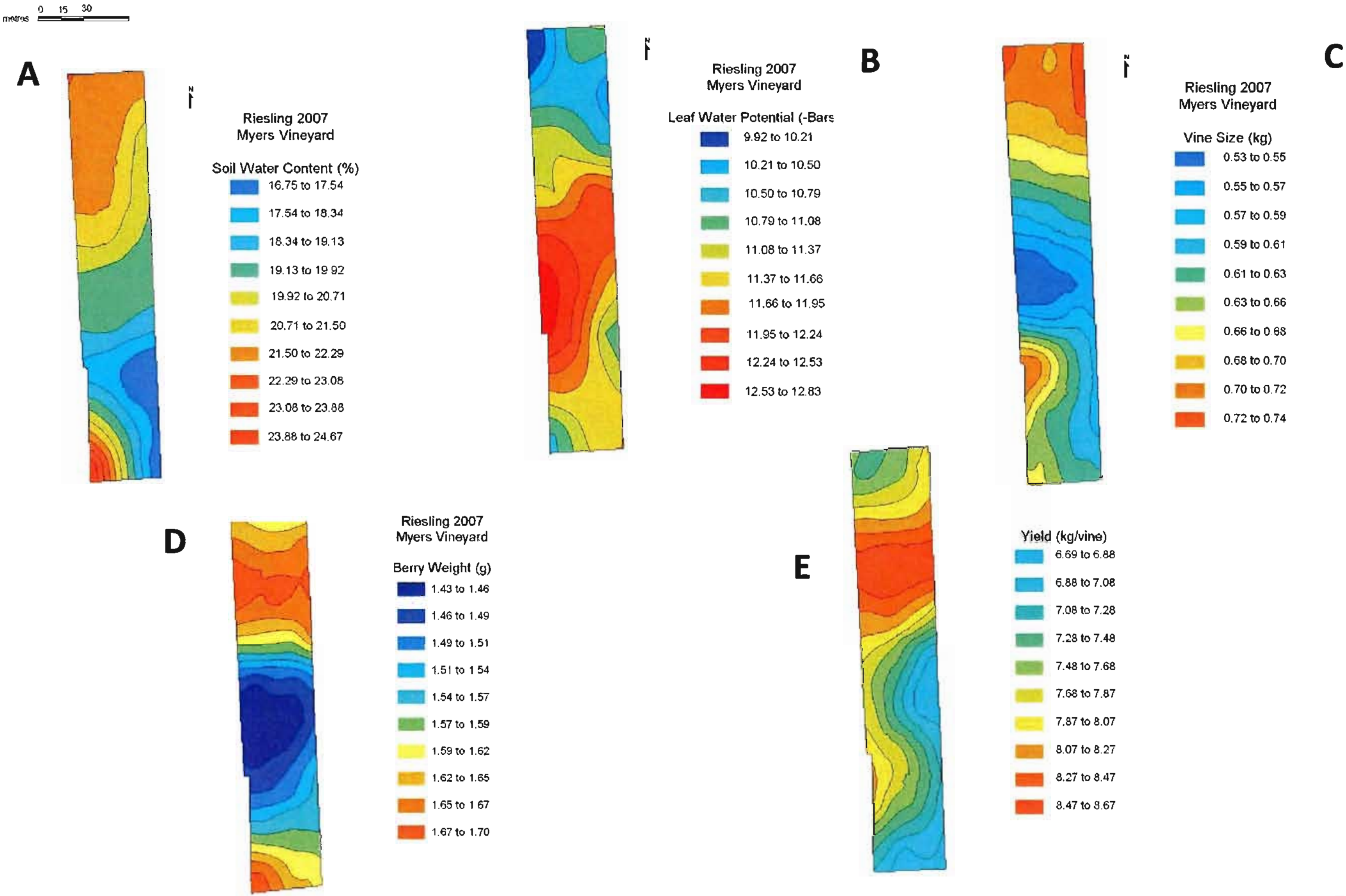

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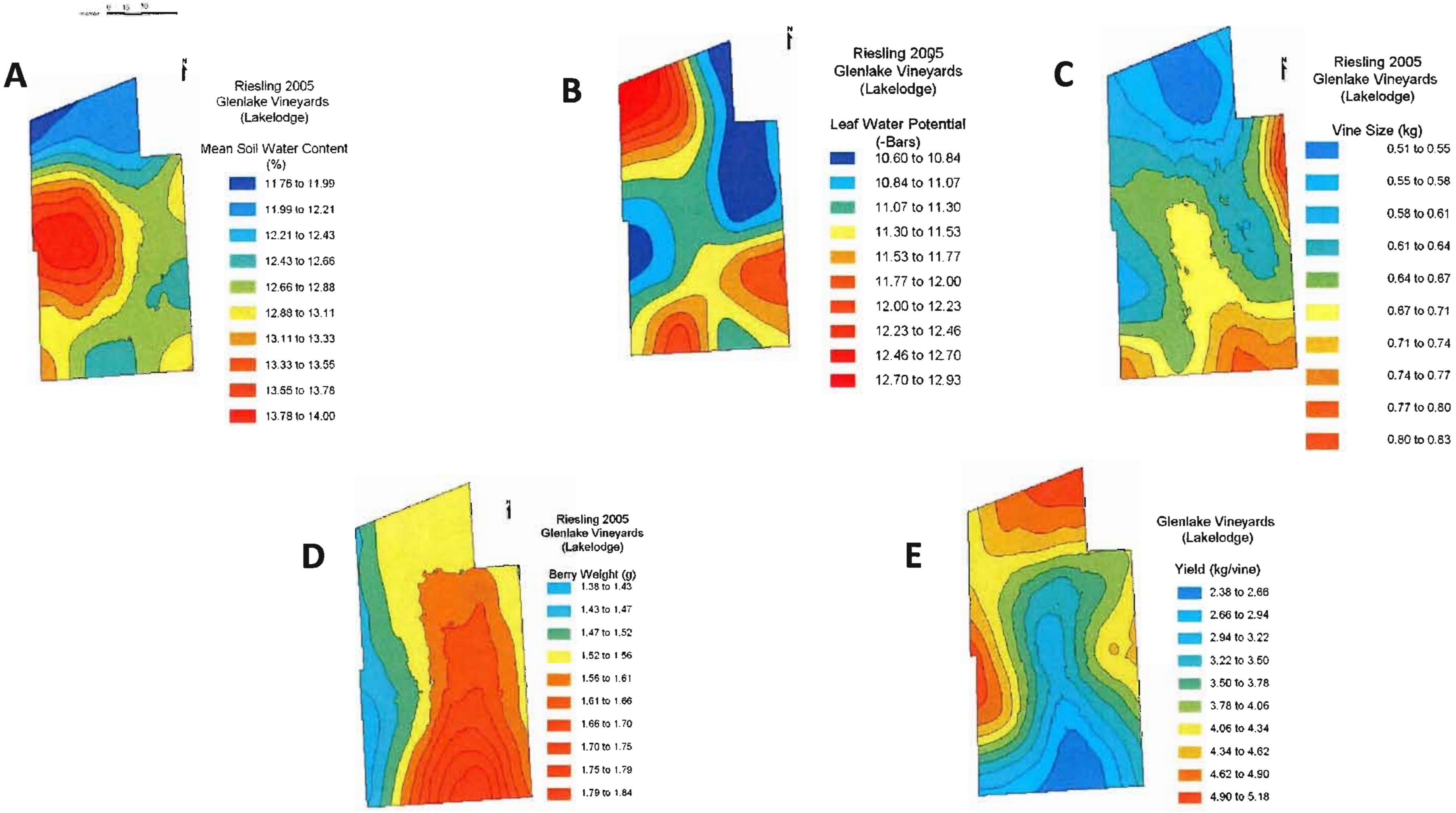

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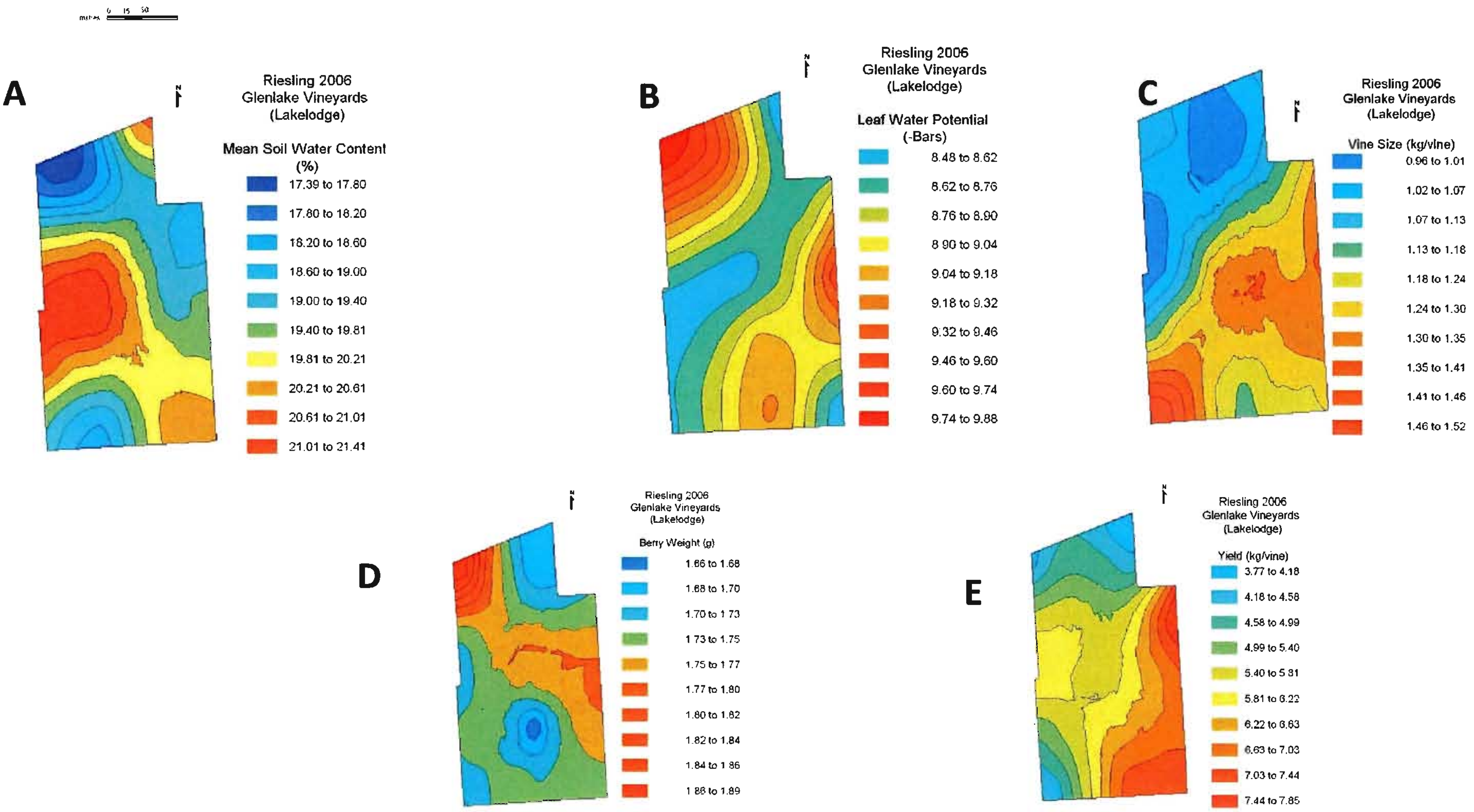

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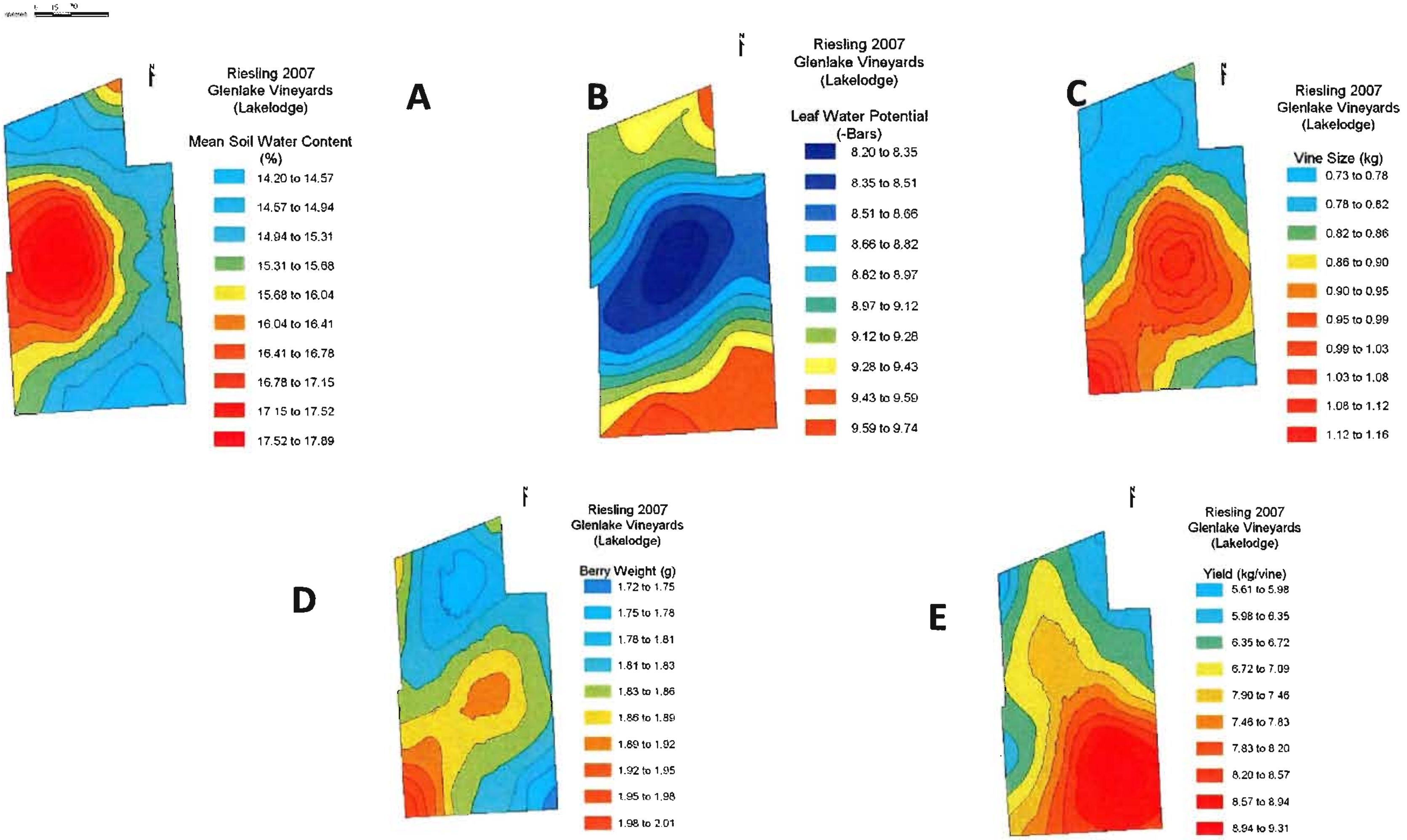

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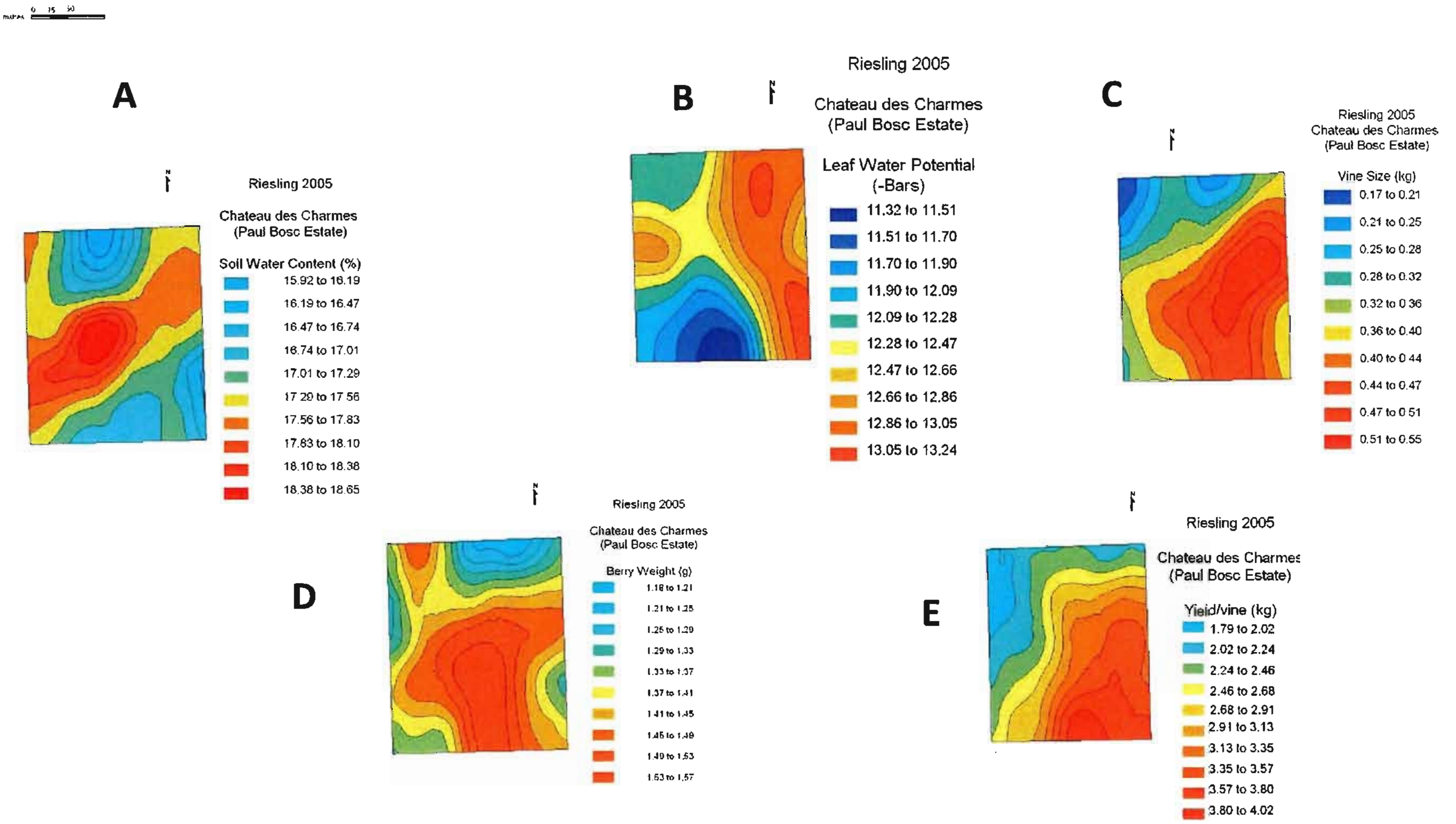

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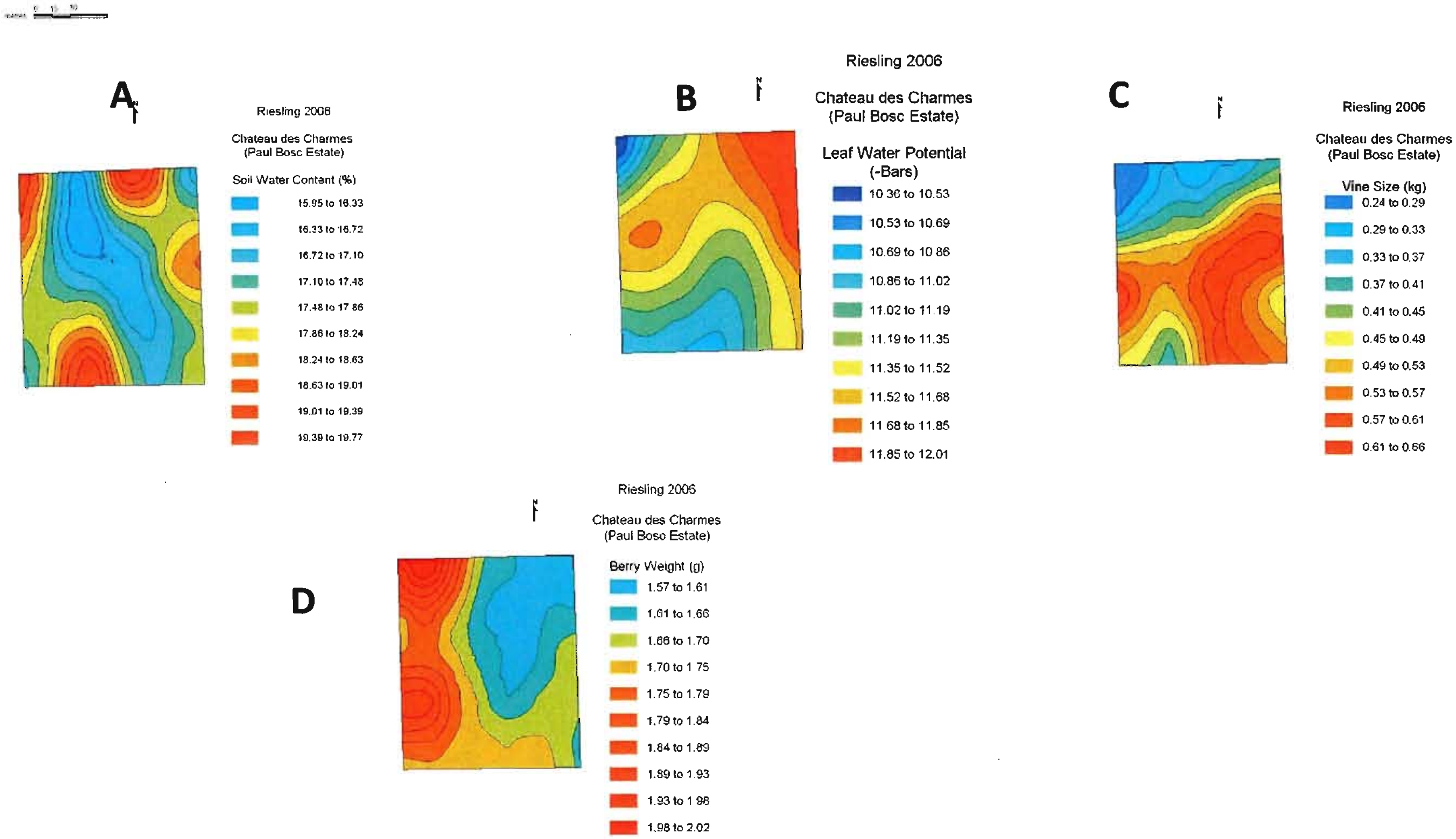

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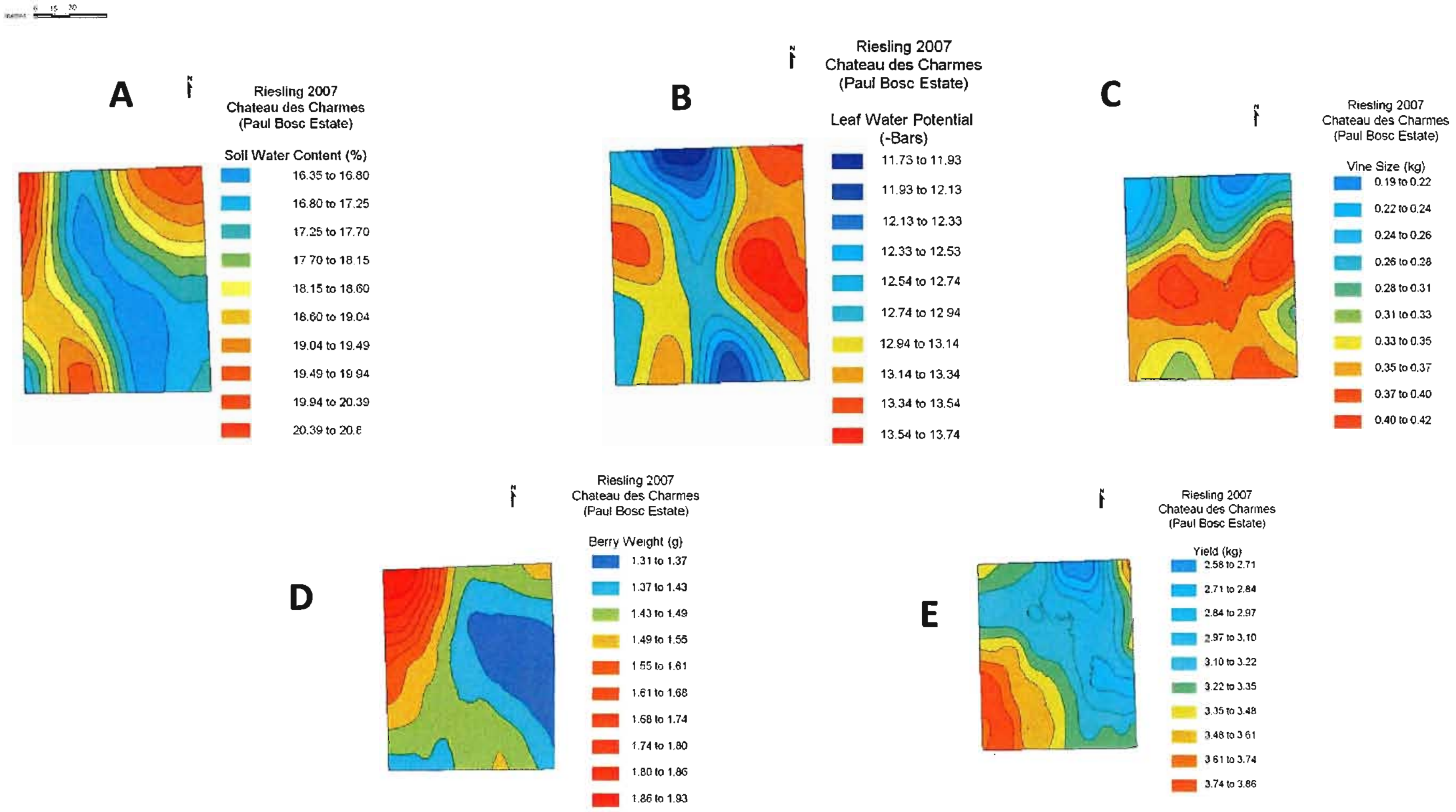

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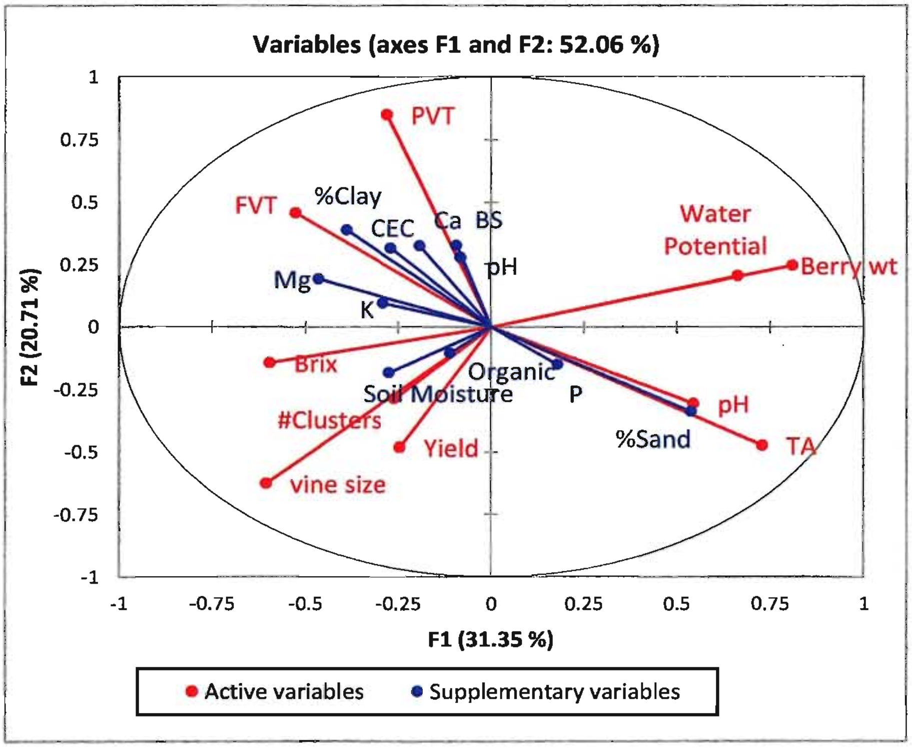

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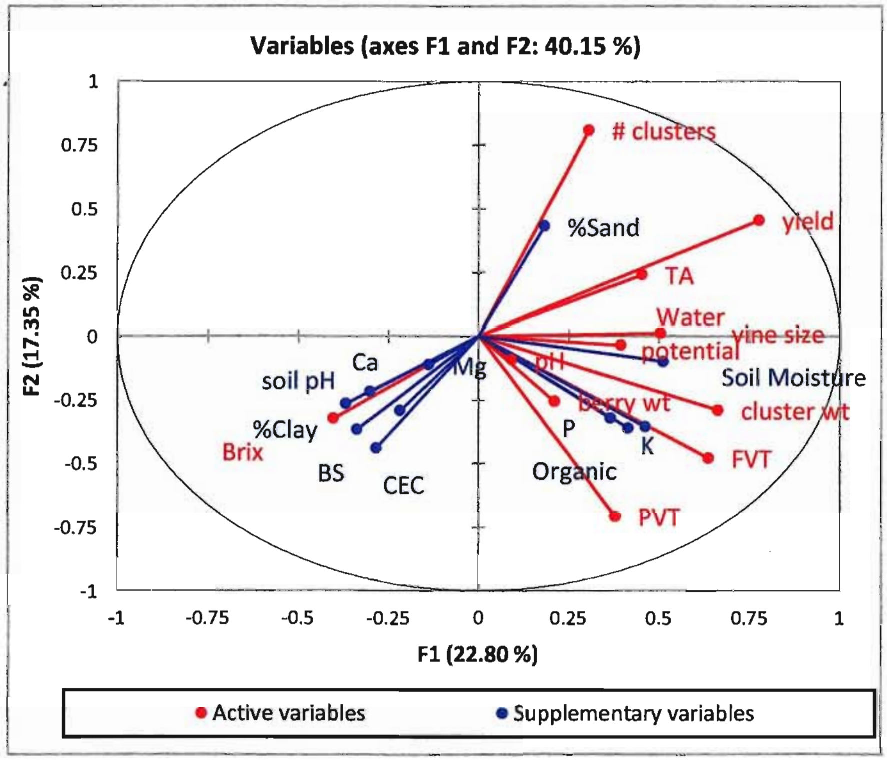

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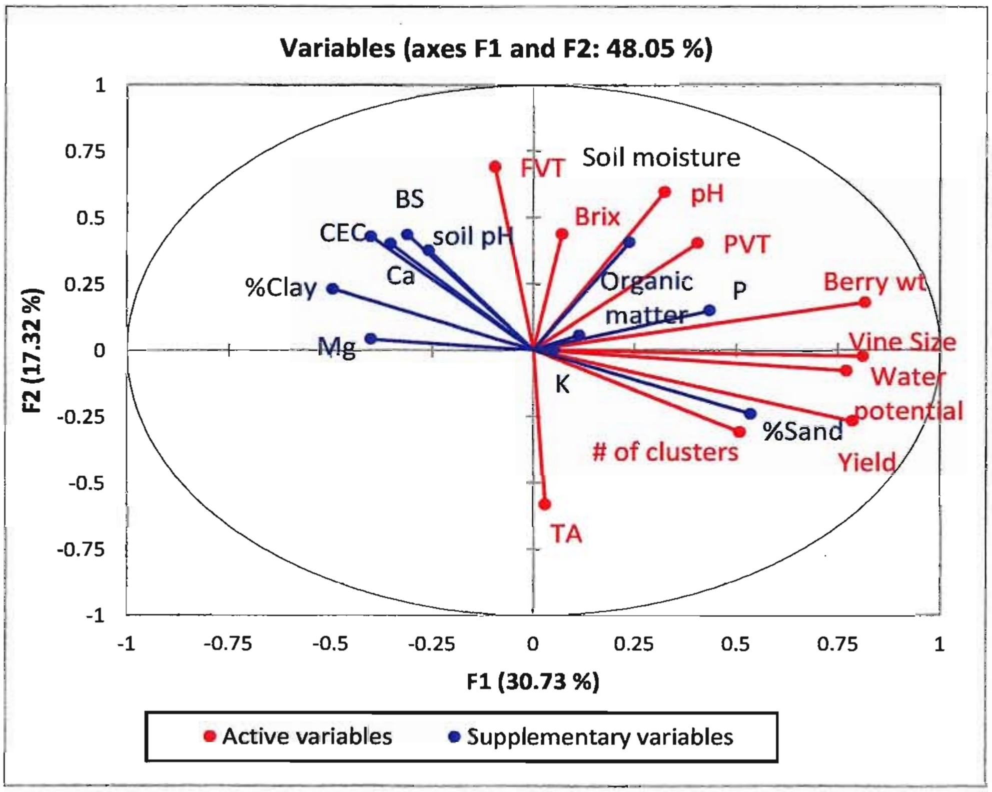

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Supplemental Table 3.1a. Correlations between water status, soil and yield component variables for Myers Vineyard, 2005-2007.

Yield Variable	**Water Status Variables**		**Soil Variables**									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (% Ca)**
Yield/vine	-0.329	-0.311**	0.226	0.270	-0.531*	-0.328	-0.447	-0.164	0.061	-0.510*	-0.051	-0.400
Clusters	-0.234	-0.285*	0.157	0.164	-0.475*	-0.431	-0.422	-0.203	-0.165	-0.637*	-0.154	-0.441
Berry weight	0.192	0.155	0.069	0.064	0.249	0.148	0.189	0.188	0.269	0.367	0.114	0.208
Vine size	0.642**	-0.054	-0.202	-0.106	0.496*	0.202	0.386	0.216	0.216	0.513*	0.402	0.146
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%) Ca**
Yield/vine	-0.114	0.097	0.281	-0.438	-0.022	0.368	-0.023	0.065	-0.249	-0.256	-0.180	0.427
Clusters	-0.087	0.174	0.403	-0.449	0.222	0.267	-0.032	0.414	-0.224	0.170	-0.012	0.177
Berry weight	-0.013	0.262*	0.302	-0.486*	0.060	0.541*	0.313	0.075	-0.134	0.497*	-0.106	0.578*
Vine size	-0.293	0.151	0.602**	-0.458	0.646**	0.062	0.566*	0.191	-0.105	0.408	0.362	0.111
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%) Ca**
Yield/vine	-0.070	0.091	0.221	-0.092	0.141	-0.087	0.207	0.250	0.218	-0.049	0.176	-0.167
Clusters	-0.309	0.081	0.039	0.128	-0.119	-0.078	0.284	0.032	0.119	-0.027	-0.010	0.013
Berry weight	0.756**	0.198	-0.136	-0.076	0.295	0.257	0.257	0.373	0.166	0.410	0.242	0.121
Vine size	0.126	0.004	0.538*	-0.311	0.604**	0.071	0.566*	0.324	-0.052	0.363	0.380	0.022

*, **: Significant r values at $p<0.05$, 0.01, respectively.

Supplemental Table 3.1b. Correlations between water status, soil and yield component variables for Glenlake Vineyards (Lakelodge), 2005-2007.

Yield Variable	**Water Status Variables**		**Soil Variables**									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (% Ca)**
Yield/vine	-0.388	-0.196	0.248	-0.214	-0.330	-0.099	-0.288	-0.142	-0.016	-0.089	-0.583*	0.132
Clusters	-0.428	-0.171	0.223	-0.180	-0.279	0.206	-0.526*	-0.488*	0.150	0.262	-0.459	0.418
Berry weight	-0.027	-0.042	-0.079	-0.111	-0.083	-0.467	0.192	0.585*	-0.523*	-0.496*	-0.024	-0.494*
Vine size	-0.407	0.270*	0.096	-0.033	-0.106	-0.309	0.163	-0.101	-0.128	-0.232	-0.232	-0.110
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%) Ca**
Yield/vine	-0.09	-0.078	-0.528*	0.532*	0.127	-0.235	-0.450	-0.151	-0.072	-0.175	-0.342	-0.061
Clusters	-0.145	-0.184	-0.364	0.362	-0.114	0.160	-0.75**	-0.211	0.027	0.170	-0.344	0.261
Berry weight	0.314	-0.195	0.318	-0.407	-0.174	0.250	-0.225	-0.565*	0.031	0.079	-0.234	0.350
Vine size	-0.149	0.001	0.015	-0.415	0.028	-0303	0.405	0.091	-0.476	-0.365	0.075	-0.195
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%) Ca**
Yield/vine	-0.056	-0.274	-0.047	0.025	-0.210	-0.519*	0.017	0.098	-0.427	-0.713**	-0.329	-0.363
Clusters	0.002	-0.209	-0.086	0.063	-0.242	-0.344	-0.327	0.078	-0.431	-0.597*	-0.342	-0.212
Berry weight	0.190	0.326	-0.085	-0.205	-0.057	-0.138	0.277	-0.160	-0.158	0.002	0.240	-0.235
Vine size	0.021	0.176	-0.130	-0.432	-0.121	-0.200	0.242	-0.135	-0.478	-0.263	0.342	-0.240

*, **: Significant r values at p<0.05, 0.01, respectively.

Supplemental Table 3.1c. Correlations between water status, soil and yield component variables for Chateau des Charmes (Paul Bosc Estate), 2005-2007.

Yield Variable	**Water Status Variables**		**Soil Variables**									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (% Ca)**
Yield/vine	-0.328	0.248*	-0.169	0.197	-0.528*	0.032	0.031	-0.390	-0.412	0.315	0.243	0.421
Clusters	-0.206	0.210	-0.078	0.133	-0.416	-0.142	0.106	-0.293	-0.416	0.120	0.028	0.283
Berry weight	-0.392	0.057	-0.042	-0.001	0.262	-0.165	0.071	0.010	0.317	-0.181	-0.149	-0.211
Vine size	-0.430*	0.078	0.127	-0.043	0.213	-0.108	0.445*	-0.102	-0.156	-0.102	-0.136	0.05
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%) Ca**
Yield/vine	-0.515*	0.066	-0.188	0.174	0.071	0.167	-0.088	0.344	0.212	0.077	-0.089	0.094
Clusters	-0.317	0.151	-0.428	0.432	-0.136	0.123	-0.319	-0.023	0.373	0.143	-0.009	0.031
Berry weight	-0.109	0.108	0.298	-0.327	0.183	-0.594*	0.233	0.125	0.419	-0.633**	-0.221	0.023
Vine size	0.145	0.207	0.278	-0.395	0.491*	-0.097	0.282	0.047	-0.163	-0.172	-0.104	0.065
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%) Ca**
Yield/vine	0.018	0.067	0.020	0.049	0.263	-0.198	0.185	0.197	0.118	-0.225	-0.212	-0.257
Clusters	-0.449*	0.129	-0.109	0.012	0.018	-0.084	0.143	0.343	-0.113	-0.102	-0.096	-0.178
Berry weight	0.332	0.282*	0.089	-0.099	0.005	-0.371	0.011	-0.099	0.287	-0.370	-0.373	-0.269
Vine size	0.455*	-0.262*	0.604*	-0.687*	0.205	-0.313	0.250	-0.137	-0.219	-0.241	-0.277	-0.027

*, **: Significant r values at $p<0.05$, 0.01, respectively.

Supplemental Table 3.1d. Correlations between water status, soil and yield component variables for Cave Spring (Home Block), 2005-2007.

Yield Variable	Water Status Variables		Soil Variables									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (% Ca)**
Yield/vine	-0.069	-0.041	0.181	-0.240	0.517*	0.218	0.357	0.301	-0.250	-0.022	-0.016	0.009
Clusters	-0.243	-0.067	-0.143	-0.019	0.424	-0.383	0.198	0.350	0.155	-0.393	-0.370	-0.429
Berry weight	0.335	0.276*	0.375	-0.464	0.688**	-0.186	0.614**	0.243	-0.115	-0.189	-0.186	-0.153
Vine size	0.071	0.059	0.052	-0.133	0.339	0.113	0.213	0.082	-0.139	0.080	0.103	0.124
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (% Ca)**
Yield/vine	0.110	0.074	0.050	0.201	-0.089	-0.028	0.473*	0.119	-0.030	0.189	0.461	-0.122
Clusters	0.005	0.082	-0.213	0.179	-0.223	-0.028	0.442	-0.064	0.099	0.124	0.207	-0.046
Berry weight	0.017	0.000	-0.076	-0.109	0.112	-0.190	0.445	0.227	-0.393	-0.062	0.151	-0.233
Vine size	-0.038	0.102	0.037	-0.135	0.287	-0.278	-0.129	0.282	-0.028	-0.329	-0.352	-0.093
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (% Ca)**
Yield/vine	-0.216	-0.253*	0.072	-0.228	0.419	-0.293	0.253	0.344	-0.478*	-0.126	0.128	-0.237
Clusters	-0.004	-0.247*	0.065	-0.384	0.309	-0.064	0.278	0.337	-0.251	-0.177	-0.100	-0.181
Berry weight	-0.025	0.102	-0.423	-0.072	0.082	-0.236	0.036	0.189	-0.056	-0.248	-0.319	-0.107
Vine size	-0.084	-0.095	-0.225	0.036	0.061	-0.246	-0.047	0.215	-0.289	-0.134	-0.170	-0.004

*, **: Significant r values at $p<0.05$, 0.01, respectively.

Supplemental Table 3.1e. Correlations between water status, soil and yield component variables for Flat Rock Cellars (Nadja's Vineyard), 2005-2007.

Yield Variable	**Water Status Variables**		**Soil Variables**									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (% Ca)**
Yield/vine	-0.328	0.248*	-0.169	0.197	-0.528*	0.032	0.031	-0.390	-0.412	0.315	0.243	0.421
Clusters	-0.206	0.210	-0.078	0.133	-0.416	-0.142	0.106	-0.293	-0.416	0.120	0.028	0.283
Berry weight	-0.392	0.057	-0.042	-0.001	0.262	-0.165	0.071	0.01	0.317	-0.181	-0.149	-0.211
Vine size	-0.430*	0.078	0.127	-0.043	0.213	-0.108	0.445	-0.102	-0.156	-0.102	-0.136	0.05
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%) Ca**
Yield/vine	-0.487*	0.100	-0.019	0.118	-0.183	0.243	-0.335	-0.098	0.172	0.183	0.240	0.032
Clusters	-0.008	0.111	-0.229	0.313	-0.133	0.060	-0.409	0.061	0.524*	0.060	0.157	-0.207
Berry weight	0.047	-0.030	0.126	0.031	-0.164	-0.162	0.083	-0.141	-0.166	-0.091	-0.128	0.057
Vine size	-0.091	0.166	0.237	-0.110	0.037	0.067	0.368	-0.083	-0.320	0.117	0.082	0.224
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%) Ca**
Yield/vine	-0.114	0.008	0.069	-0.238	0.375	0.062	0.453*	0.149	-0.234	0.077	0.049	0.099
Clusters	-0.232	-0.001	-0.112	-0.070	0.031	0.206	0.199	-0.126	-0.108	0.185	0.170	0.173
Berry weight	0.280	0.132	0.036	-0.092	-0.056	-0.257	0.128	-0.121	-0.341	-0.116	-0.197	0.077
Vine size	0.002	0.116	0.065	0.029	-0.093	-0.210	0.108	-0.281	-0.188	-0.169	-0.224	0.040

*, **: Significant r values at p<0.05, 0.01, respectively.

Supplemental Table 3.1f. Correlations between water status, soil and yield component variables for Henry of Pelham, 2005-2007.

Yield Variable	Water Status Variables		Soil Variables									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (% Ca)**
Yield/vine	-0.051	-0.006	-0.152	-0.023	0.036	-0.111	0.039	0.233	-0.063	-0.118	-0.091	-0.077
Clusters	0.008	-0.044	-0.057	-0.131	-0.025	-0.121	0.065	0.137	-0.090	-0.110	-0.088	-0.088
Berry weight	-0.053	0.144	0.287	-0.248	-0.284	0.345	-0.218	0.006	-0.190	0.180	0.167	0.231
Vine size												
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%) Ca**
Yield/vine	-0.184	-0.119	-0.152	0.040	-0.145	-0.160	-0.587*	0.157	0.217	-0.207	-0.163	-0.284
Clusters	-0.371	-0.031	-0.088	0.059	-0.230	-0.285	-0.337	0.021	0.333	-0.328	-0.287	-0.427
Berry weight	0.151	-0.089	0.209	-0.329	0.370	-0.077	-0.254	-0.383	-0.434	-0.182	-0.209	-0.003
Vine size	-0.006	0.018	0.312	-0.246	0.061	0.135	0.054	-0.049	-0.323	-0.038	-0.066	0.165
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%) Ca**
Yield/vine	0.399	0.246*	0.171	-0.108	0.299	0.205	-0.185	-0.013	-0.170	0.323	0.292	0.387
Clusters	0.214	0.091	0.228	0.097	0.273	0.085	0.079	0.098	-0.155	0.272	0.225	0.312
Berry weight	0.643**	0.367**	0.216	-0.375	-0.046	0.204	-0.022	-0.315	-0.296	0.000	-0.002	0.149
Vine size	0.039	0.223*	0.042	0.005	0.330	0.287	-0.179	0.158	-0.349	0.191	0.168	0.284

*, **: Significant r values at $p<0.05$, 0.01, respectively.

Supplemental Table 3.1g. Correlations between water status, soil and yield component variables for Paragon Vineyards, 2005-2007.

Yield Variable	**Water Status Variables**		**Soil Variables**									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (% Ca)**
Yield/vine	-0.160	-0.088	0.231	-0.434	-0.041	0.149	-0.137	-0.275	-0.093	-0.147	-0.107	-0.012
Clusters	-0.459*	-0.152	0.138	-0.332	-0.075	0.107	-0.044	-0.315	-0.053	-0.084	-0.094	0.139
Berry weight	0.099	-0.019	0.370	0.082	-0.766**	0.239	-0.394	-0.597**	-0.148	0.159	0.060	0.286
Vine size	-0.108	-0.035	0.286	-0.246	-0.281	0.071	-0.451*	-0.238	-0.265	-0.170	-0.136	-0.170
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%) Ca**
Yield/vine	-0.359	-0.137	0.366	-0.416	0.062	-0.122	0.054	-0.026	-0.385	-0.233	-0.270	0.150
Clusters	-0.242	-0.091	0.236	-0.211	-0.055	0.188	-0.045	-0.118	-0.221	0.081	0.036	0.280
Berry weight	-0.443*	0.132	0.453*	-0.165	-0.646**	-0.286	-0.593**	-0.431	-0.441	-0.350	-0.304	0.126
Vine size	-0.199	-0.148	0.064	-0.149	-0.026	-0.146	-0.222	-0.033	-0.225	-0.212	-0.175	-0.086
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%) Ca**
Yield/vine	0.064	0.004	0.191	-0.223	-0.290	-0.314	-0.230	-0.109	-0.397	-0.308	-0.263	0.207
Clusters	0.245	0.146	0.101	-0.017	-0.420	-0.262	-0.252	-0.249	-0.195	-0.274	-0.288	0.336
Berry weight	0.538*	-0.197	0.233	-0.092	-0.409	0.235	-0.122	-0.300	-0.273	0.153	0.079	0.470*
Vine size	0.225	0.013	0.147	-0.194	-0.162	0.025	-0.197	-0.115	-0.339	-0.027	-0.025	0.316

*, **: Significant r values at $p<0.05, 0.01$, respectively.

Supplementary Figures

Supplemental Figure 3.1a. Spatial distribution of leaf water potential (-bars), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.2a. Spatial distribution of soil moisture (%), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.3a. Spatial distribution of vine size (kg/vine), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.4a. Spatial distribution of yield (kg/vine), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.5a. Spatial distribution of berry weight (g), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.6a. Spatial distribution of soil texture, Myers Vineyard, Vineland, ON; A: sand (%); B: clay (%).

Supplemental Figure 3.7a. Spatial distribution of soil physical properties, Myers Vineyard, Vineland, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).

Supplemental Figure 3.8a. Spatial distribution of soil composition (mg/kg soil), Myers Vineyard, Vineland, ON; A: K; B: P; C: Ca; D: Mg.

Supplemental Figure 3.9a. Principal component analysis of viticulture and soil variables for Myers Vineyard, ON; (a) 2005; (b) 2006; (c) 2007.

Supplemental Figure 3.1b. Spatial distribution of leaf water potential (-bars), Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.2b. Spatial distribution of soil moisture (%),Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.3b. Spatial distribution of vine size (kg/vine), Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.4b. Spatial distribution of yield (kg/vine), Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.5b. Spatial distribution of berry weight (g), Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.6b. Spatial distribution of soil texture, Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; A: sand (%); B: clay (%).

Supplemental Figure 3.7b. Spatial distribution of soil physical properties, Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).

Supplemental Figure 3.8b. Spatial distribution of soil composition (mg/kg soil), Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; A: K; B: P; C: Ca; D: Mg.

Supplemental Figure 3.9b. Principal component analysis of viticulture and soil variables for Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; (a) 2005; (b) 2006; (c) 2007.

Supplemental Figure 3.1c. Spatial distribution of leaf water potential (-bars), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.2c. Spatial distribution of soil moisture (%), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.3c. Spatial distribution of vine size (kg/vine), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.4c. Spatial distribution of yield (kg/vine), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.5c. Spatial distribution of berry weight (g), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.6c. Spatial distribution of soil texture, Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: sand (%); B: clay (%).

Supplemental Figure 3.7c. Spatial distribution of soil physical properties, Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).

Supplemental Figure 3.8c. Spatial distribution of soil composition (mg/kg soil), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: K; B: P; C: Ca; D: Mg.

Supplemental Figure 3.9c. Principal component analysis of viticulture and soil variables for Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; (a) 2005; (b) 2006; (c) 2007.

Supplemental Figure 3.1d. Spatial distribution of leaf water potential (-bars), Cave Spring Vineyards (Home Block), Beamsville, ON, Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.2d. Spatial distribution of soil moisture (%), Cave Spring Vineyards (Home Block), Beamsville, ON; A: 2005; B: 2006; C:2007.

Supplemental Figure 3.3d. Spatial distribution of vine size (kg/vine), Cave Spring Vineyards (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.4d. Spatial distribution of yield (kg/vine), Cave Spring Vineyards (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.5d. Spatial distribution of berry weight (g), Cave Spring Vineyards (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.6d. Spatial distribution of soil texture, Cave Spring Vineyards (Home Block), Beamsville, ON; A: sand (%); B: clay (%).

Supplemental Figure 3.7d. Spatial distribution of soil physical properties, Cave Spring Vineyards (Home Block), Beamsville, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).

Supplemental Figure 3.8d. Spatial distribution of soil composition (mg/kg soil), Cave Spring Vineyards (Home Block), Beamsville, ON; A: K; B: P; C: Ca; D: Mg.

Supplemental Figure 3.9d. Principal component analysis of viticulture and soil variables for Cave Spring Vineyards (Home Block), Beamsville, ON (a) 2005; (b) 2006; (c) 2007.

Supplemental Figure 3.1e. Spatial distribution of leaf water potential (-bars), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.2e. Spatial distribution of soil moisture (%), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C:2007.

Supplemental Figure 3.3e. Spatial distribution of vine size (kg/vine), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.4e. Spatial distribution of yield (kg/vine), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.5e. Spatial distribution of berry weight (g), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.6e. Spatial distribution of soil texture, Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: sand (%); B: clay (%).

Supplemental Figure 3.7e. Spatial distribution of soil physical properties, Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).

Supplemental Figure 3.8e. Spatial distribution of soil composition (mg/kg soil), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: K; B: P; C: Ca; D: Mg.

Supplemental Figure 3.9e. Principal component analysis of viticulture and soil variables for Flat Rock Cellars (Nadja's Vineyard), Jordan, ON (a) 2005; (b) 2006; (c) 2007.

Supplemental Figure 3.1f. Spatial distribution of leaf water potential (-bars), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.2f. Spatial distribution of soil moisture (%), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.3f. Spatial distribution of vine size (kg/vine), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.4f. Spatial distribution of yield (kg/vine), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.5f. Spatial distribution of berry weight (g), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.6f. Spatial distribution of soil texture, Henry of Pelham, St. Catharines, ON; A: sand (%); B: clay (%).

Supplemental Figure 3.7f. Spatial distribution of soil physical properties, Henry of Pelham, St. Catharines, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).

Supplemental Figure 3.8f. Spatial distribution of soil composition (mg/kg soil), Henry of Pelham, St. Catharines, ON; A: K; B: P; C: Ca; D: Mg.

Supplemental Figure 3.9f. Principal component analysis of viticulture and soil variables for Henry of Pelham, St. Catharines, ON (a) 2005; (b) 2006; (c) 2007.

Supplemental Figure 3.1g. Spatial distribution of leaf water potential (-bars), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.2g. Spatial distribution of soil moisture (%), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.3g. Spatial distribution of vine size (kg/vine), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.4g. Spatial distribution of yield (kg/vine), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.

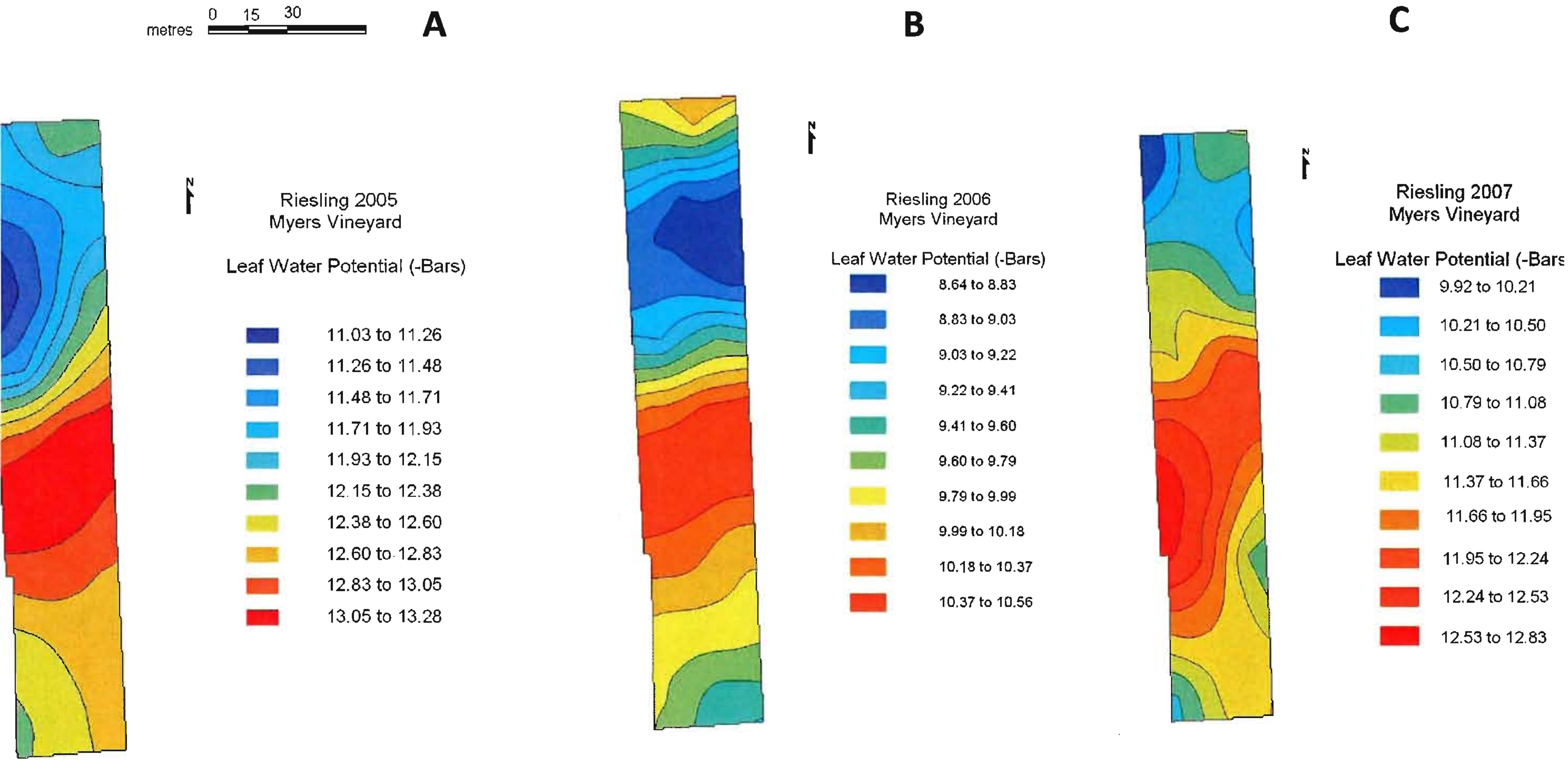
Supplemental Figure 3.5g. Spatial distribution of berry weight (g), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 3.6g. Spatial distribution of soil texture, Paragon Vineyards, Jordan, ON; A: sand (%); B: clay (%).

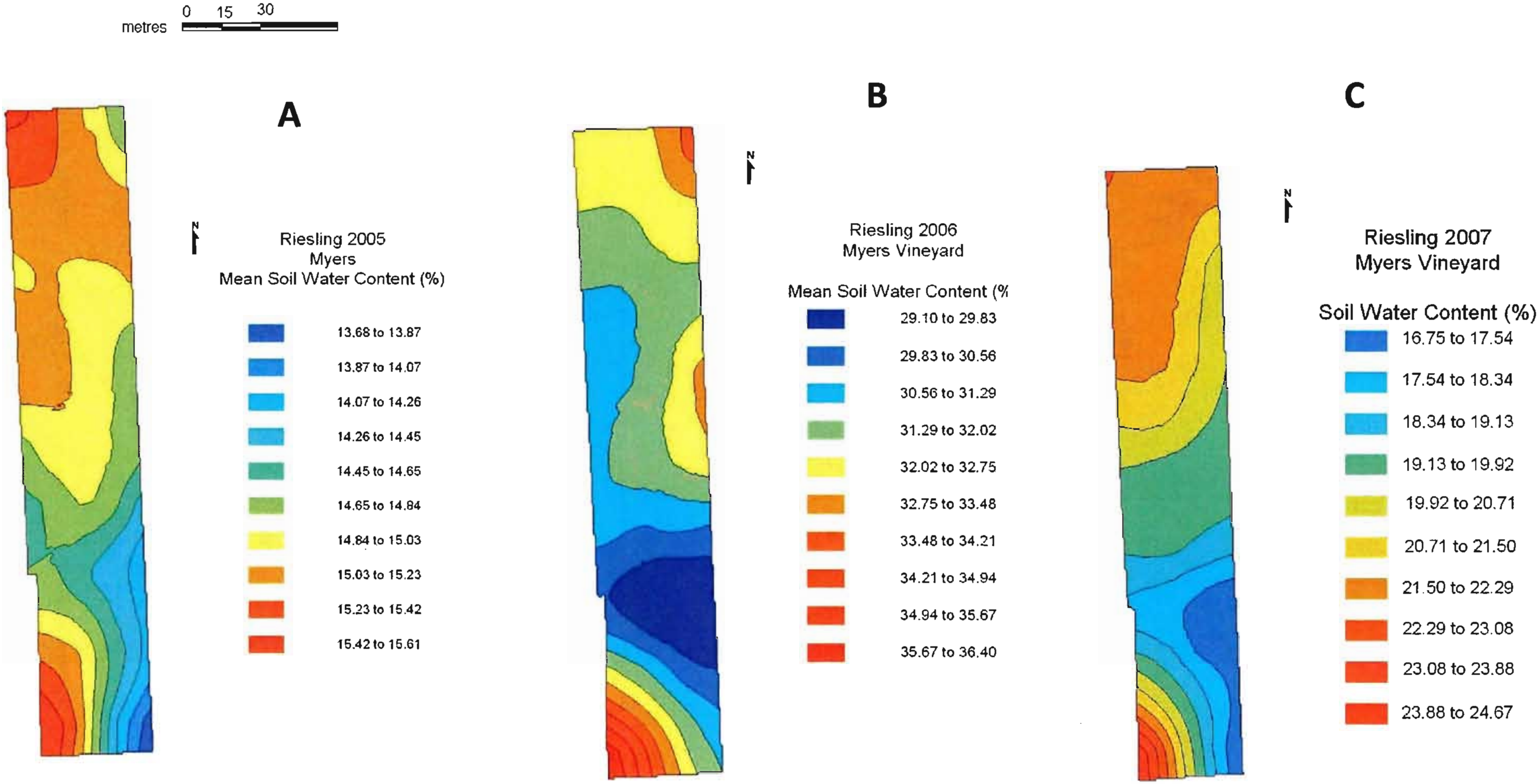
Supplemental Figure 3.7g. Spatial distribution of soil physical properties, Paragon Vineyards, Jordan, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).

Supplemental Figure 3.8g. Spatial distribution of soil composition (mg/kg soil), Paragon Vineyards, Jordan, ON; A: K; B: P; C: Ca; D: Mg.

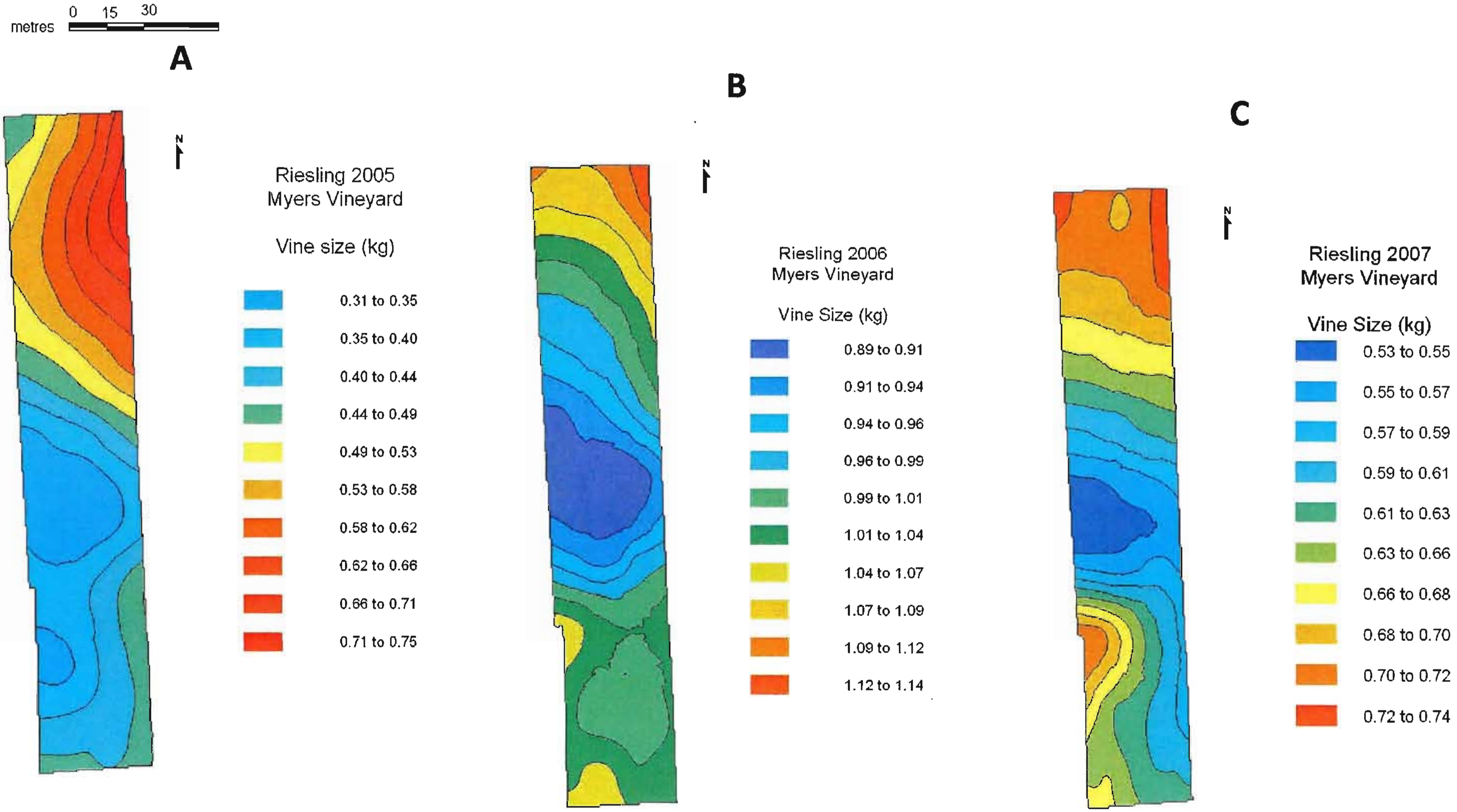
Supplemental Figure 3.9g. Principal component analysis of viticulture and soil variables for Paragon Vineyards, Jordan, ON (a) 2005; (b) 2006; (c).



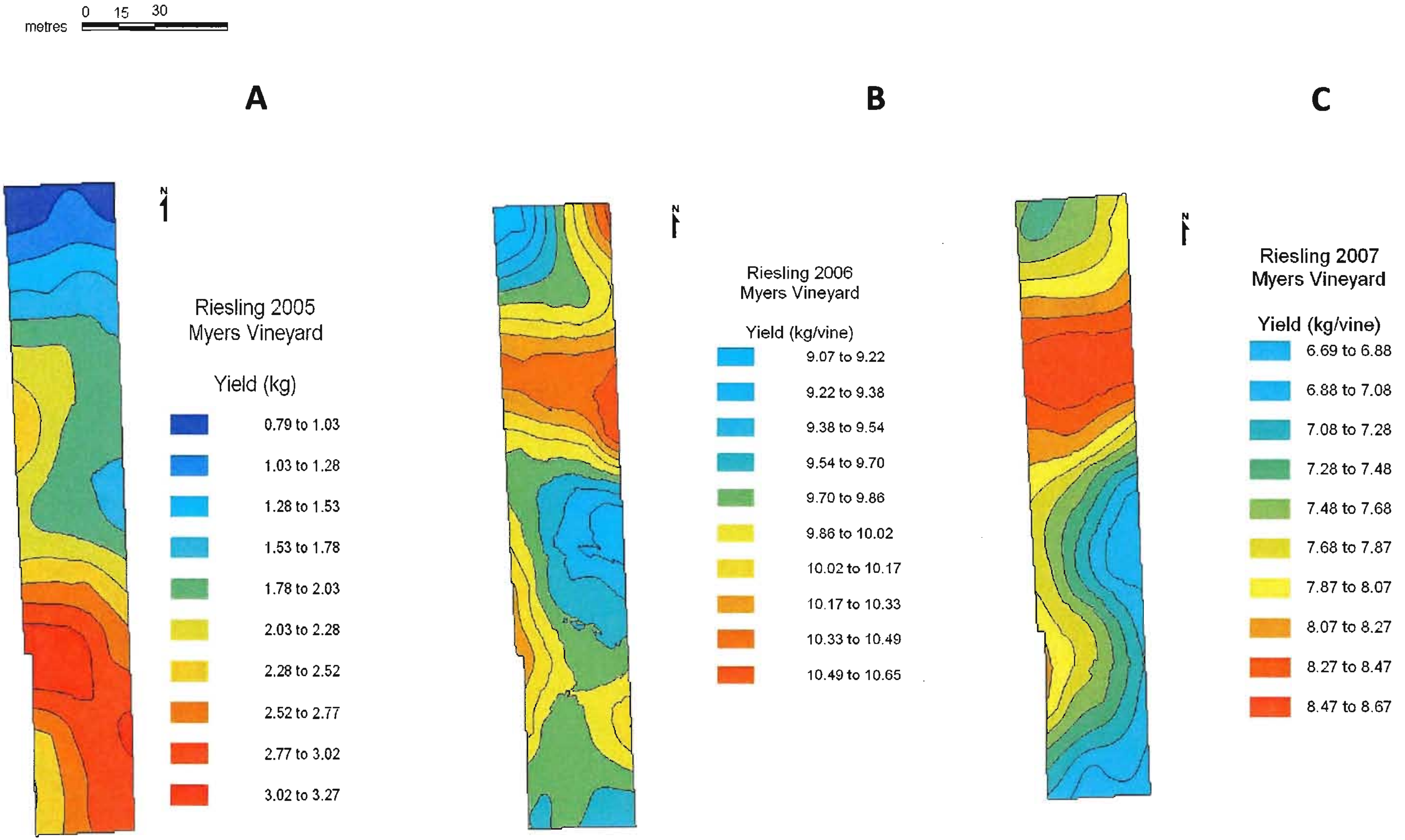
Supplemental Figure 3.1a. Spatial distribution of leaf water potential (-bars), Myers Vineyard, Vineland,ON; A: 2005; B: 2006; C: 2007.



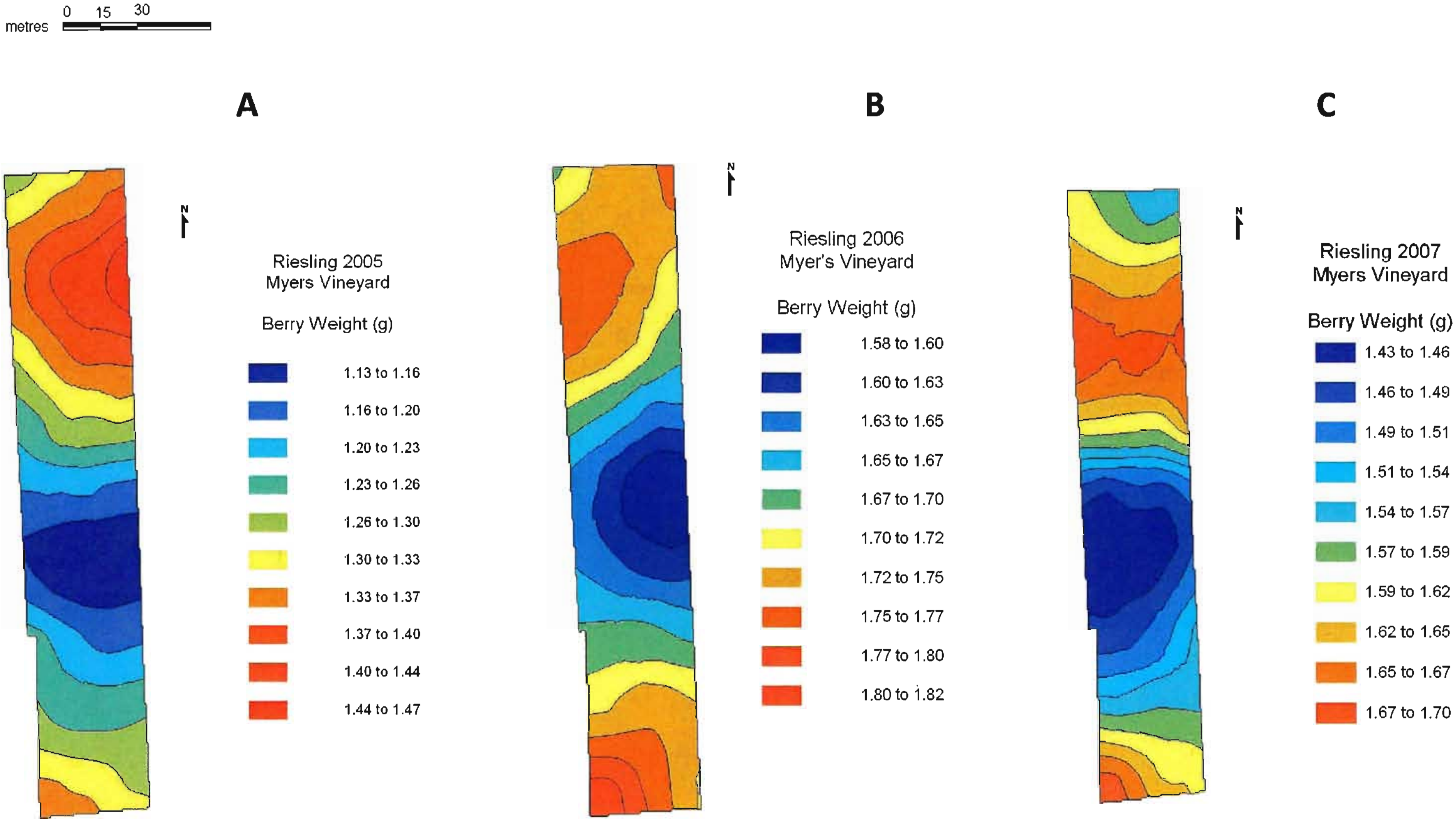
Supplemental Figure 3.2a. Spatial distribution of soil moisture (%), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C:2007.



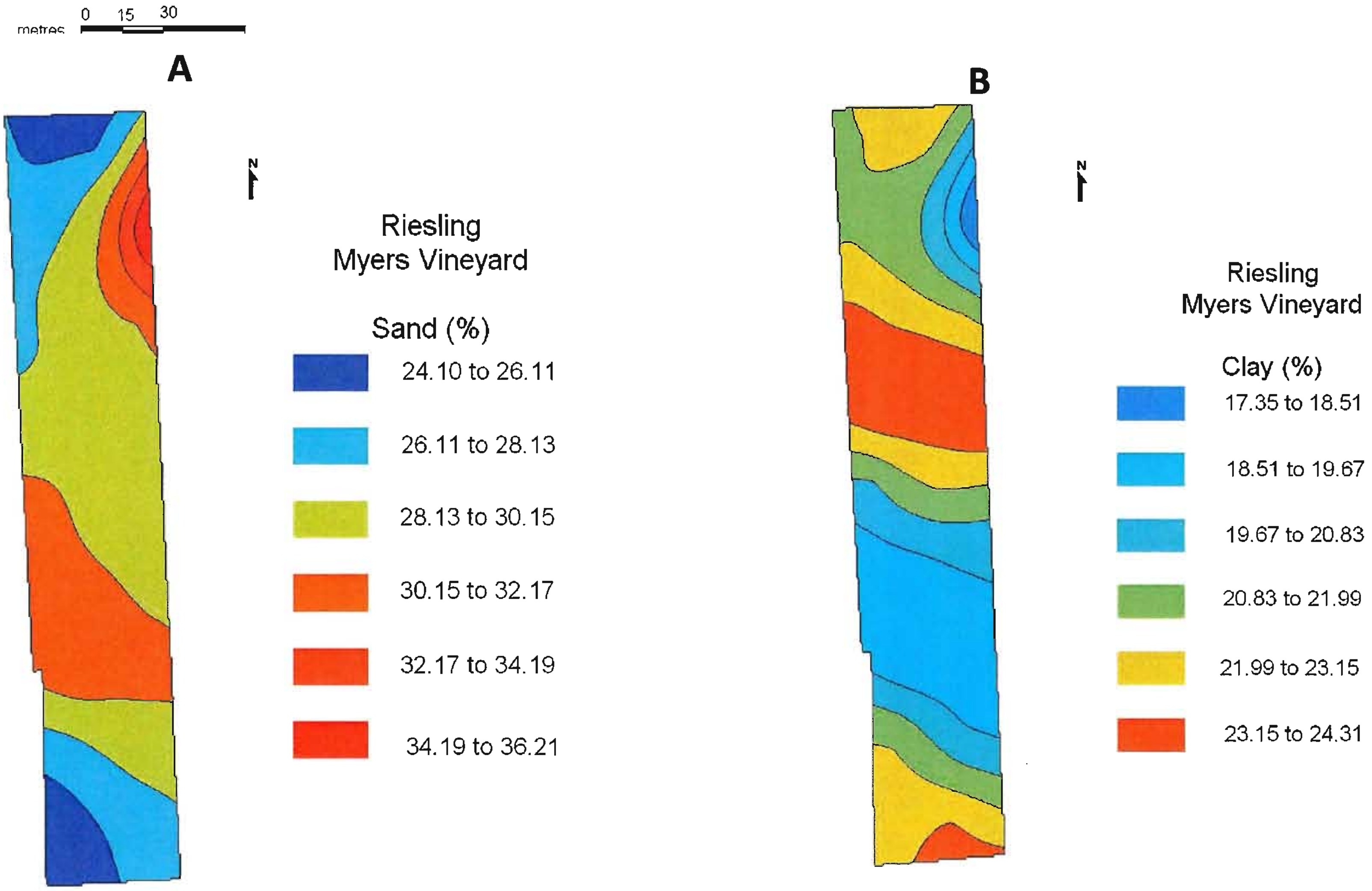
Supplemental Figure 3.3a. Spatial distribution of vine size (kg/vine), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C: 2007.



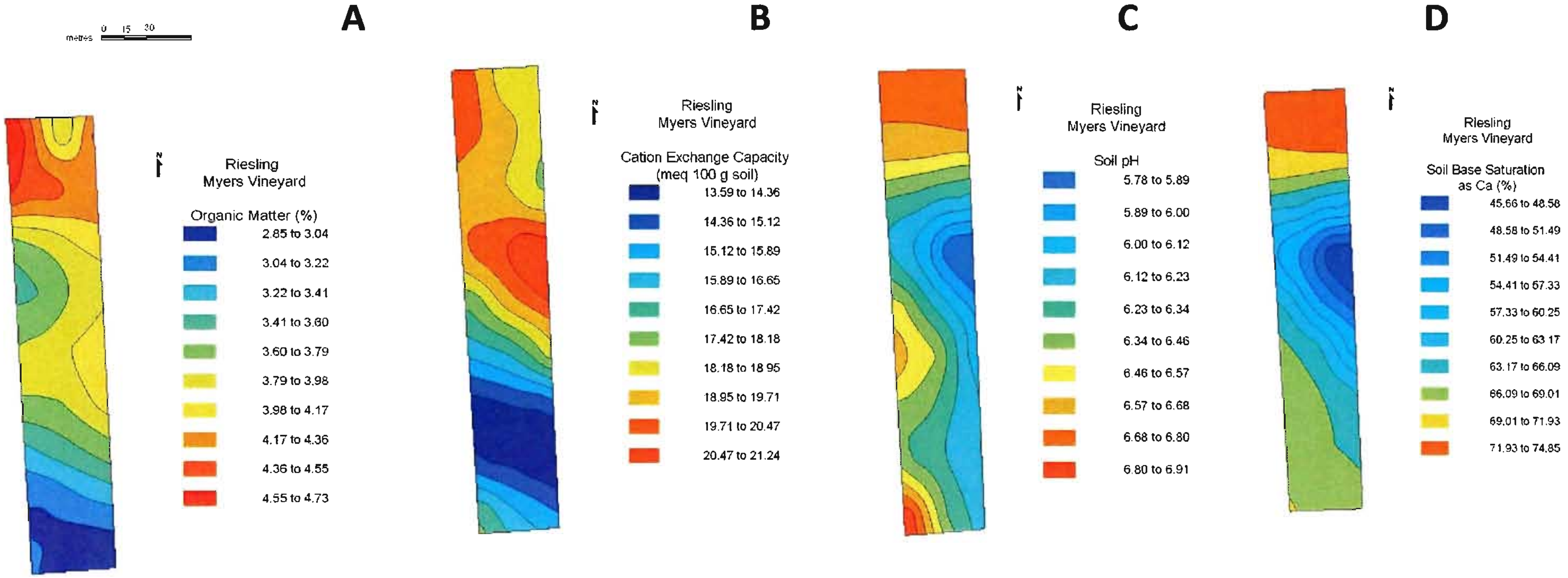
Supplemental Figure 3.4a. Spatial distribution of yield (kg/vine), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C:2007.



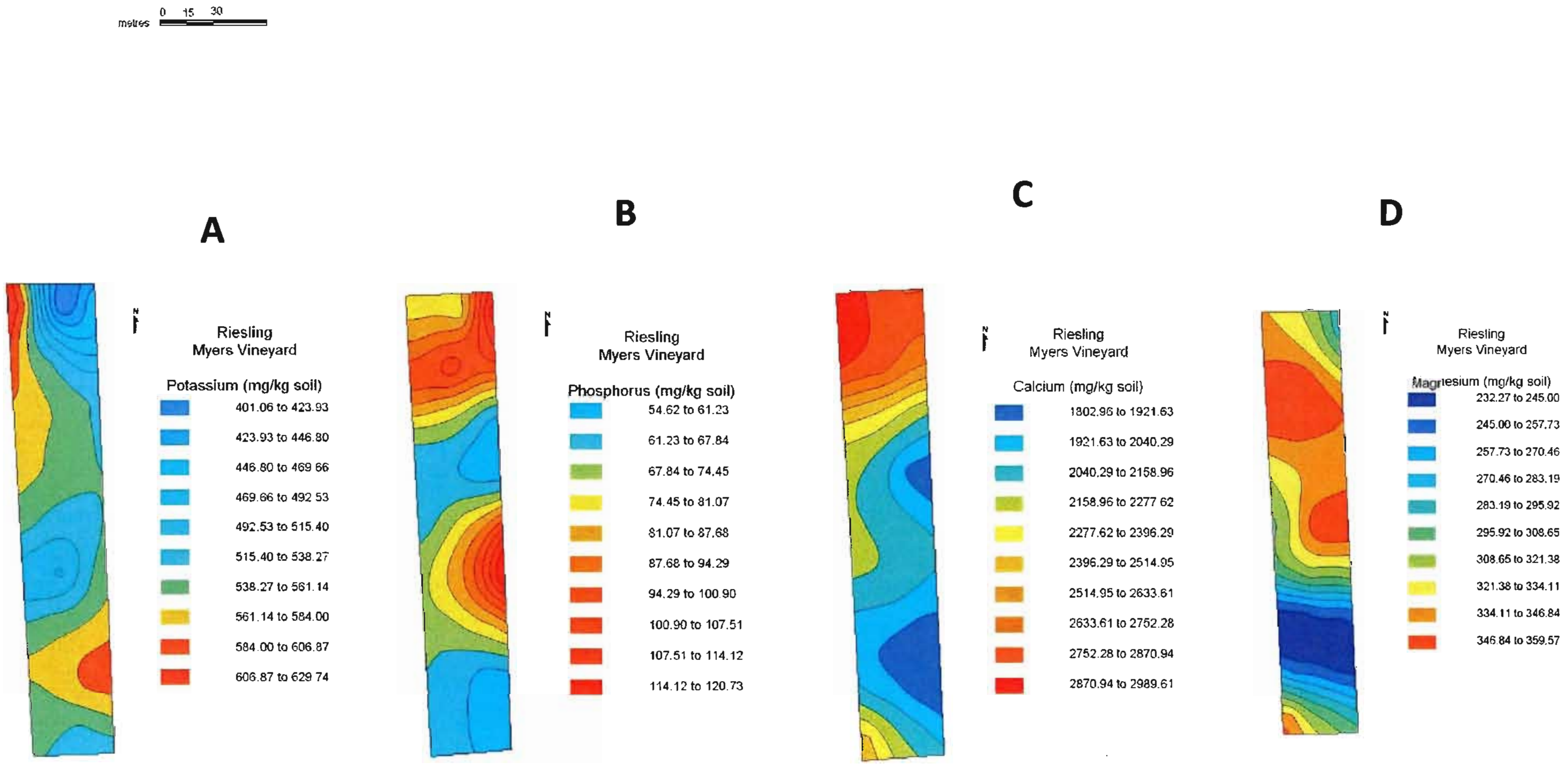
Supplemental Figure 3.5a. Spatial distribution of berry weight (g), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C: 2007.



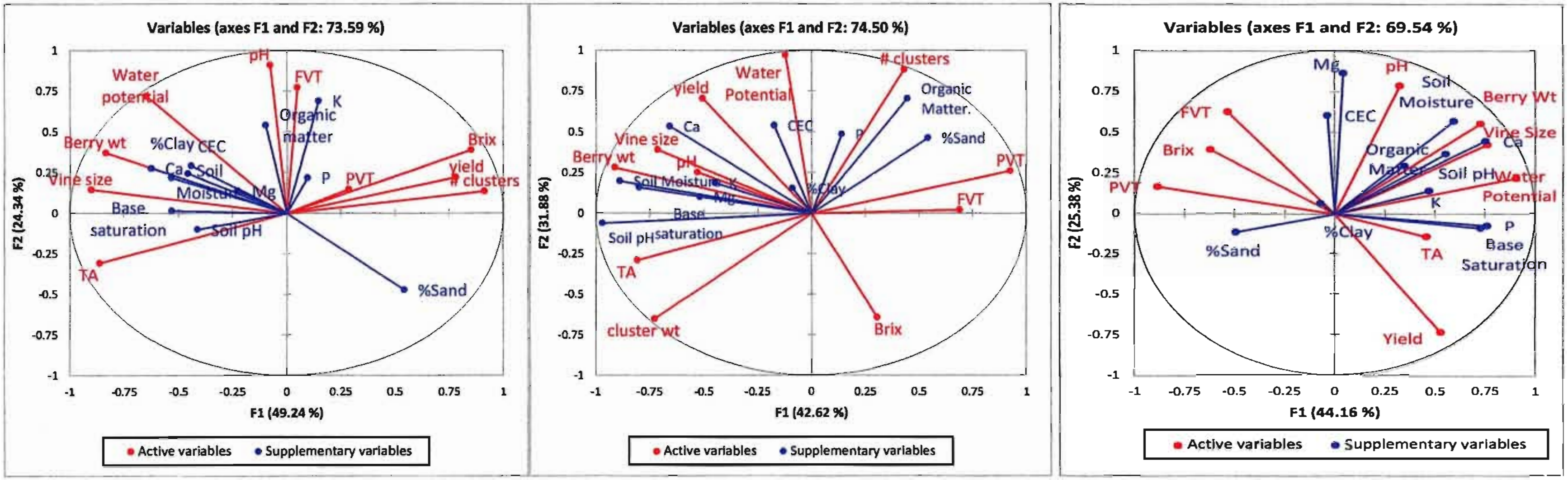
Supplemental Figure 3.6a. Spatial distribution of soil texture, Myers Vineyard, Vineland, ON; A: sand (%); B: clay (%).



Supplemental Figure 3.7a. Spatial distribution of soil physical properties, Myers Vineyard, Vineland, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).

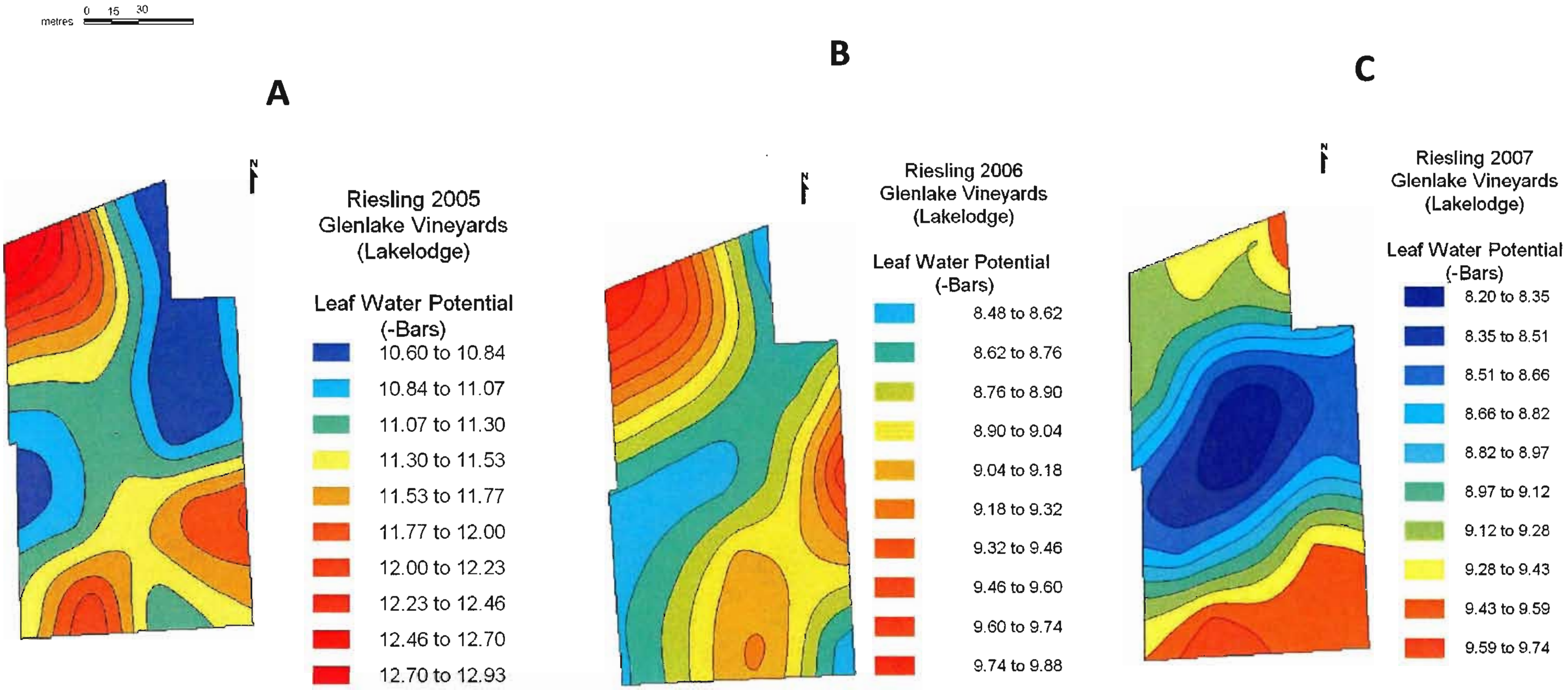


Supplemental Figure 3.8a. Spatial distribution of soil composition (mg/kg soil), Myers Vineyard, Vineland, ON; A: K; B: P; C: Ca; D: Mg

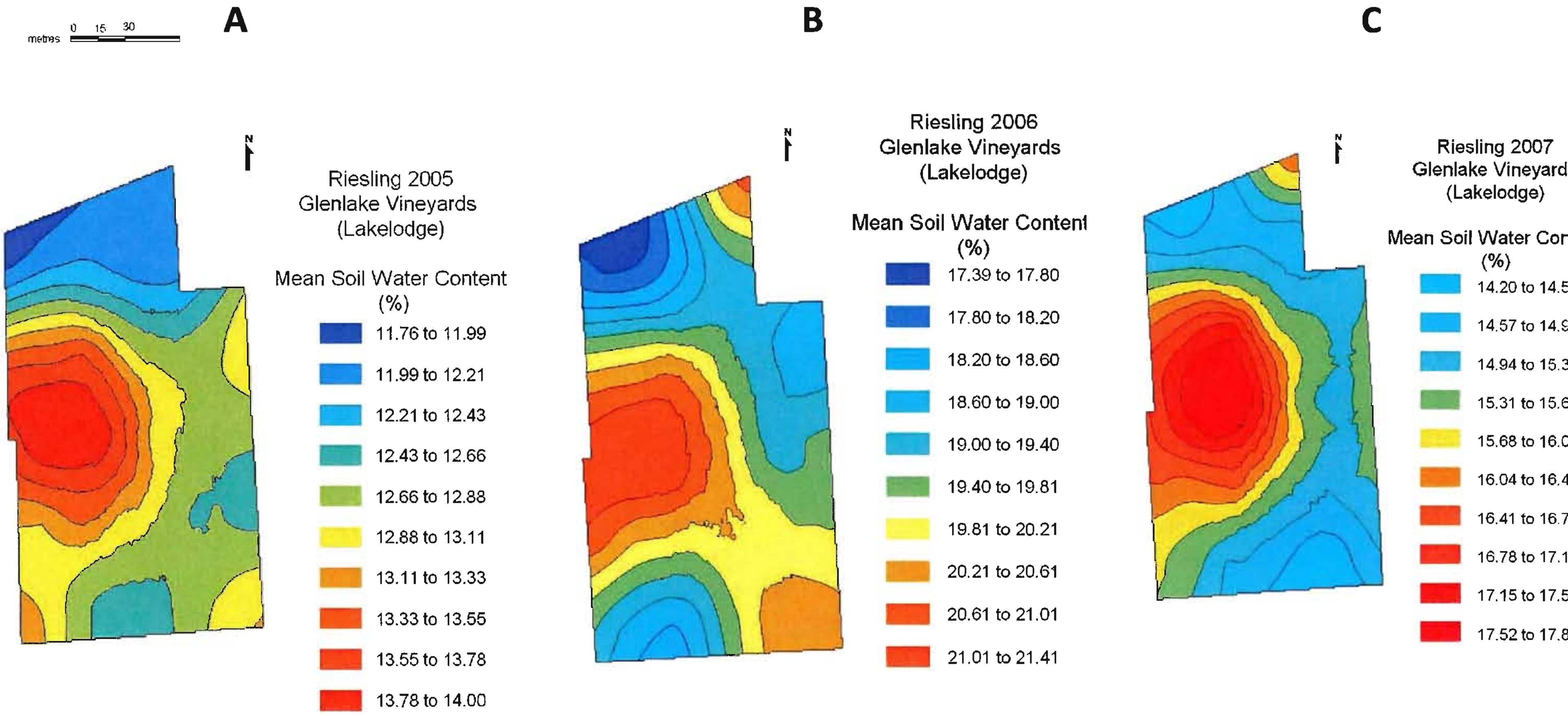


2005 2006 2007

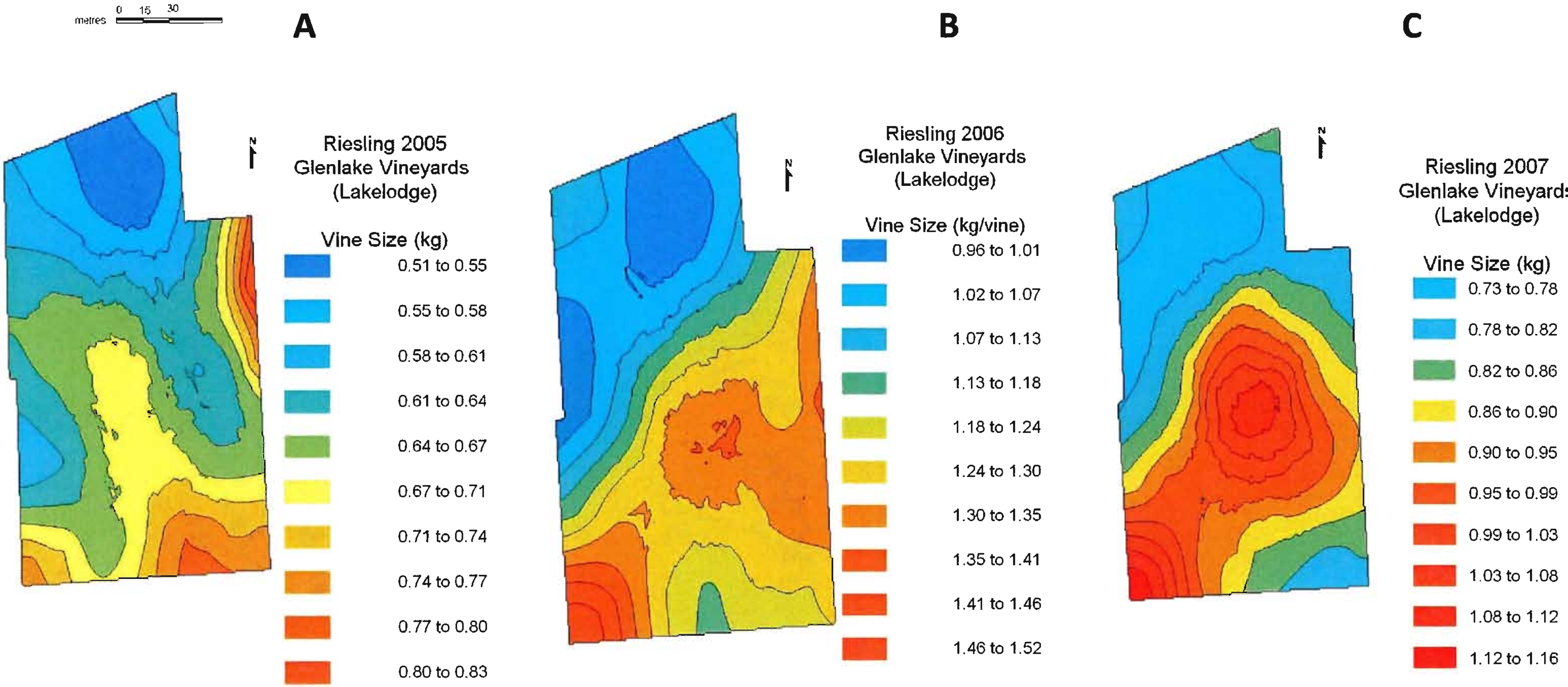
Supplemental Figure 3.9a. Principal component analysis of viticulture and soil variables for Myers Vineyard, 2005; 2006; 2007. *Supplementary variables in blue are soil variables.*



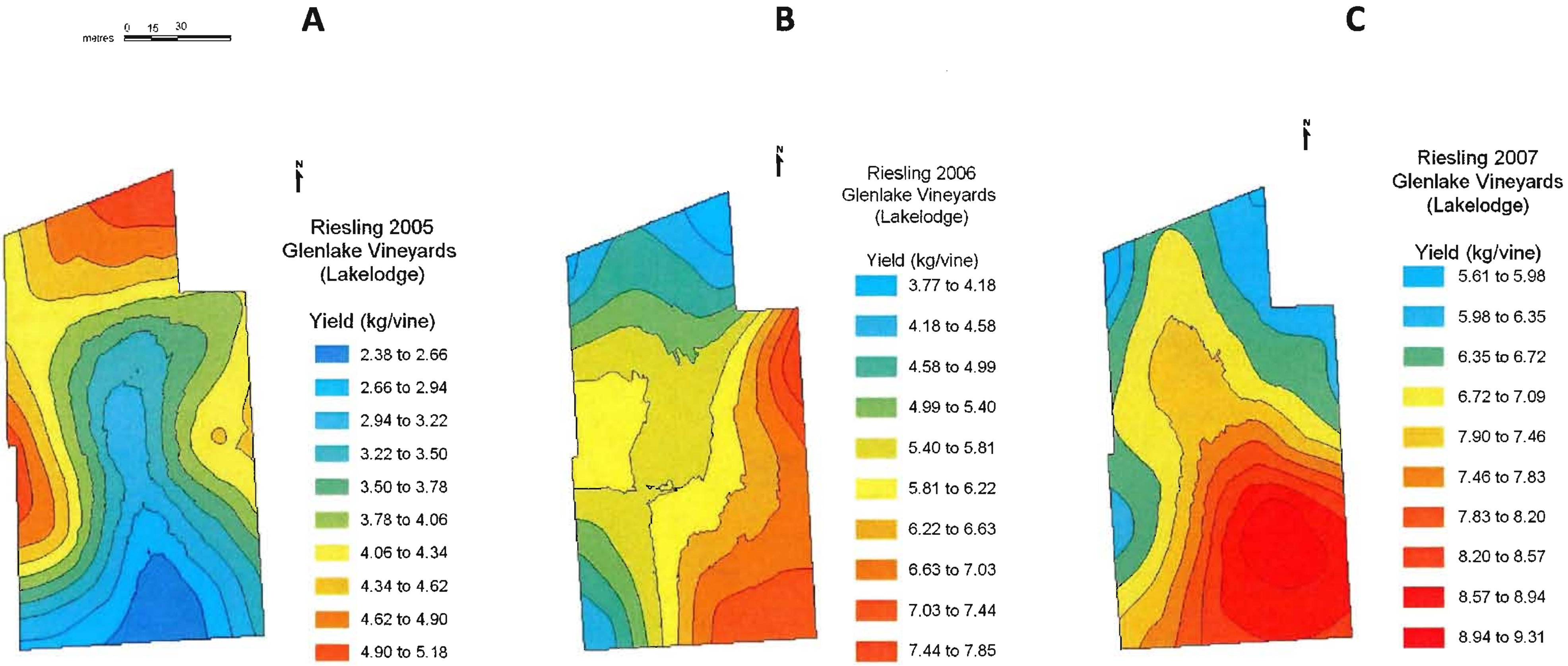
Supplemental Figure 3.1b. Spatial distribution of leaf water potential (-bars), Glenlake Vineyards (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.



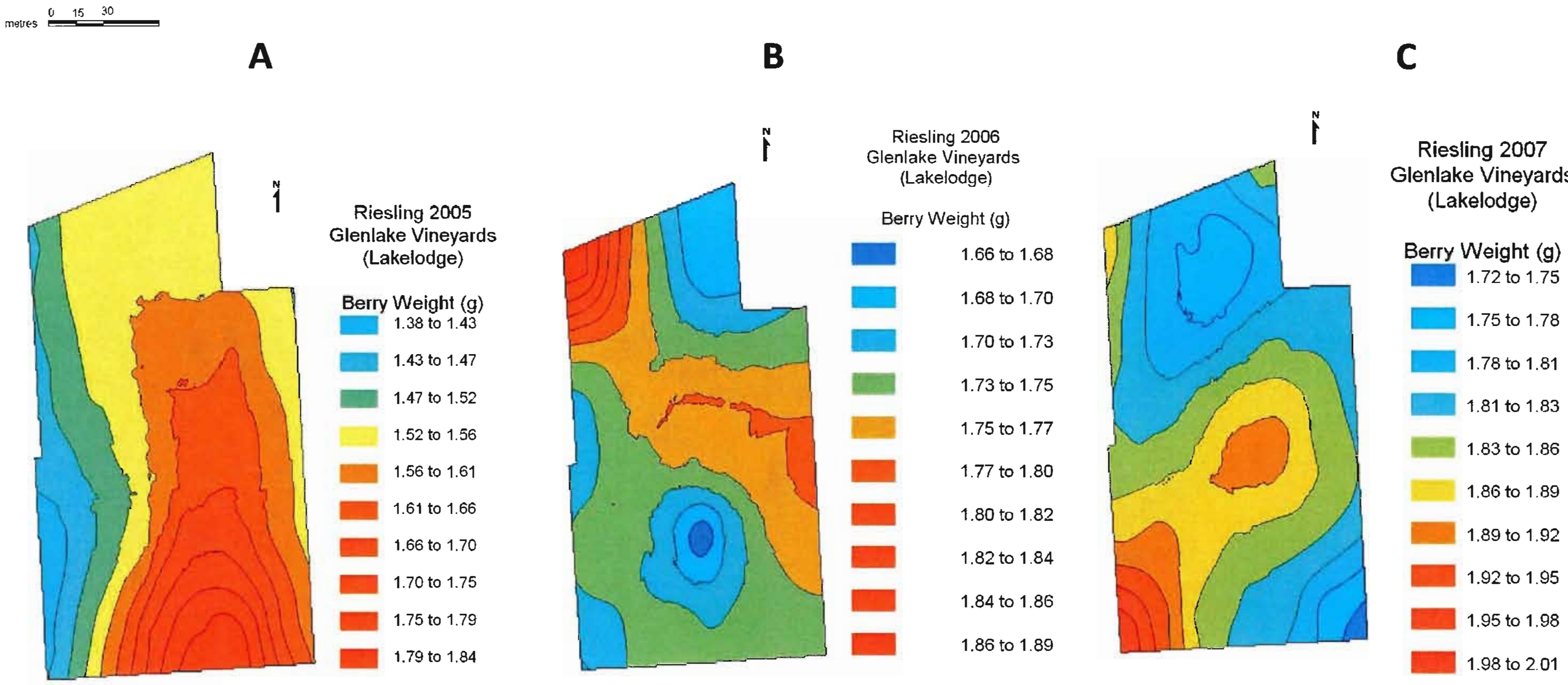
Supplemental Figure 3.2b. Spatial distribution of soil moisture (%), Glenlake Vineyards (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.



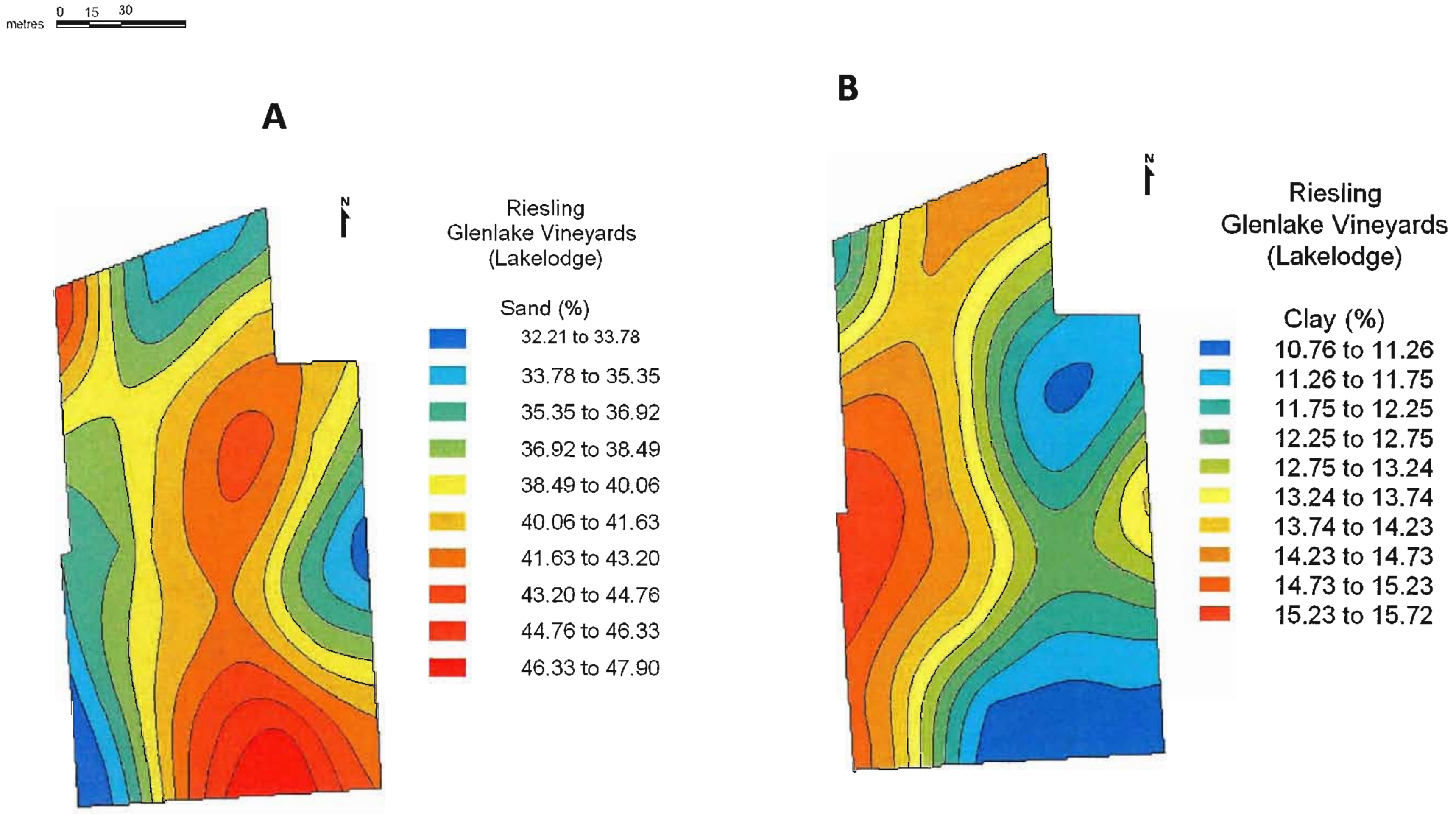
Supplemental Figure 3.3b. Spatial distribution of vine size (kg/vine), Glenlake Vineyards (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.



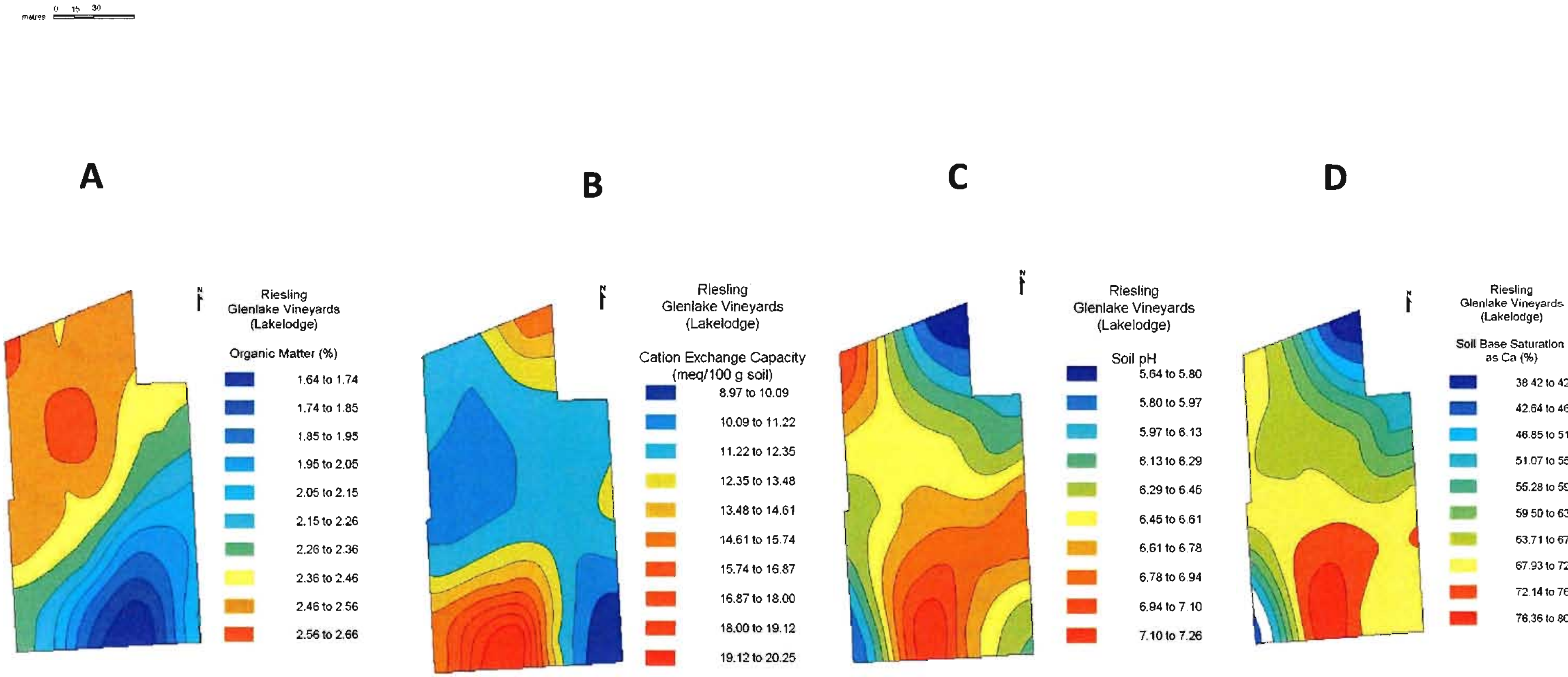
Supplemental Figure 3.4b. Spatial distribution of yield (kg/vine), Glenlake Vineyards (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.



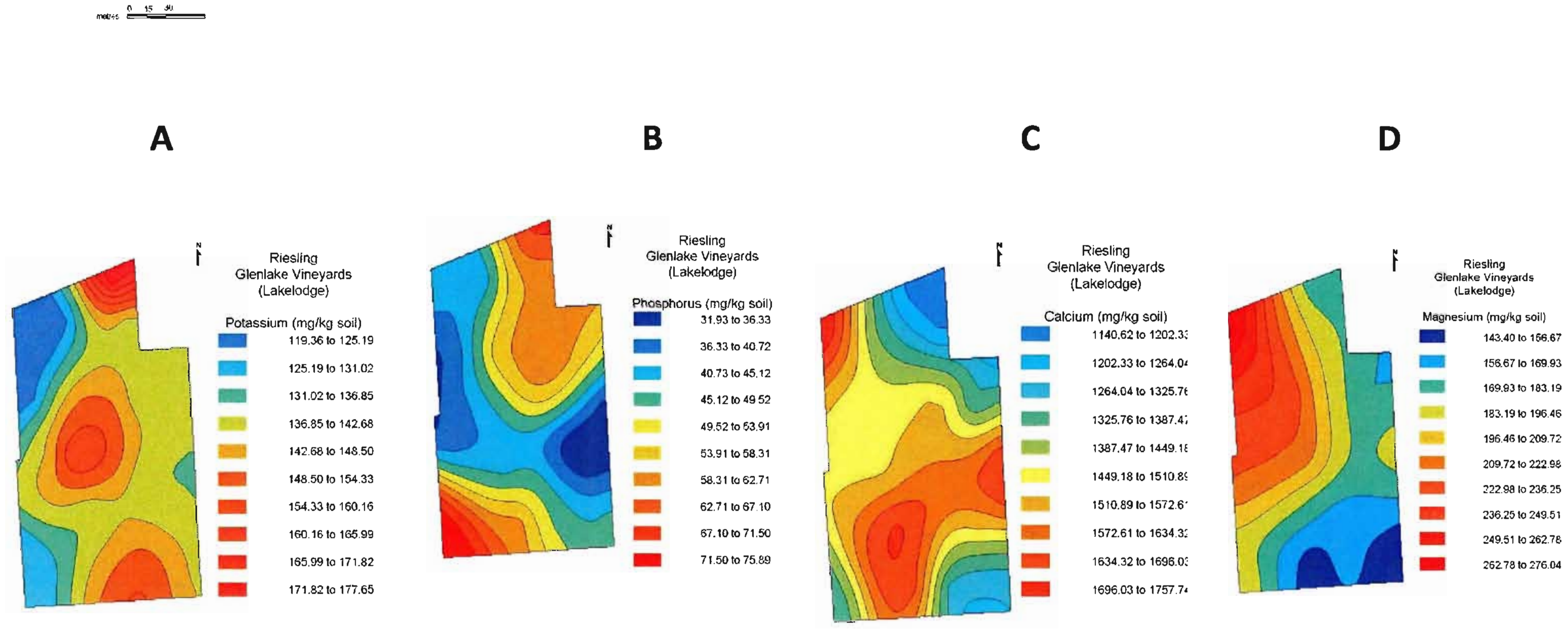
Supplemental Figure 3.5b. Spatial distribution of berry weight (g), Glenlake Vineyards (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.



Supplemental Figure 3.6b. Spatial distribution of soil texture, Glenlake Vineyards (Lakelodge), Niagara-on-the-lake, ON; A: sand (%); B: clay (%).

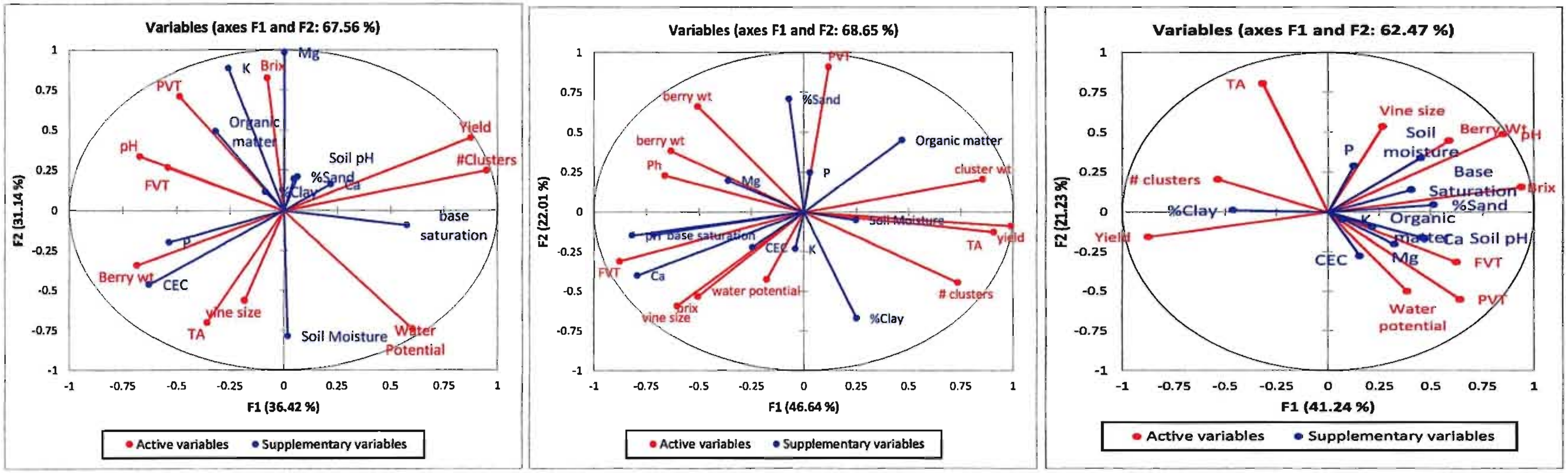


Supplemental Figure 3.7b. Spatial distribution of soil physical properties, Glenlake Vineyards (Lakelodge), Niagara-on-the-lake, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).

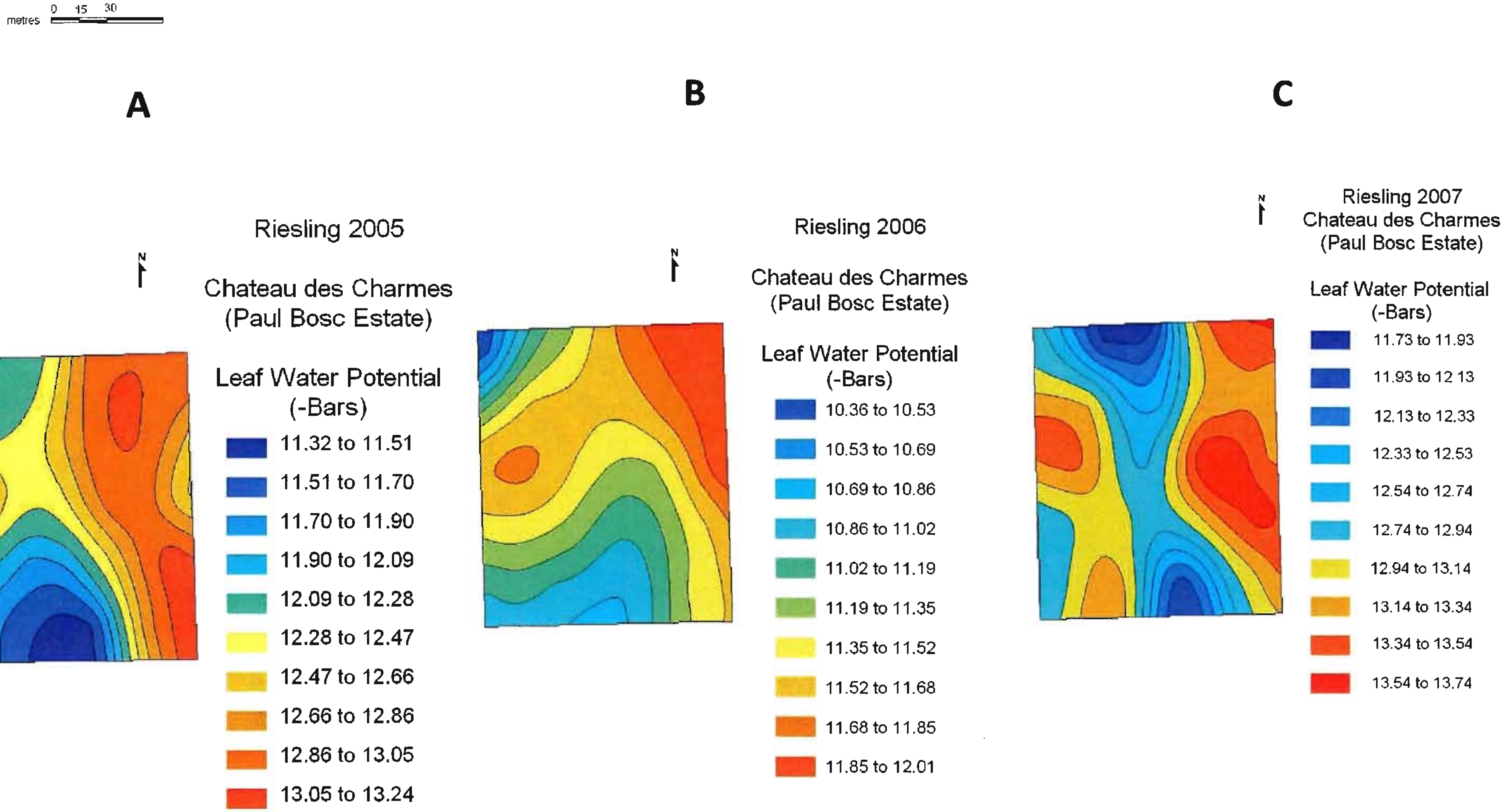


Supplemental Figure 3.8b. Spatial distribution of soil composition (mg/kg soil), Glenlake Vineyards (Lakelodge), Niagara-on-the-lake, ON; A: K; B: P; C: Ca; D: Mg

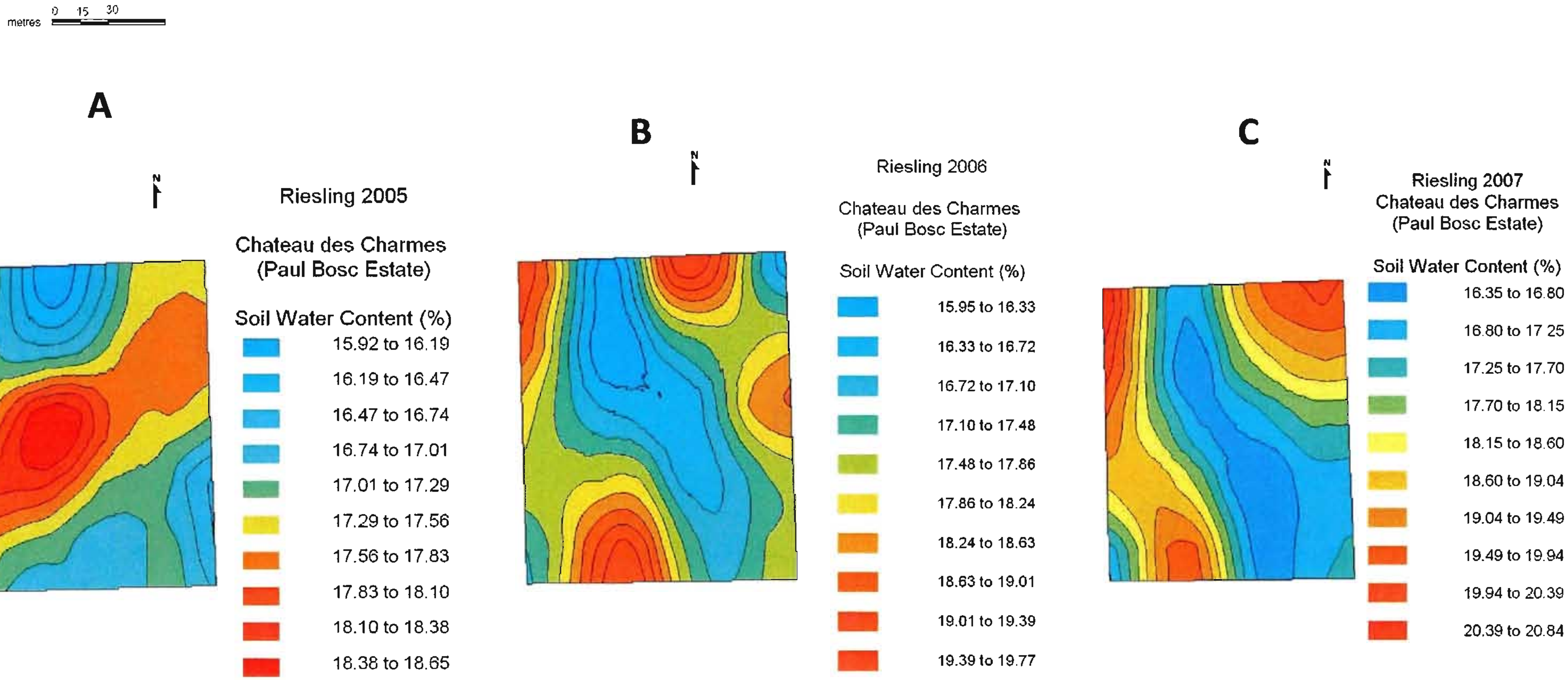
2005 2006 2007



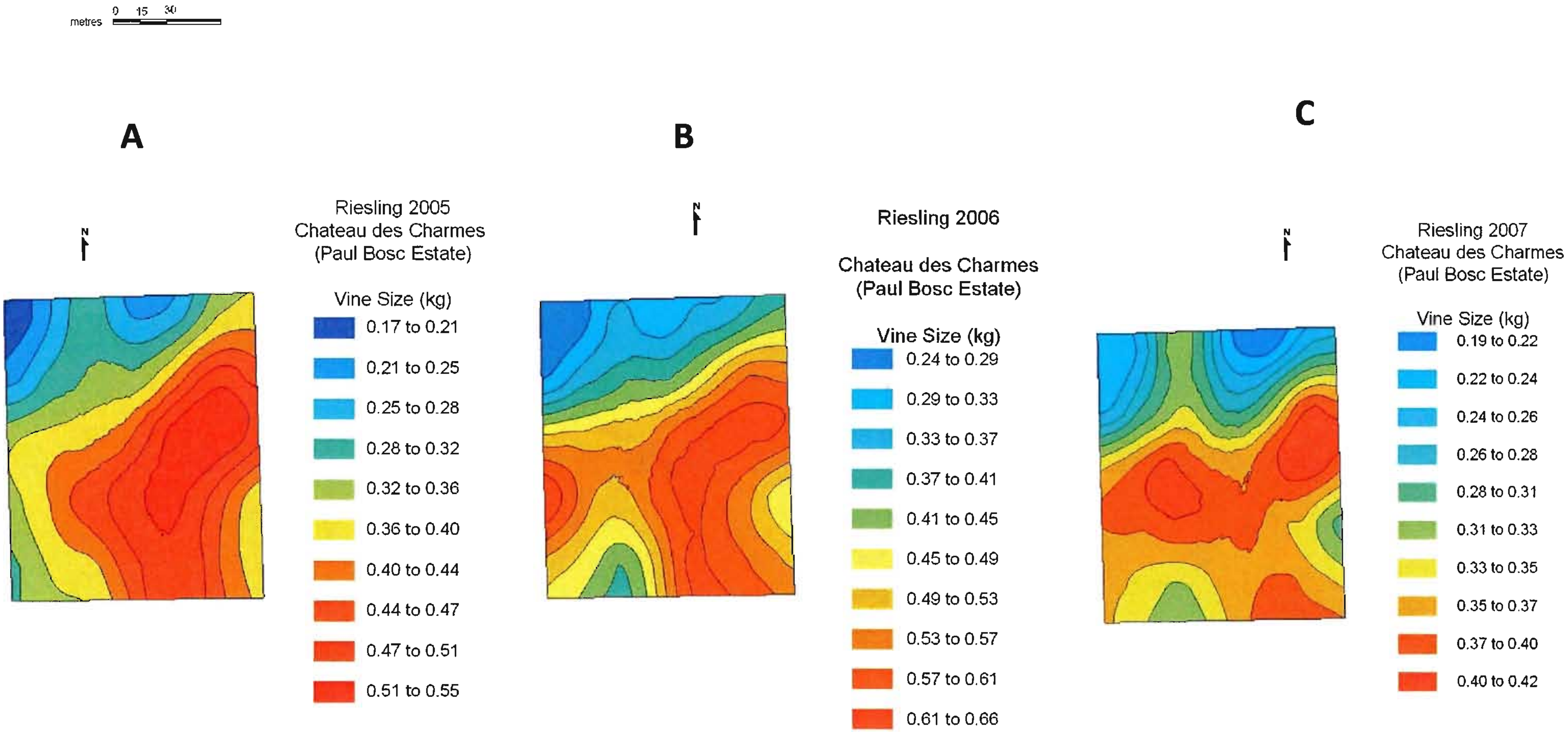
Supplemental Figure 3.9b. Principal component analysis of viticulture and soil variables for Glenlake Vineyards (Lakelodge), 2005-2007. *Supplementary variables in blue are soil variables.*



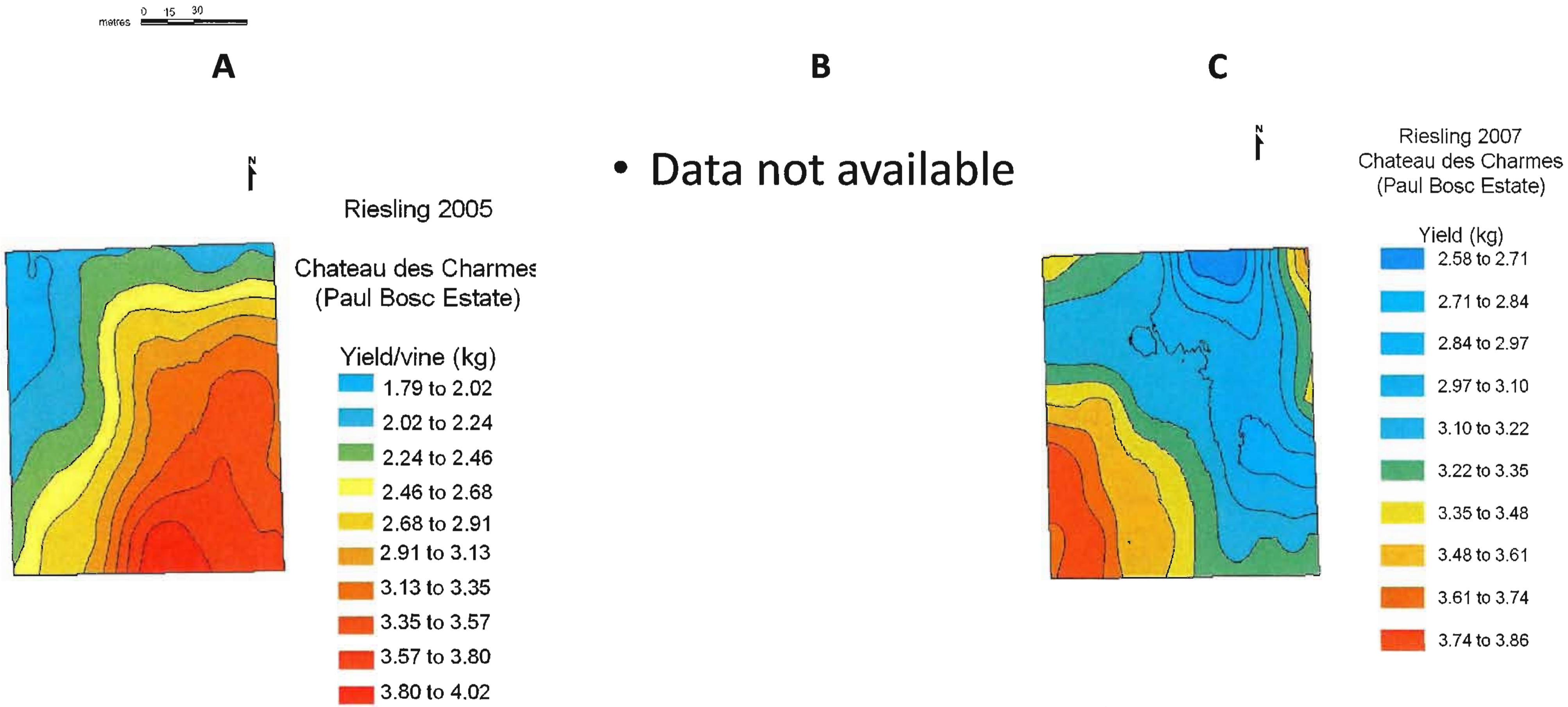
Supplemental Figure 3.1c. Spatial distribution of leaf water potential (-bars), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-Lake, ON; A: 2005; B: 2006; C: 2007.



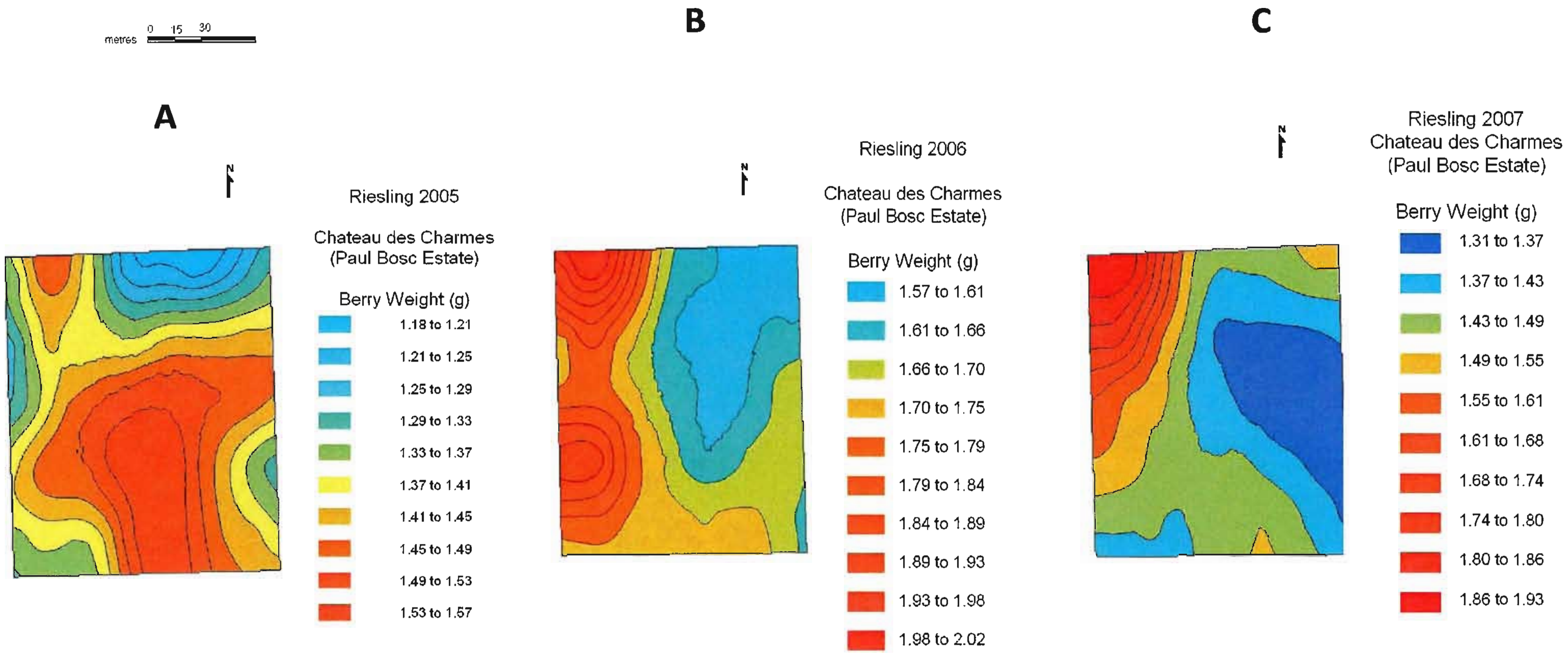
Supplemental Figure 3.2c. Spatial distribution of soil moisture (%), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-Lake, ON; A: 2005; B: 2006; C: 2007.



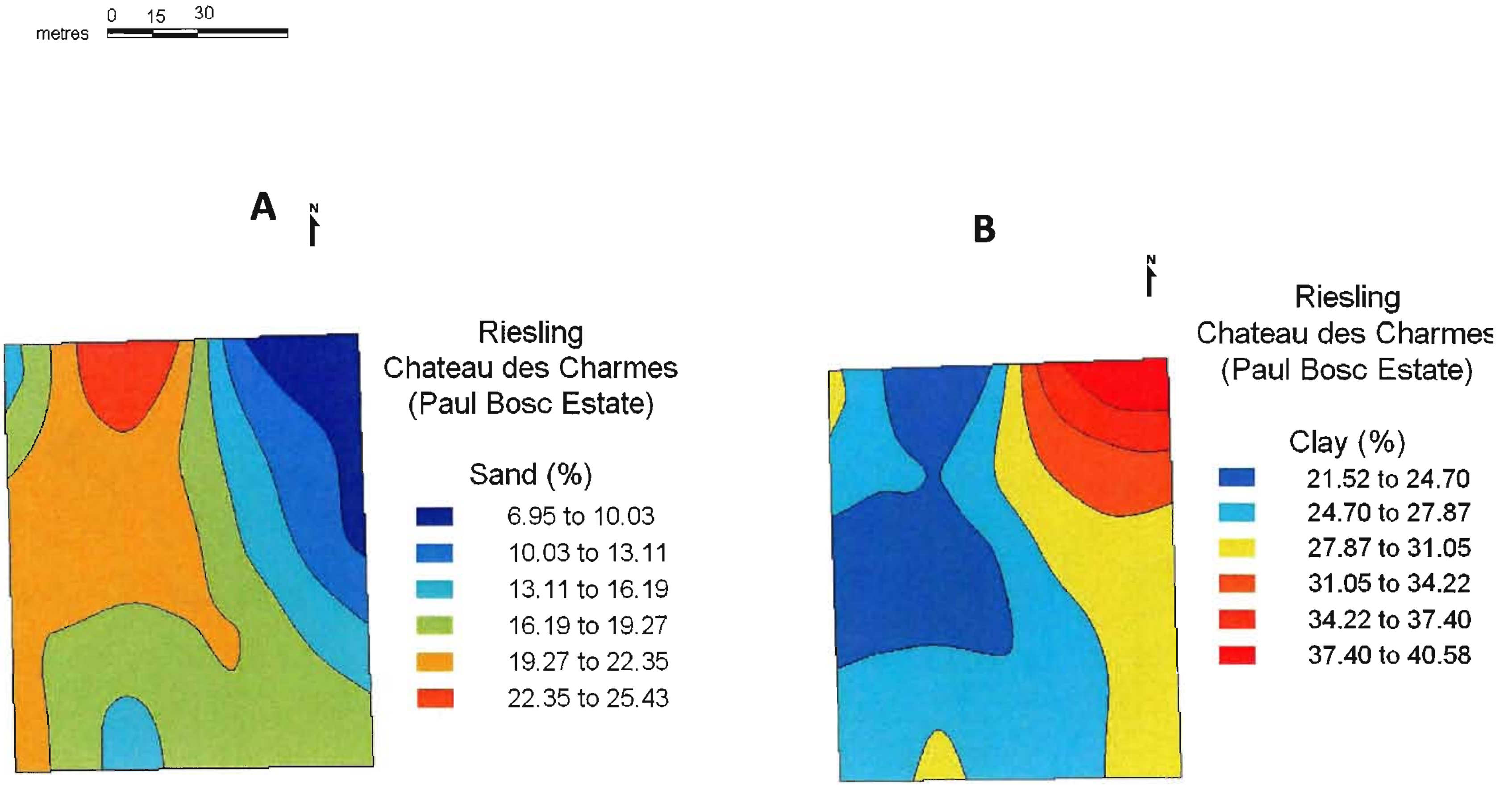
Supplemental Figure 3.3c. Spatial distribution of vine size (kg/vine), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-Lake, ON; A: 2005; B: 2006; C: 2007.



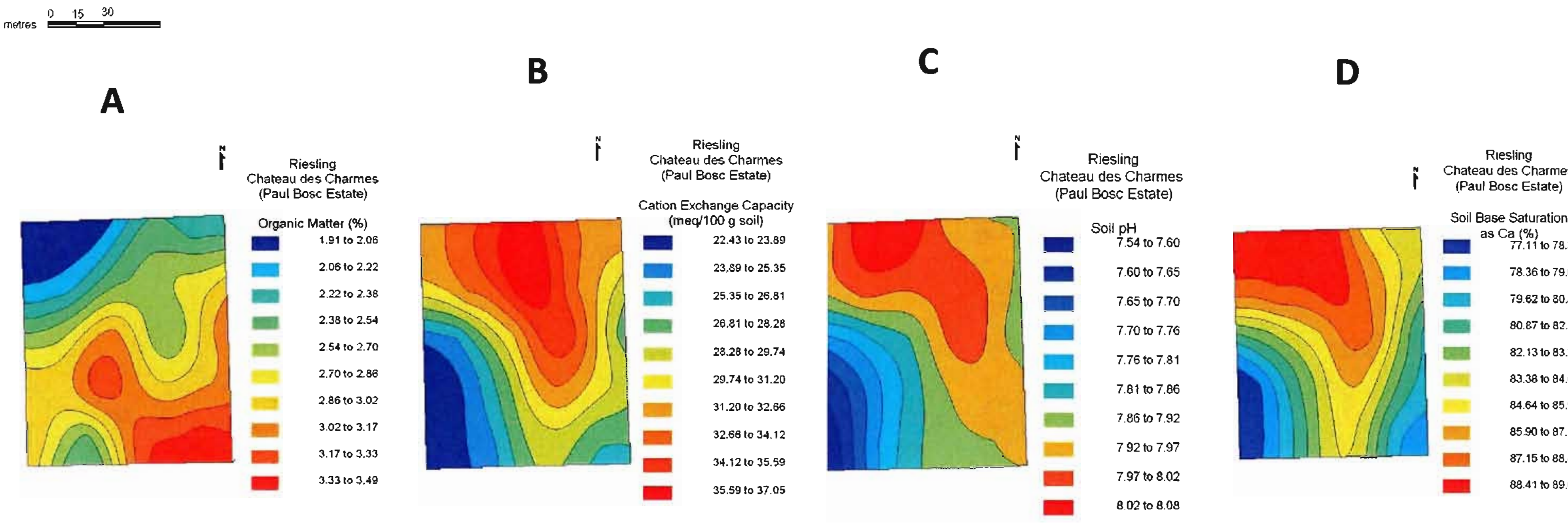
Supplemental Figure 3.4c. Spatial distribution of yield (kg/vine), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-Lake, ON; A: 2005; B: 2006; C: 2007.



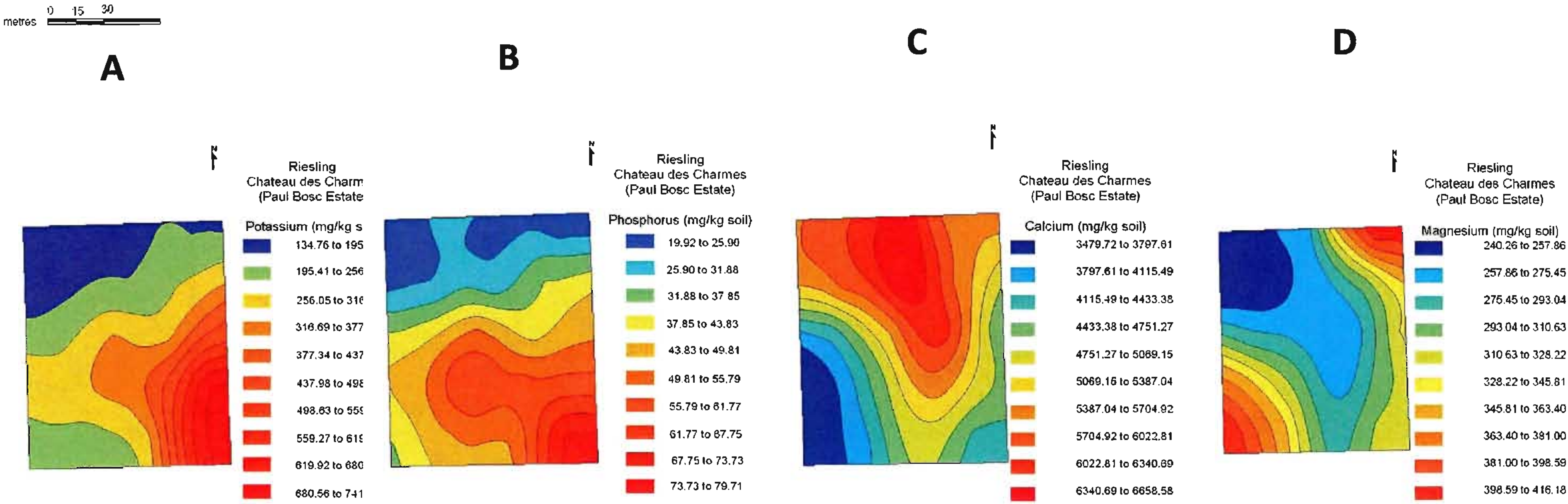
Supplemental Figure 3.5c. Spatial distribution of berry weight (g), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-Lake, ON; A: 2005; B: 2006; C: 2007.



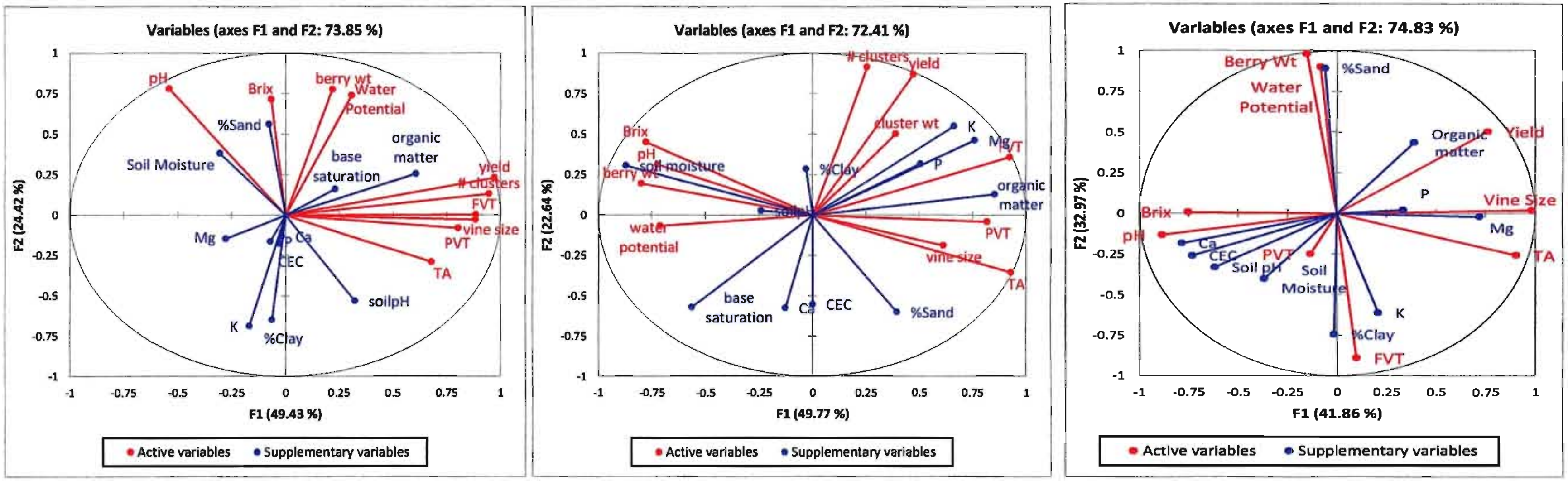
Supplemental Figure 3.6c. Spatial distribution of soil texture, Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-Lake, ON; A: sand (%); B: clay (%).



Supplemental Figure 3.7c. Spatial distribution of soil physical properties, Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).



Supplemental Figure 3.8c. Spatial distribution of soil composition Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: K; B: P; C: Ca; D: Mg

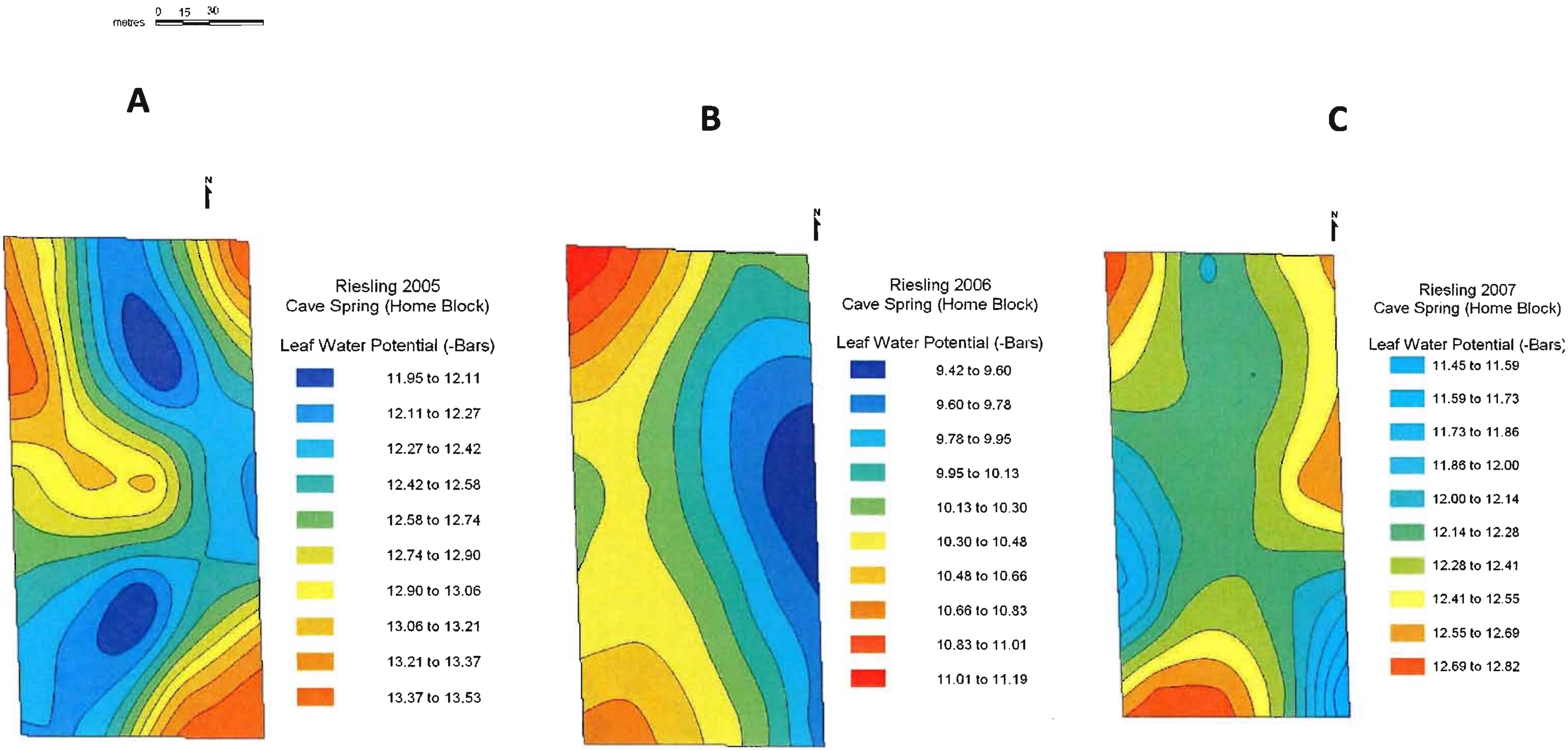


2005

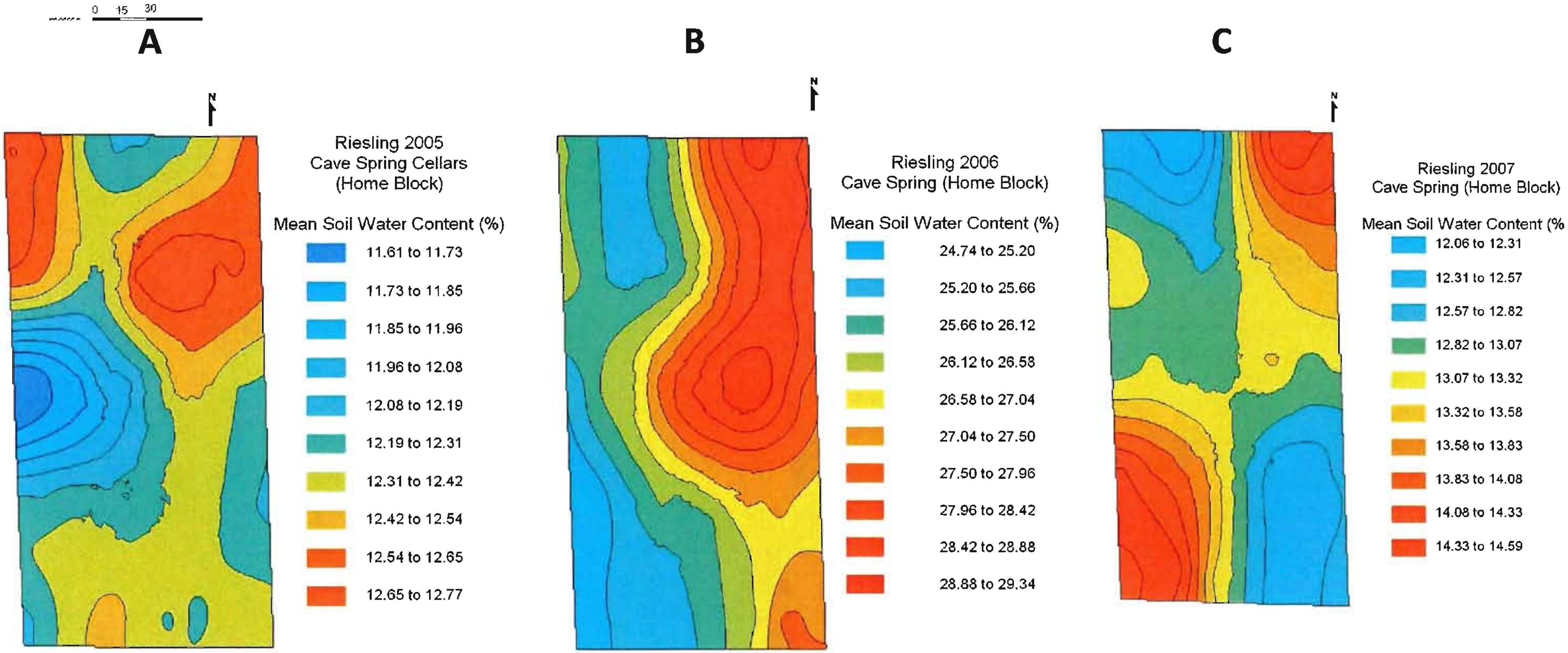
2006

2007

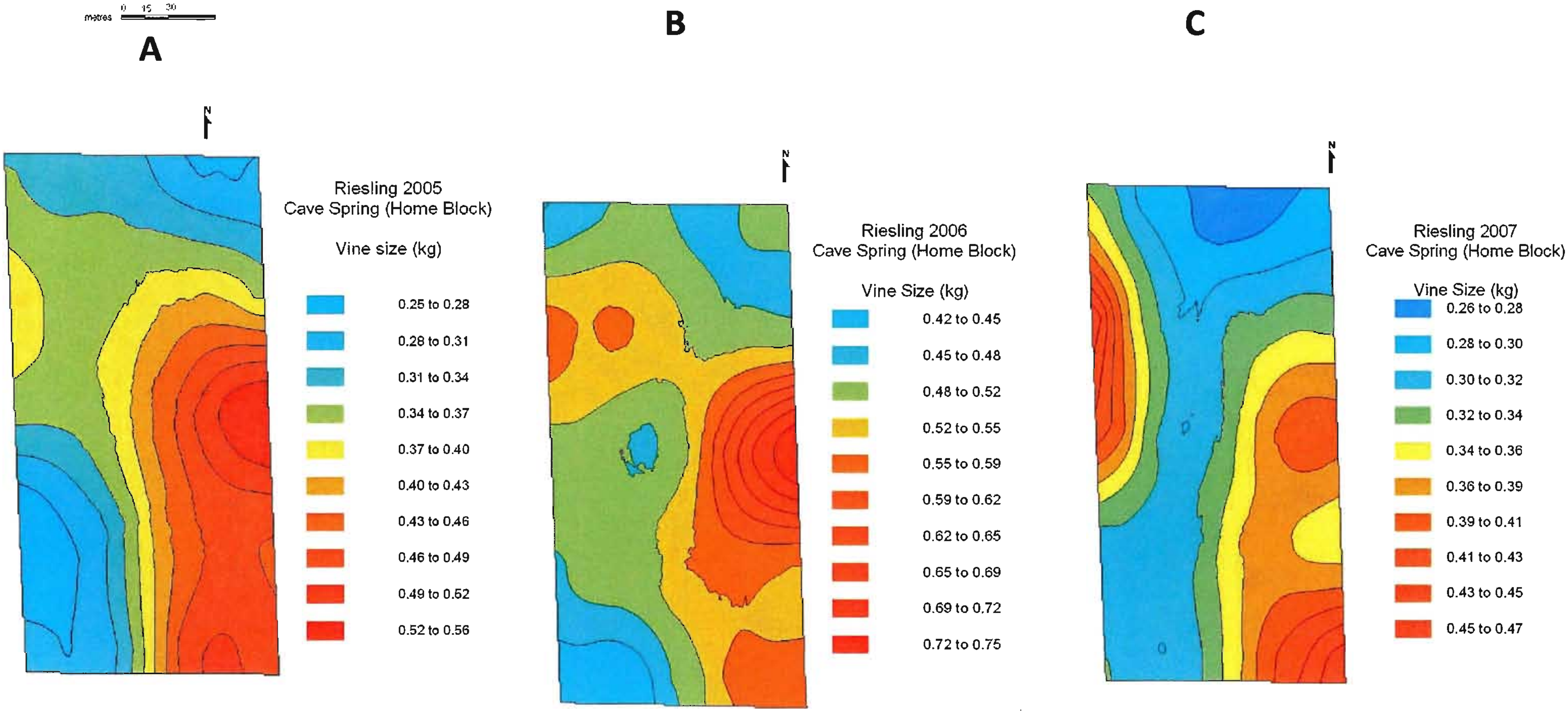
Supplemental Figure 3.9c. Principal component analysis of viticulture and soil variables for Chateau des Charmes (Paul Bosc Estate), 2005-2007. *Supplementary variables in blue are soil variables.*



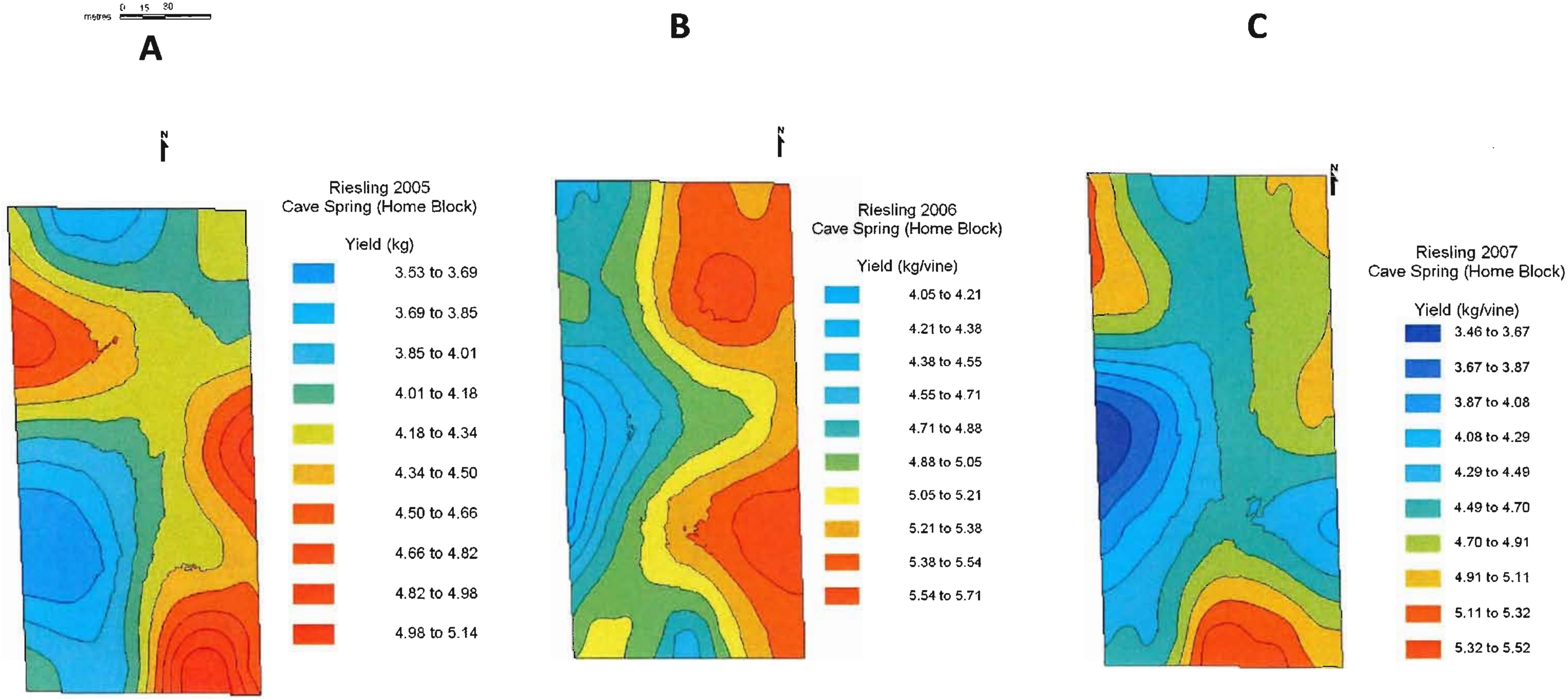
Supplemental Figure 3.1d. Spatial distribution of leaf water potential (-bars), Cave Spring Cellars (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.



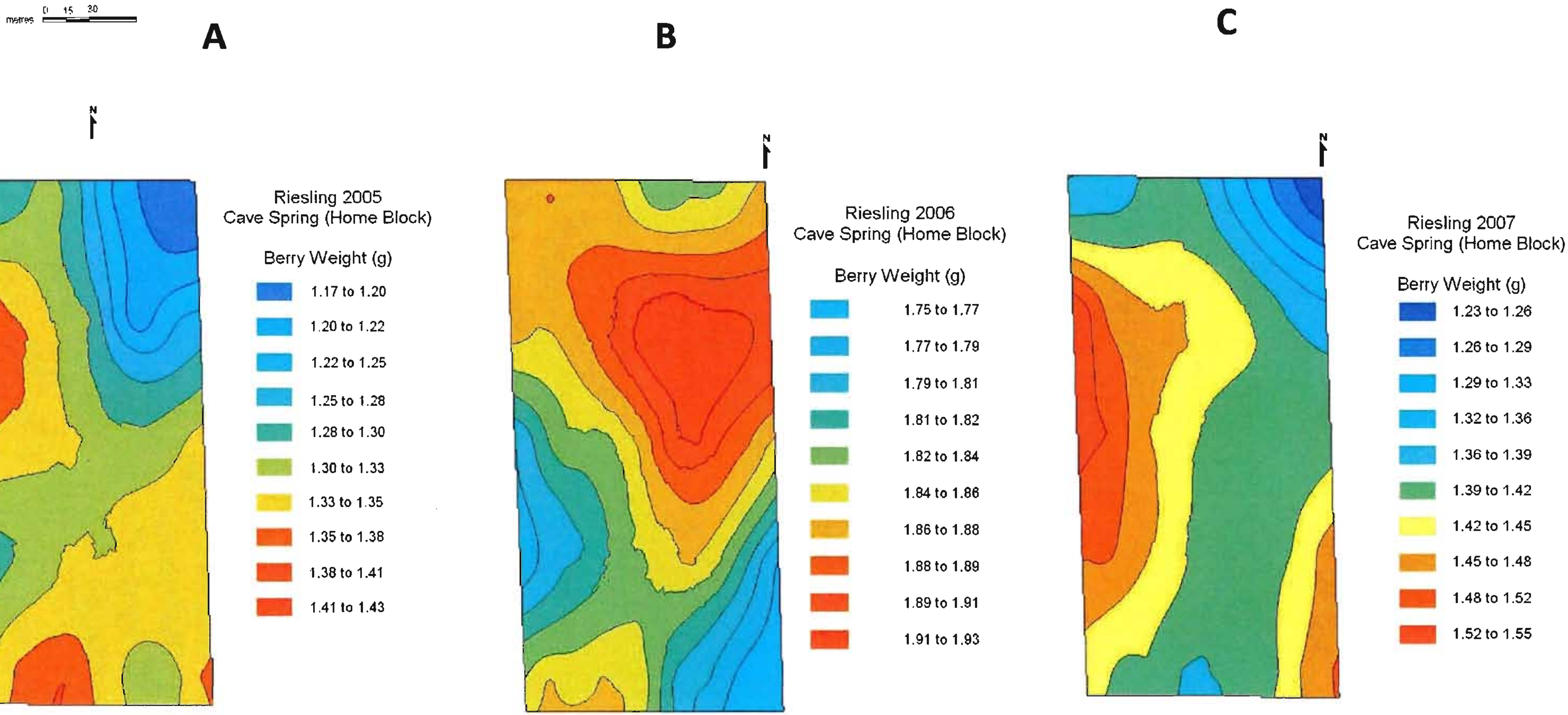
Supplemental Figure 3.2d. Spatial distribution of soil moisture (%), Cave Spring Cellars (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.



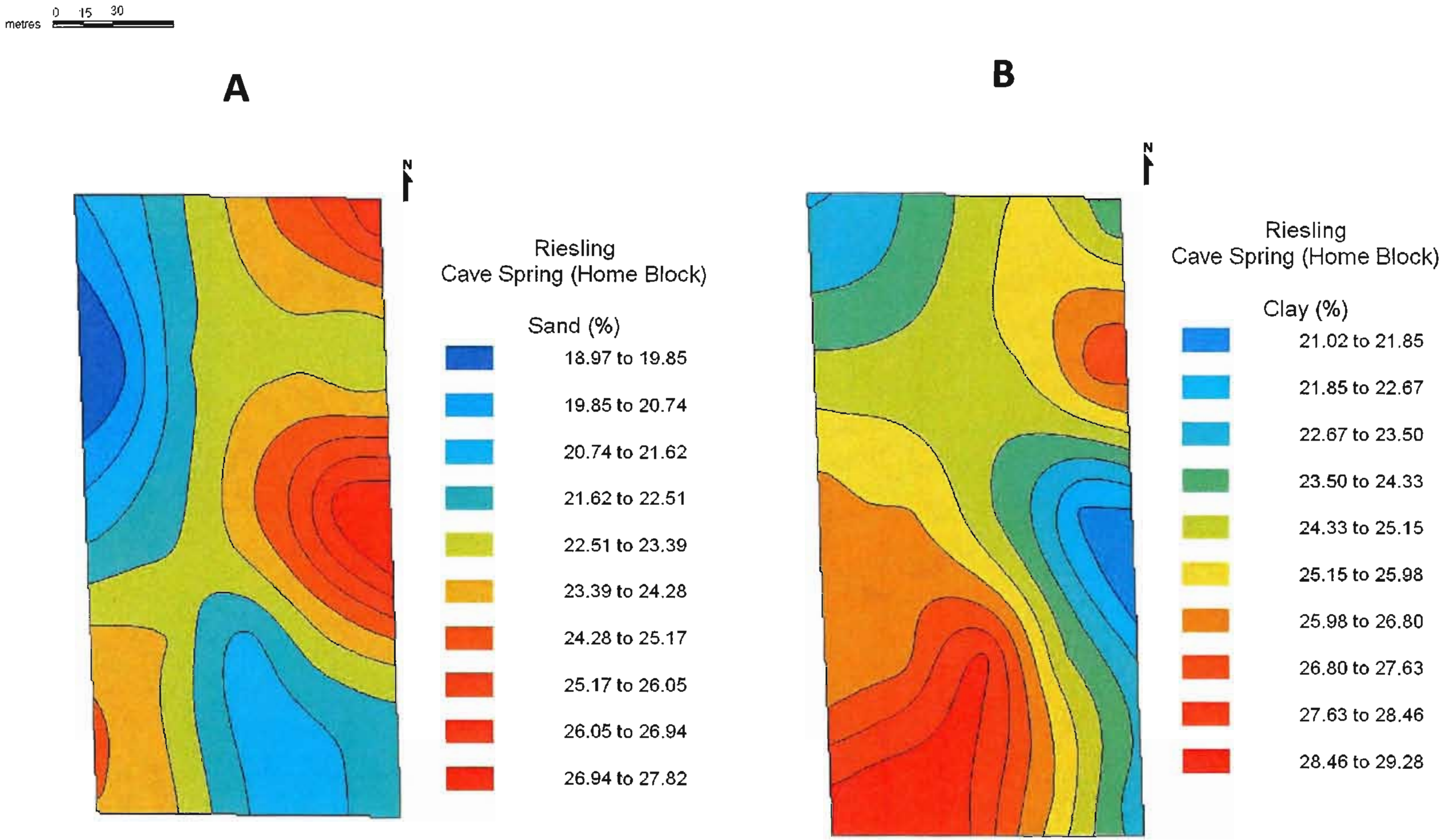
Supplemental Figure 3.3d. Spatial distribution of vine size (kg/vine), Cave Spring Cellars (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.



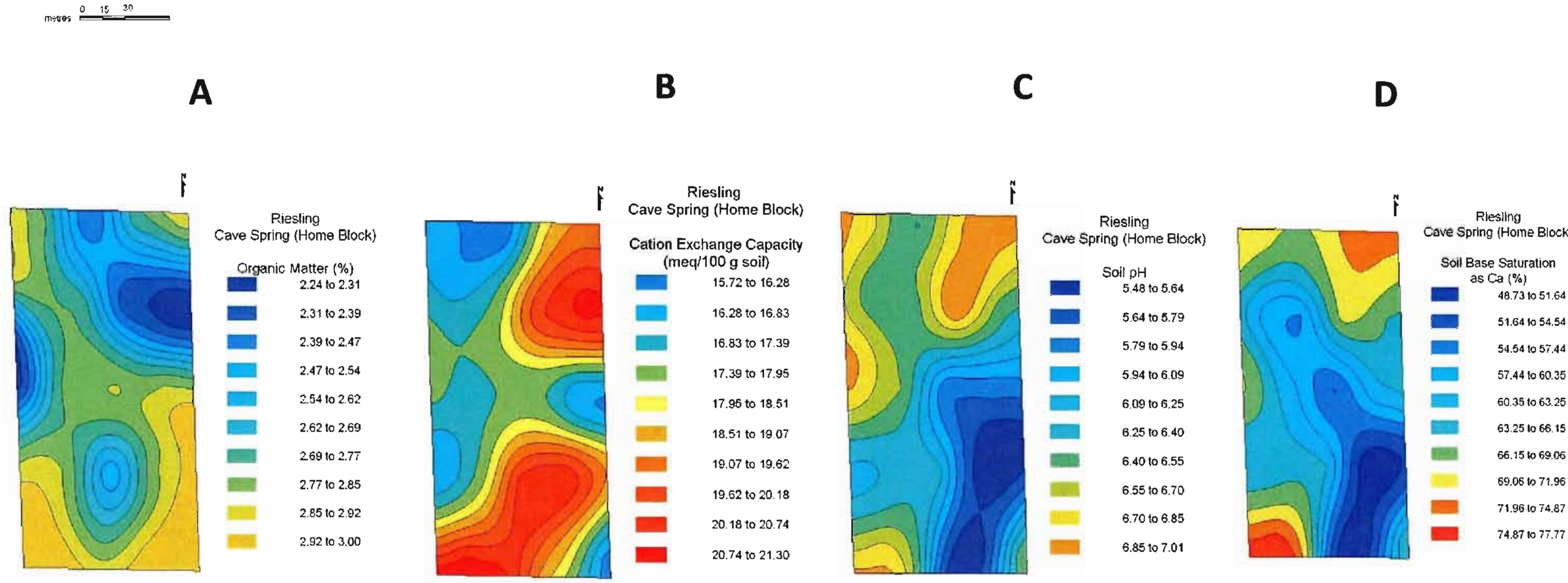
Supplemental Figure 3.4d. Spatial distribution of yield (kg/vine), Cave Spring Cellars (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.



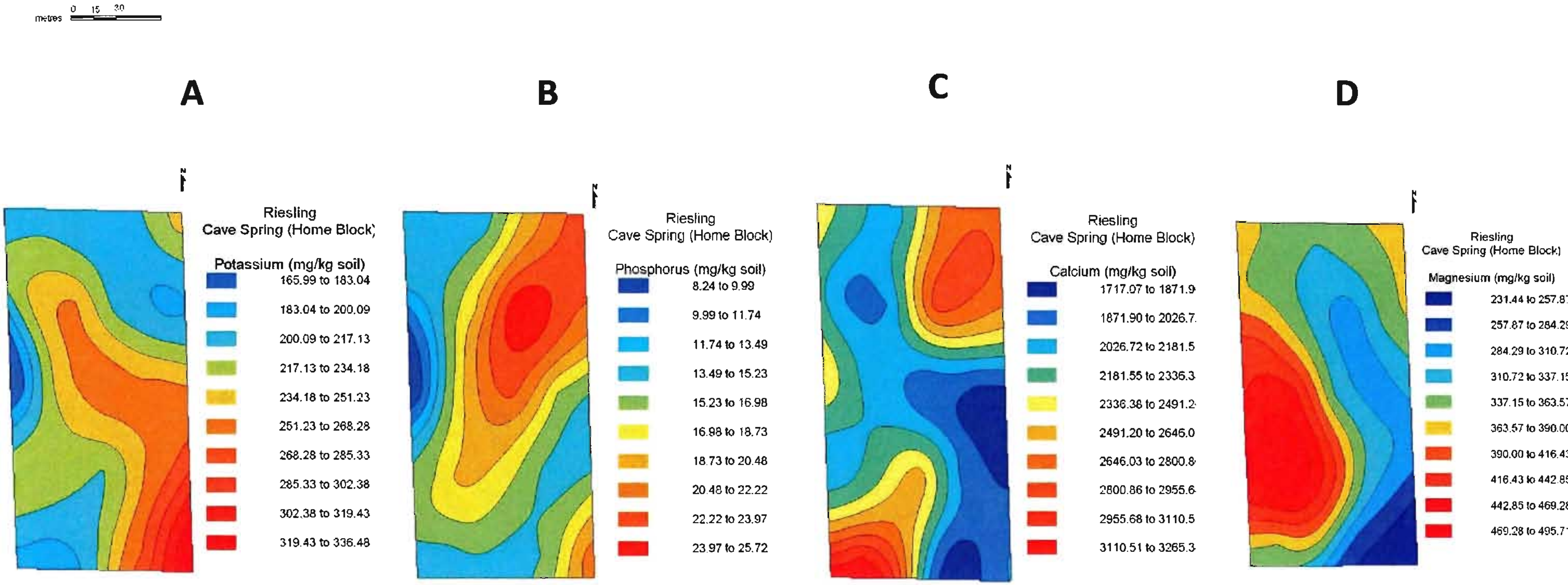
Supplemental Figure 3.5d. Spatial distribution of berry weight (g), Cave Spring Cellars (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.



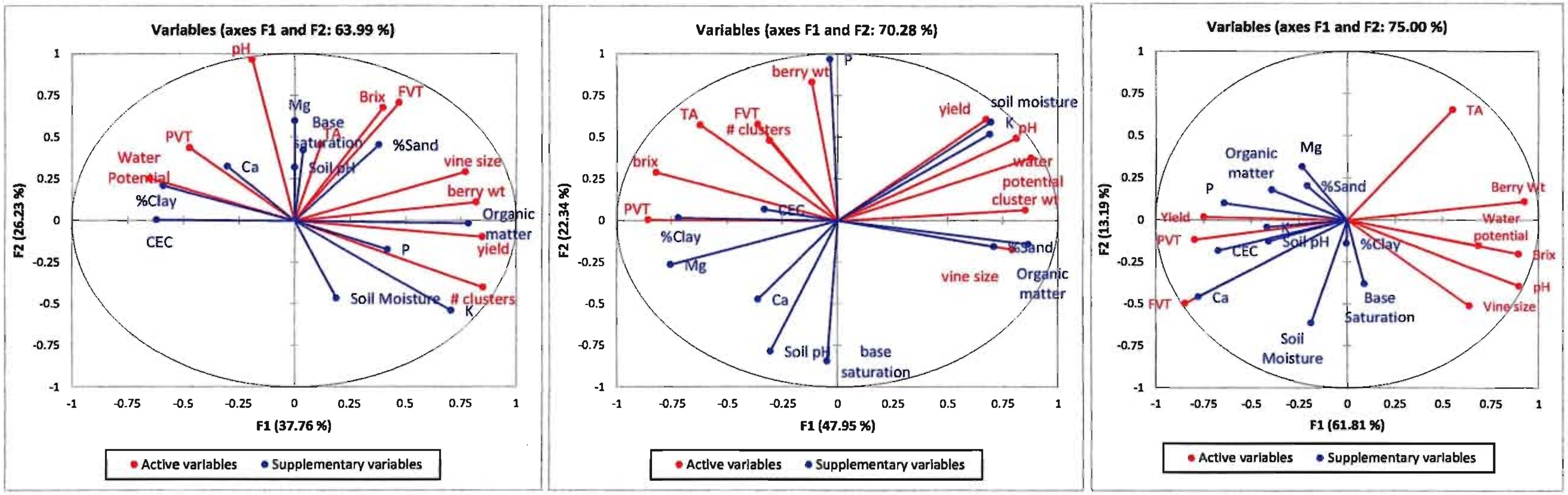
Supplemental Figure 3.6d. Spatial distribution of soil texture, Cave Spring Cellars (Home Block), Beamsville, ON; A: sand (%); B: clay (%).



Supplemental Figure 3.7d. Spatial distribution of soil physical properties, Cave Spring Cellars (Home Block), Beamsville, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).



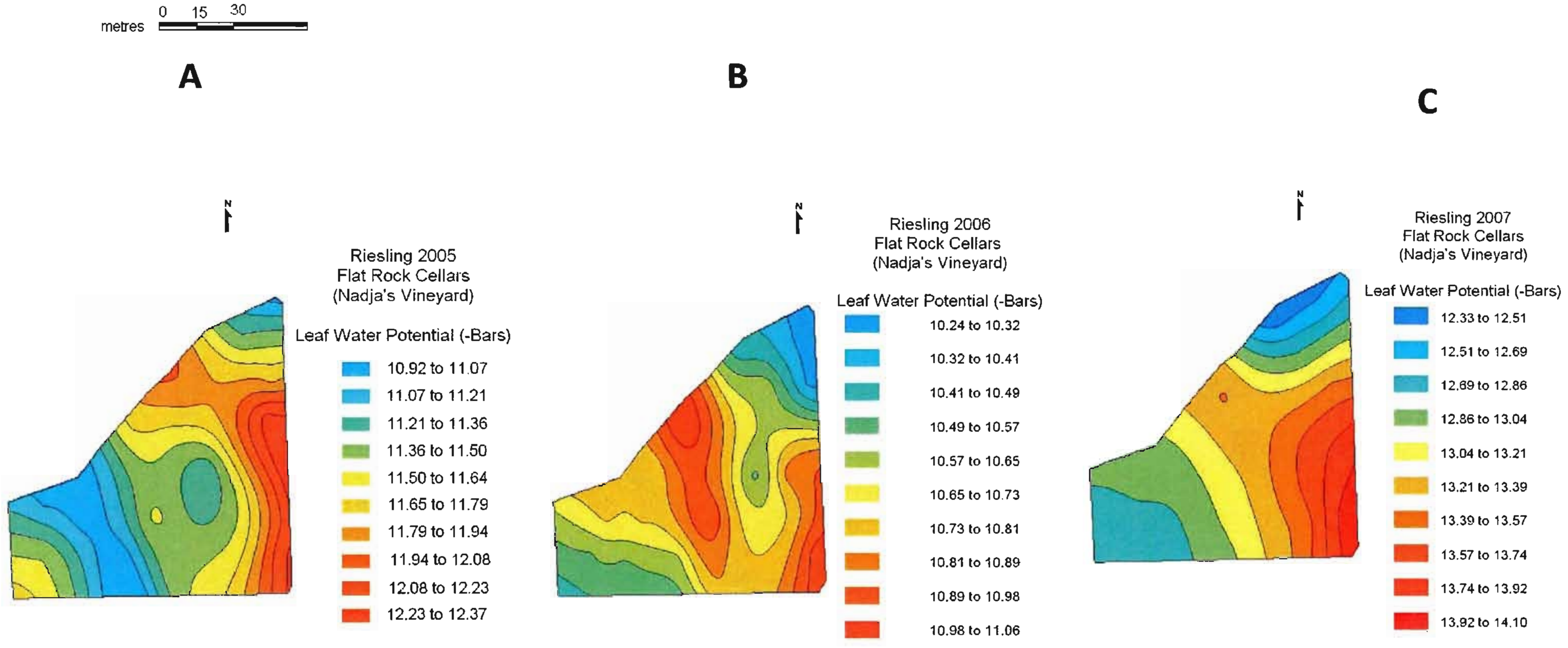
Supplemental Figure 3.8d. Spatial distribution of soil composition, Cave Spring Cellars (Home Block), Beamsville, ON; A: K; B: P; C: Ca; D: Mg


2005

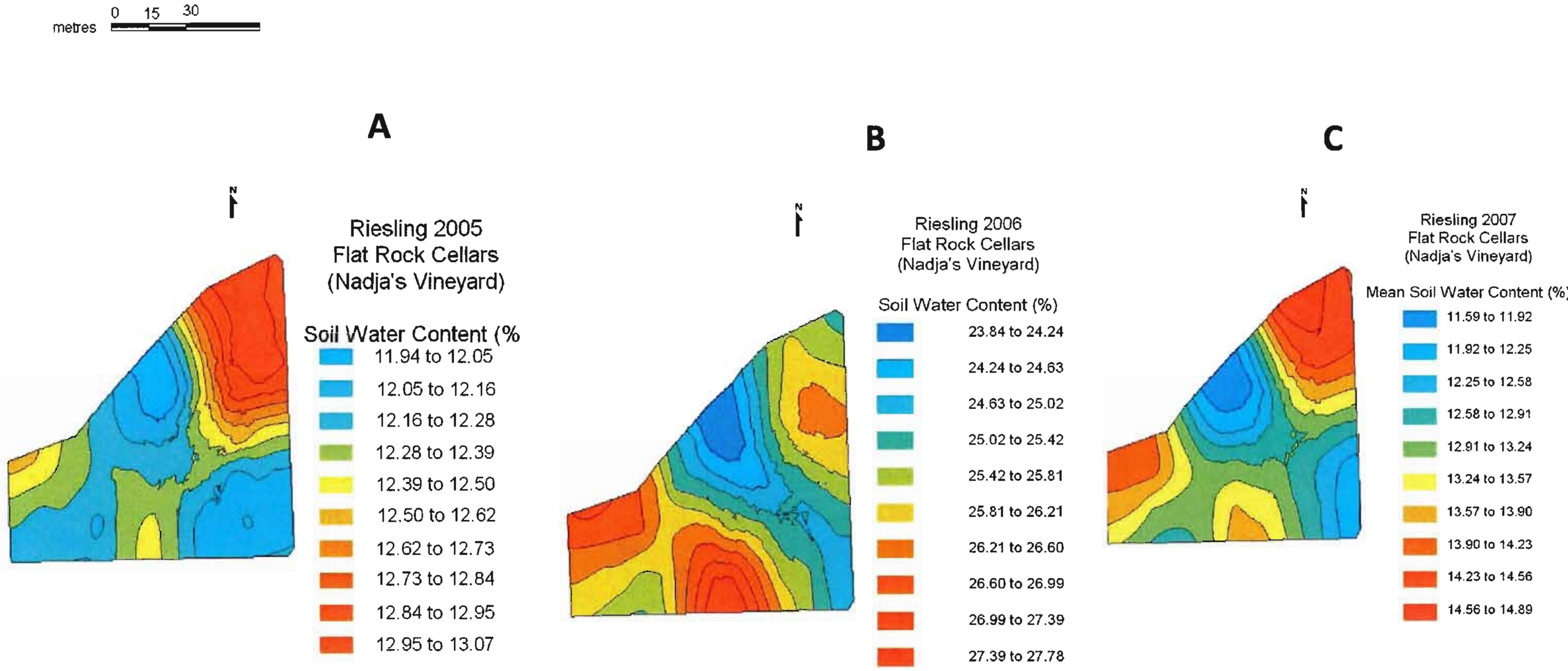
2006

2007

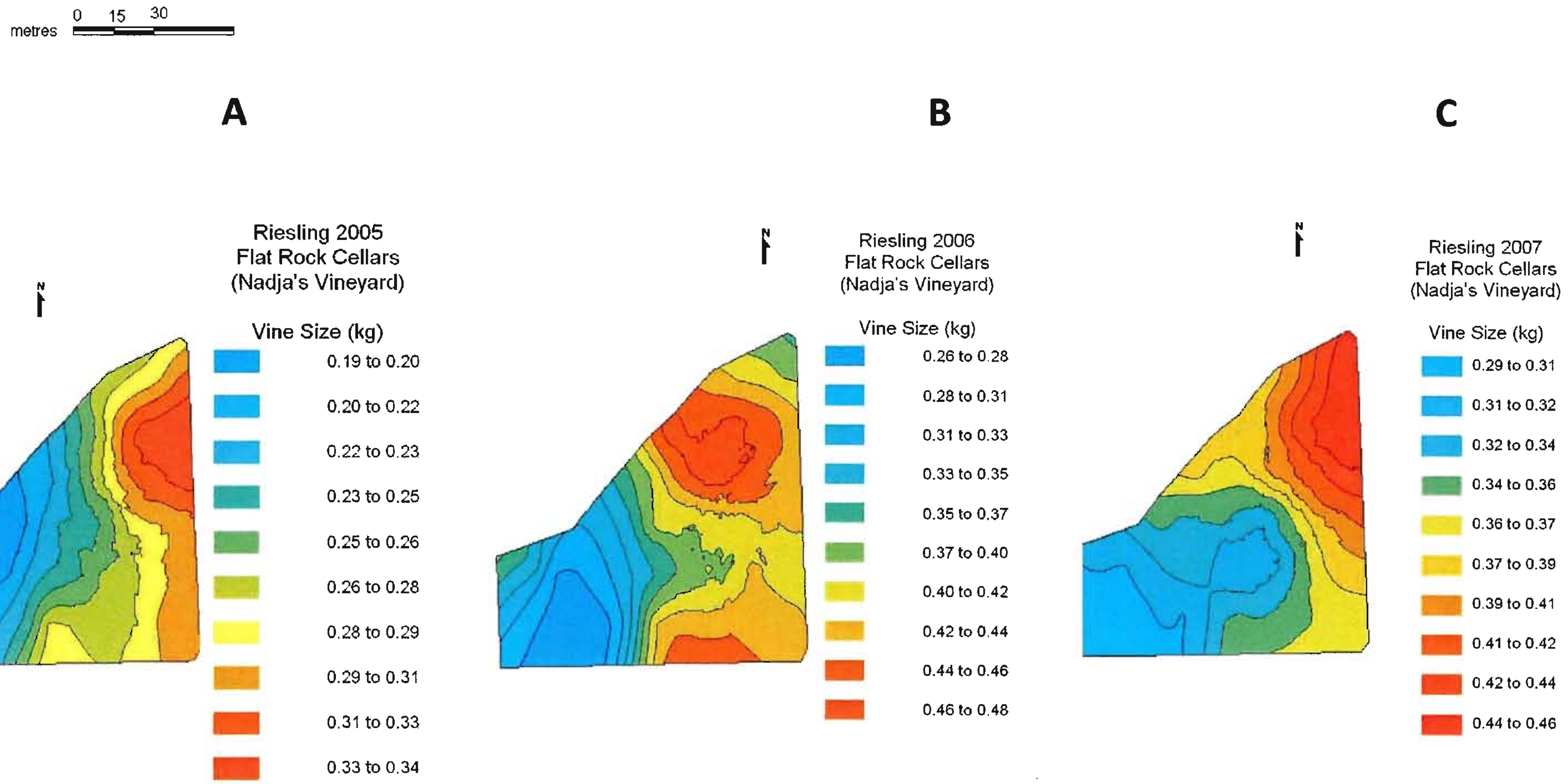
Supplemental Figure 3.9d. Principal component analysis of viticulture and soil variables for Cave Spring Cellars (Home Block), 2005-2007. *Supplementary variables in blue are soil variables.*



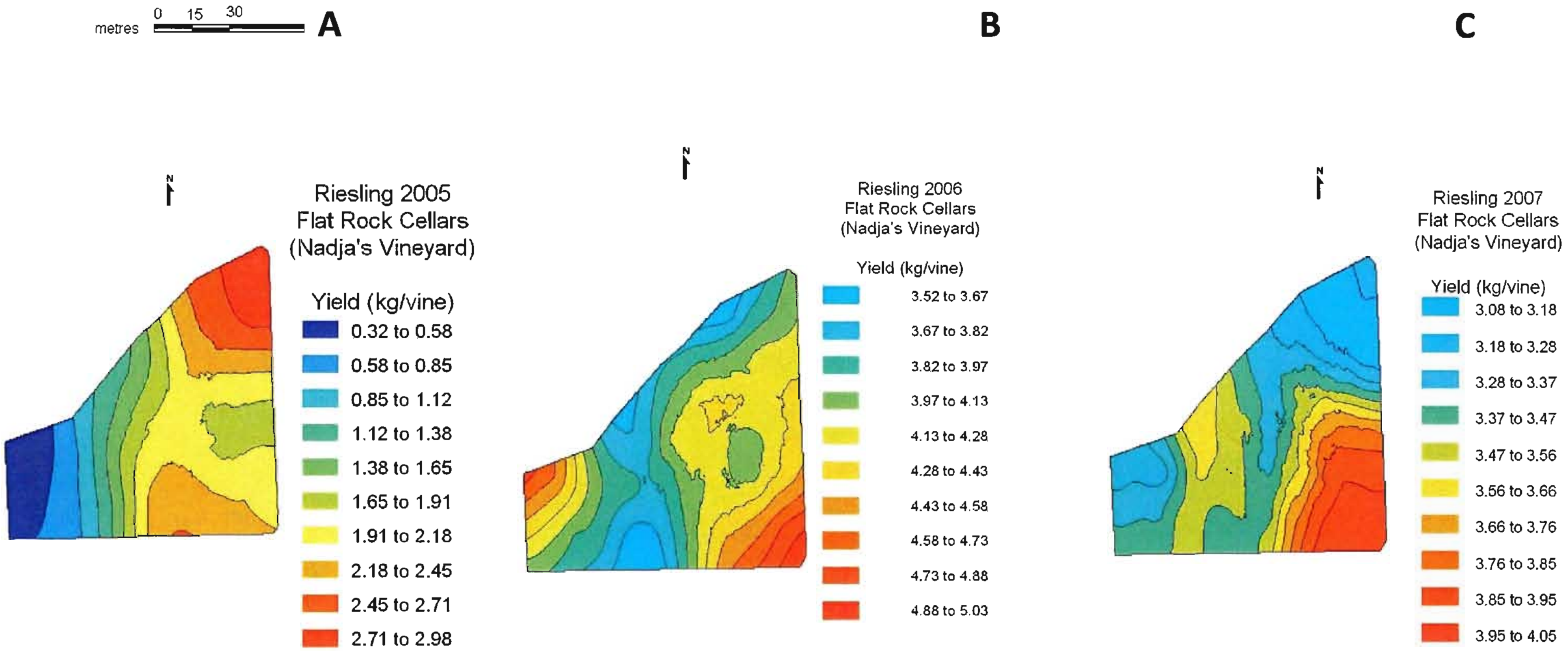
Supplemental Figure 3.1e. Spatial distribution of leaf water potential (-bars), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.



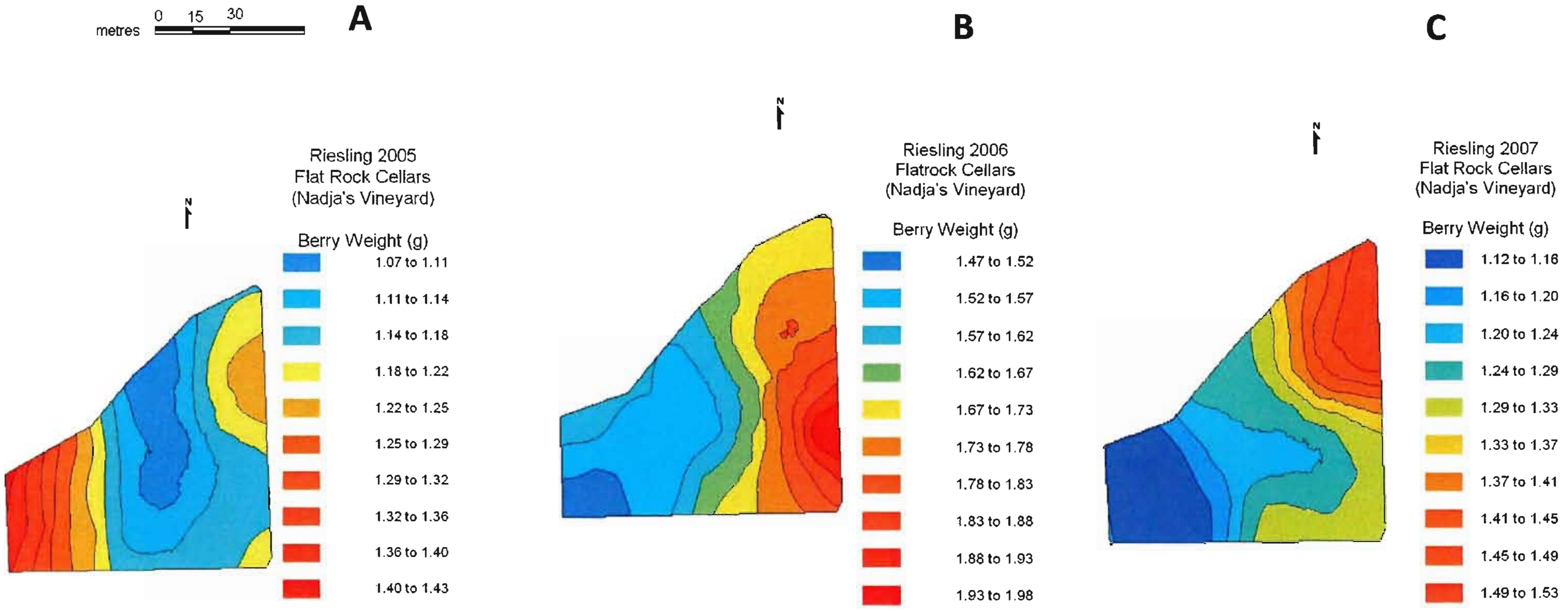
Supplemental Figure 3.2e. Spatial distribution of soil moisture (%), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.



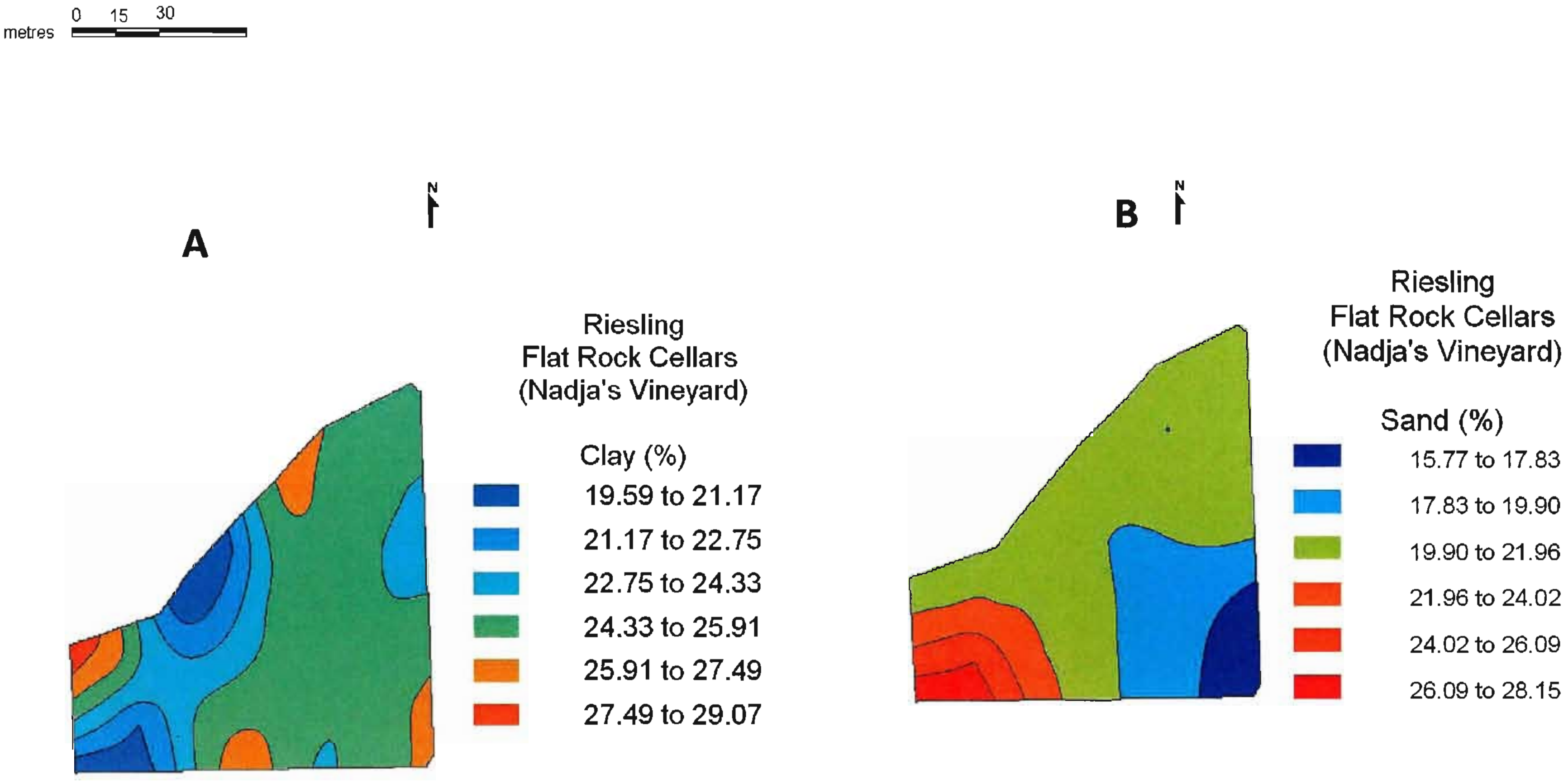
Supplemental Figure 3.3e. Spatial distribution of vine size (kg/vine), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.



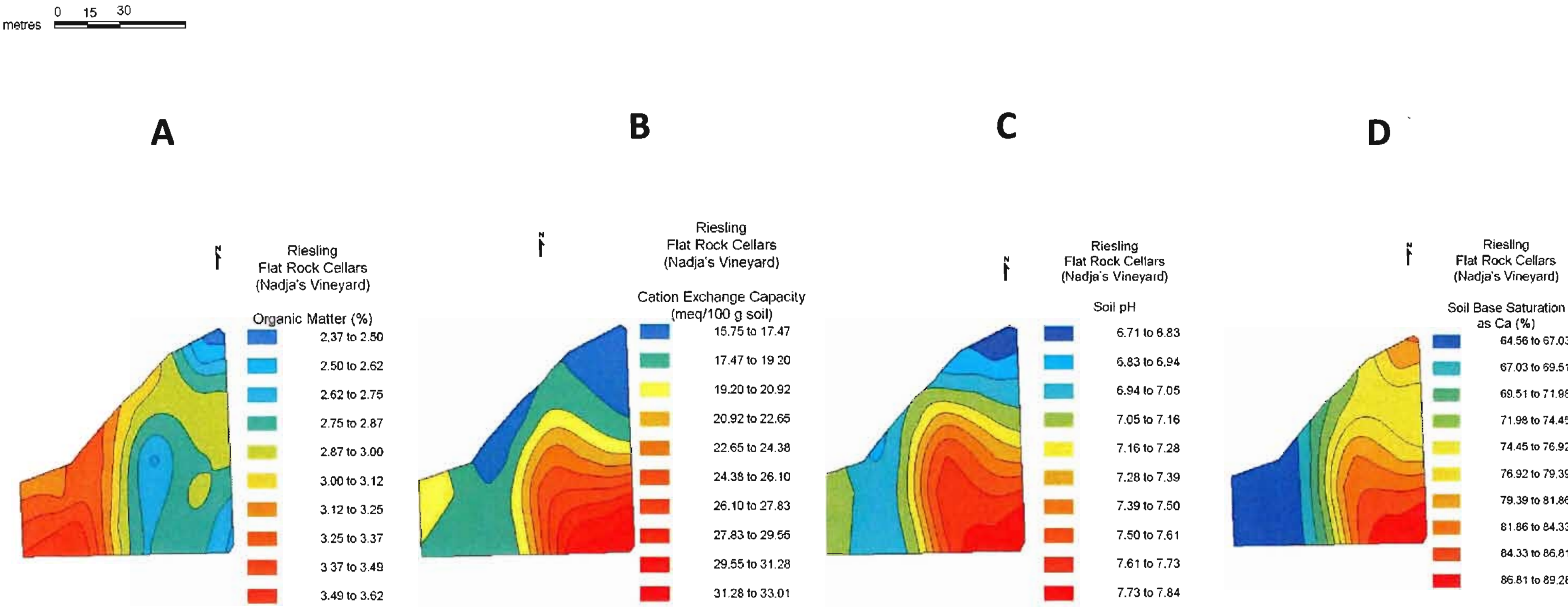
Supplemental Figure 3.4e. Spatial distribution of yield (kg/vine), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.



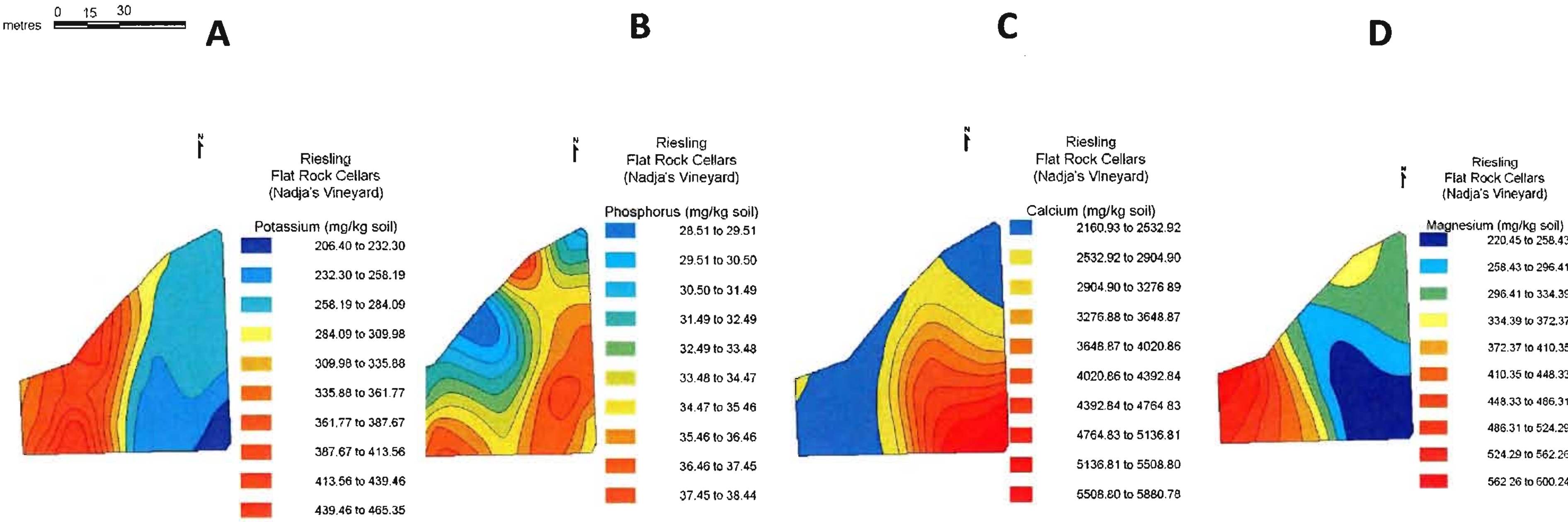
Supplemental Figure 3.5e. Spatial distribution of berry weight (g), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.



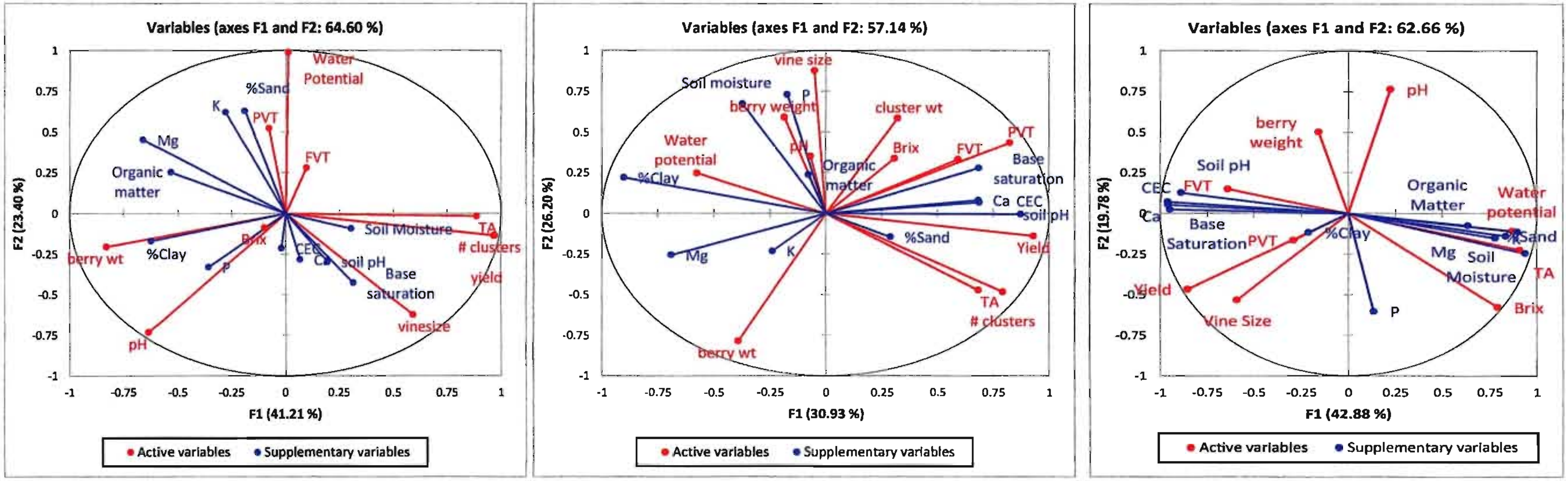
Supplemental Figure 3.6e. Spatial distribution of soil texture, Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: sand (%); B: clay (%).



Supplemental Figure 3.7e. Spatial distribution of soil physical properties, Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).



Supplemental Figure 3.8e. Spatial distribution of soil composition, Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: K; B: P; C: Ca; D: Mg



2005

Variables (axes F1 and F2: 64.60 %)

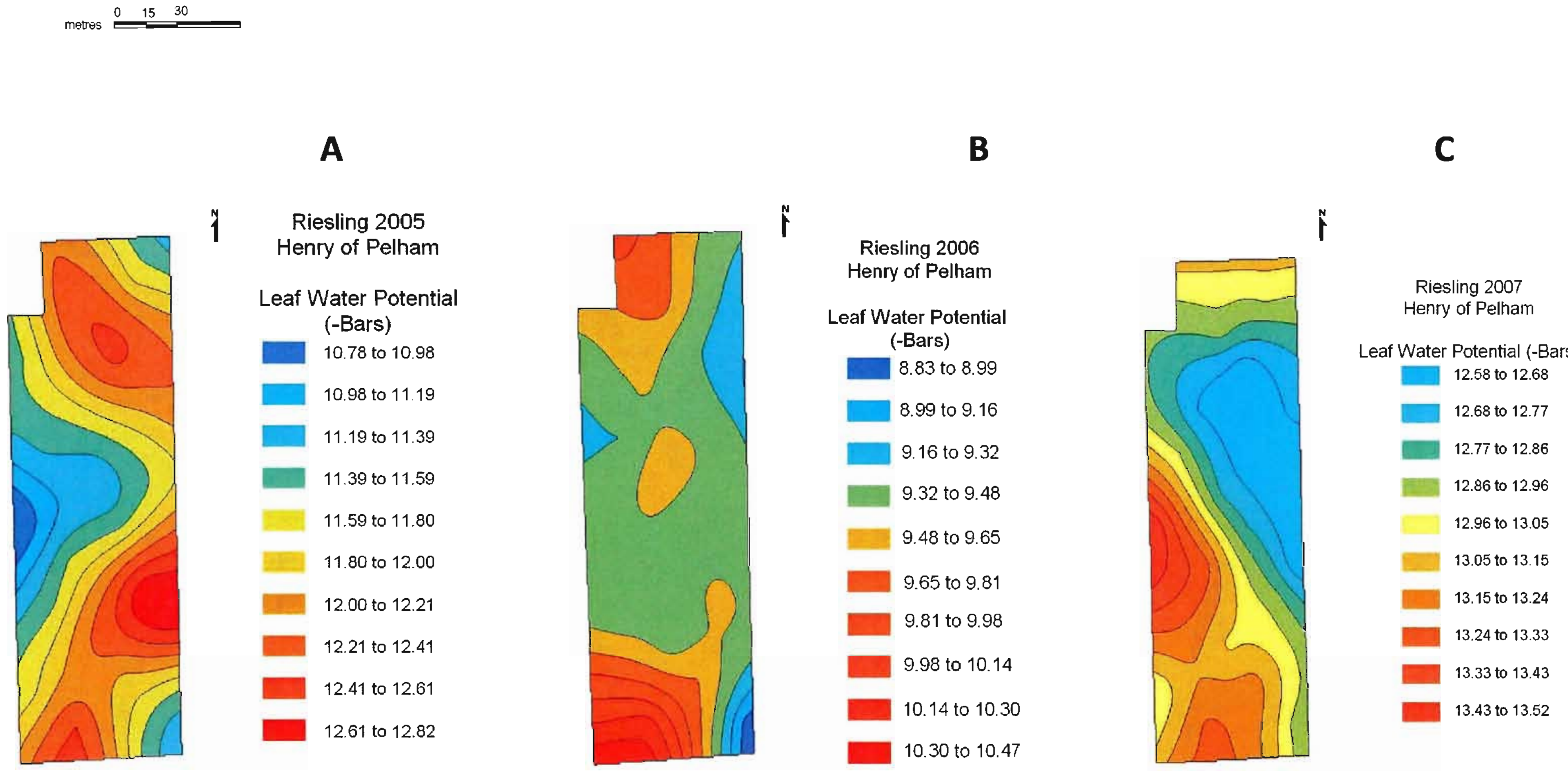
2006

Variables (axes F1 and F2: 57.14 %)

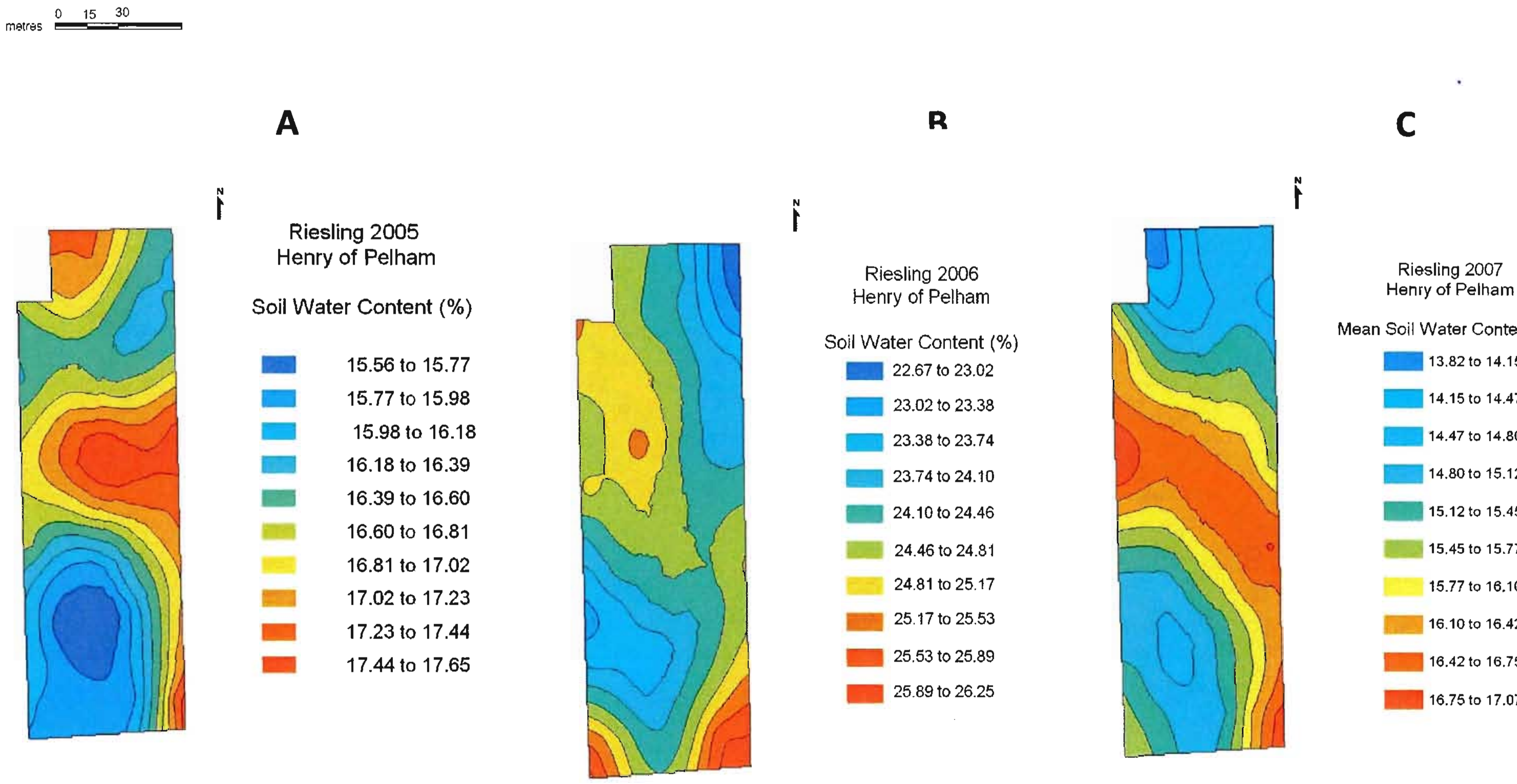
2007

Variables (axes F1 and F2: 62.66 %)

Supplemental Figure 3.9e. Principal component analysis of viticulture and soil variables for Flat Rock Cellars (Nadja's Vineyard), 2005-2007. *Supplementary variables in blue are soil variables.*



Supplemental Figure 3.1f. Spatial distribution of leaf water potential (-bars), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.



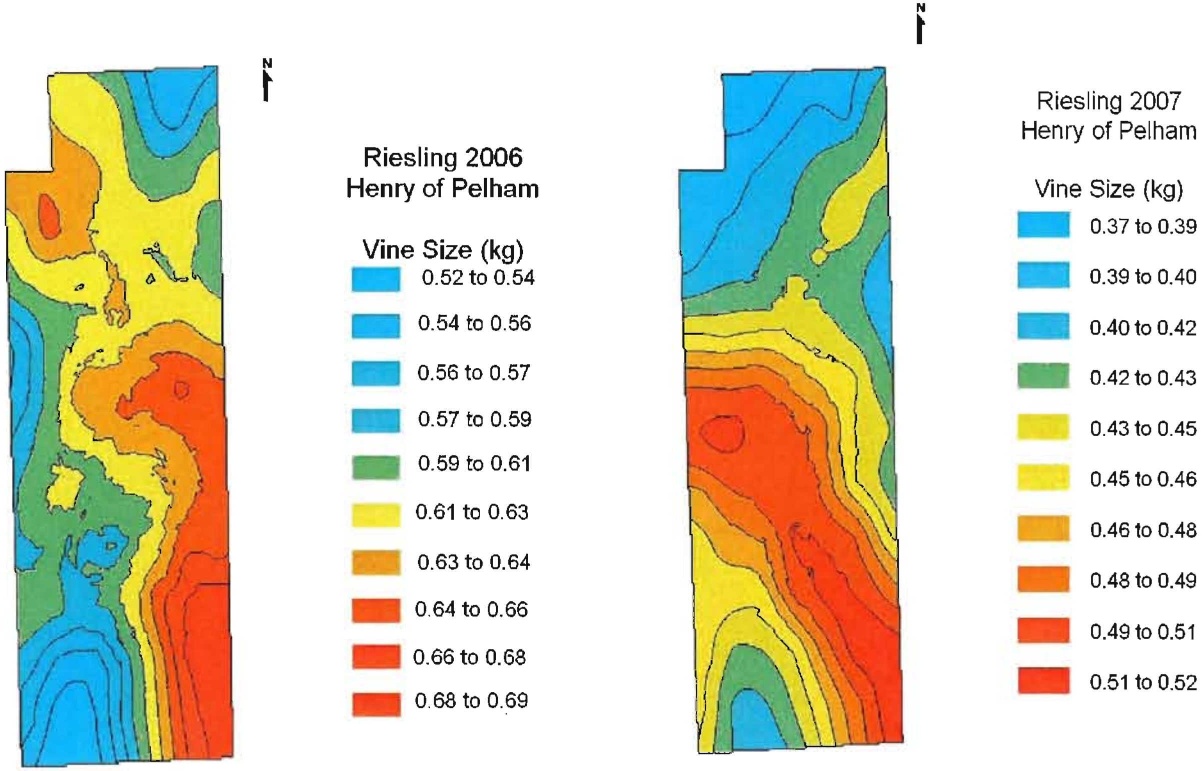
Supplemental Figure 3.2f. Spatial distribution of soil moisture (%), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.

A

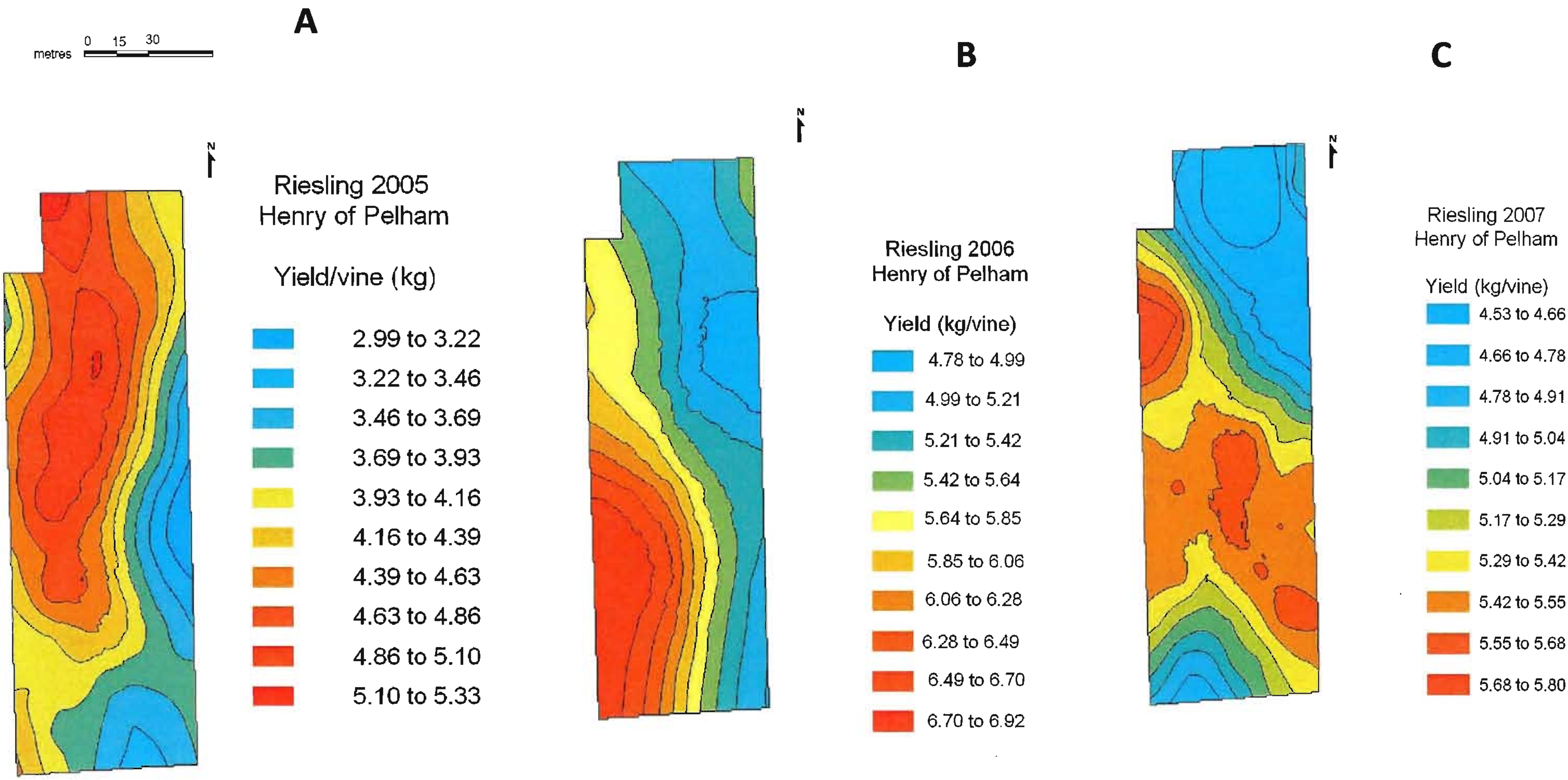
- Data not available

B

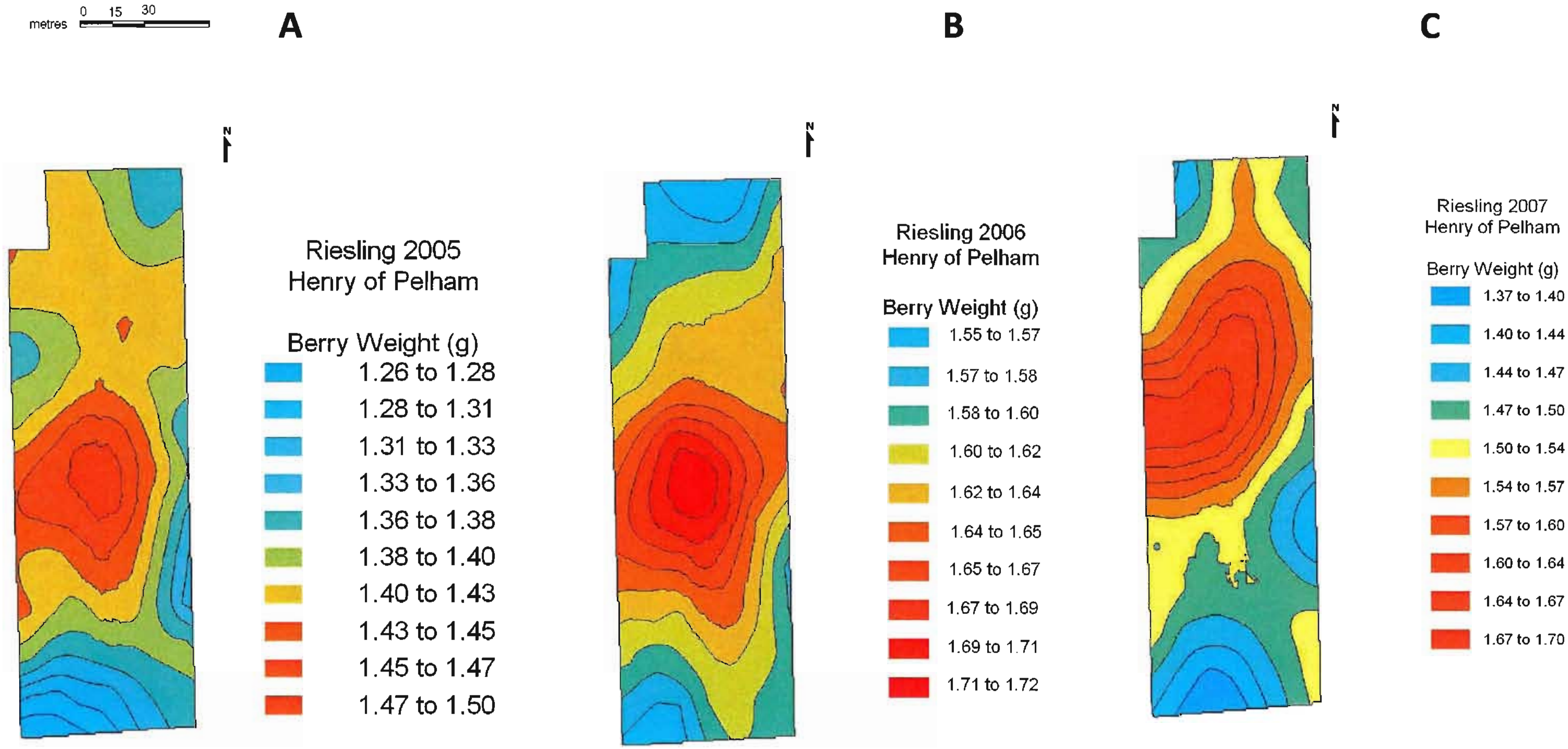
C



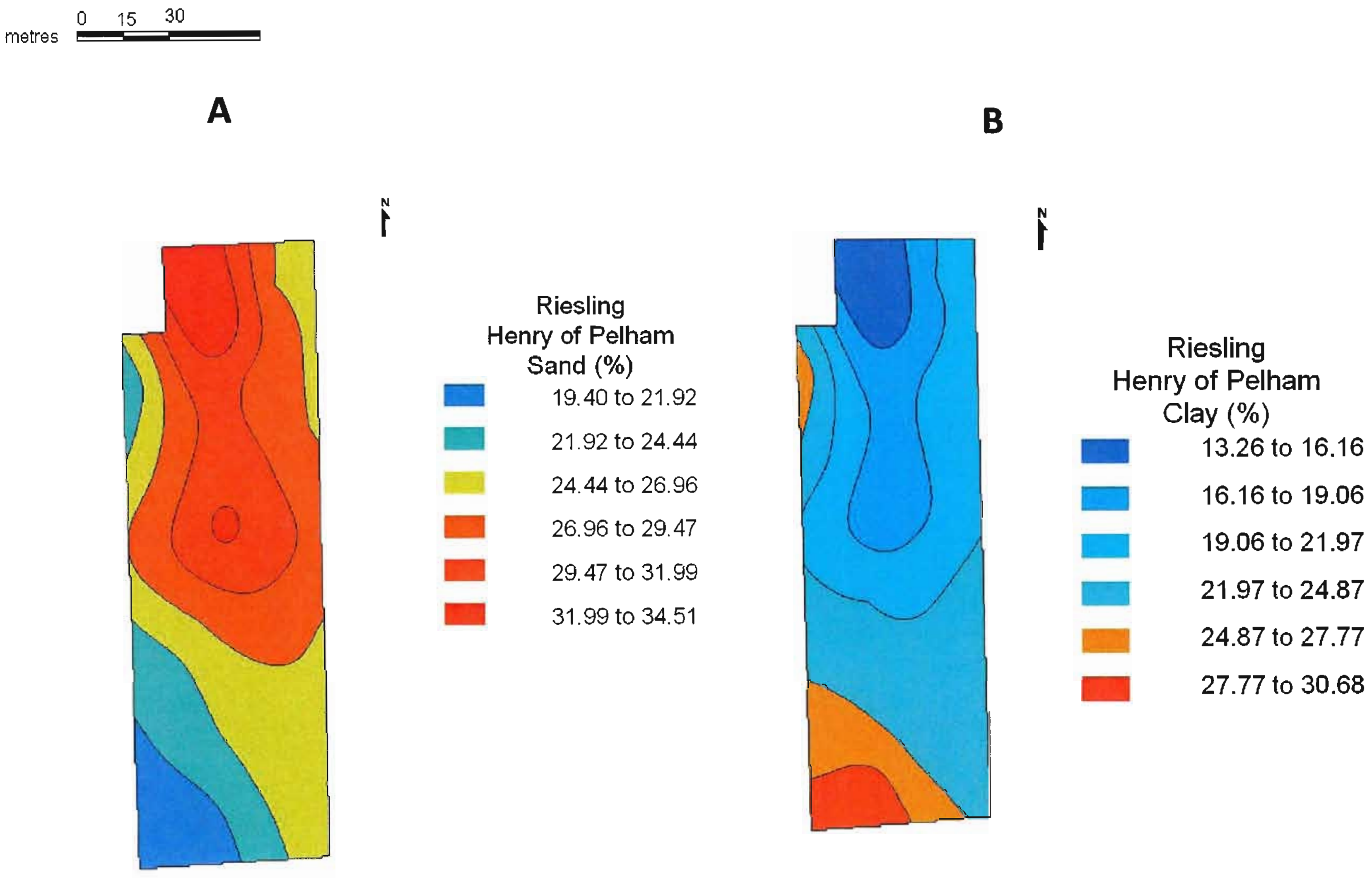
Supplemental Figure 3.3f. Spatial distribution of vine size (kg/vine), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.



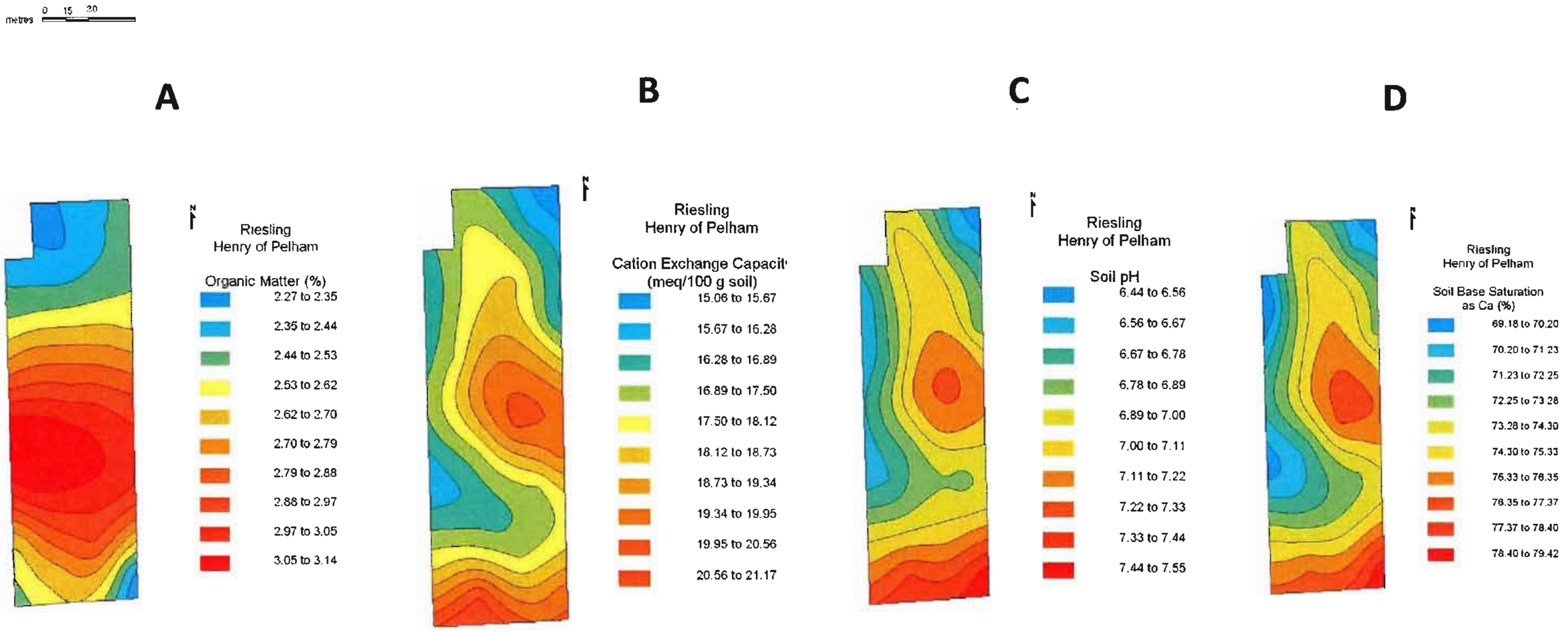
Supplemental Figure 3.4f. Spatial distribution of yield (kg/vine), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.



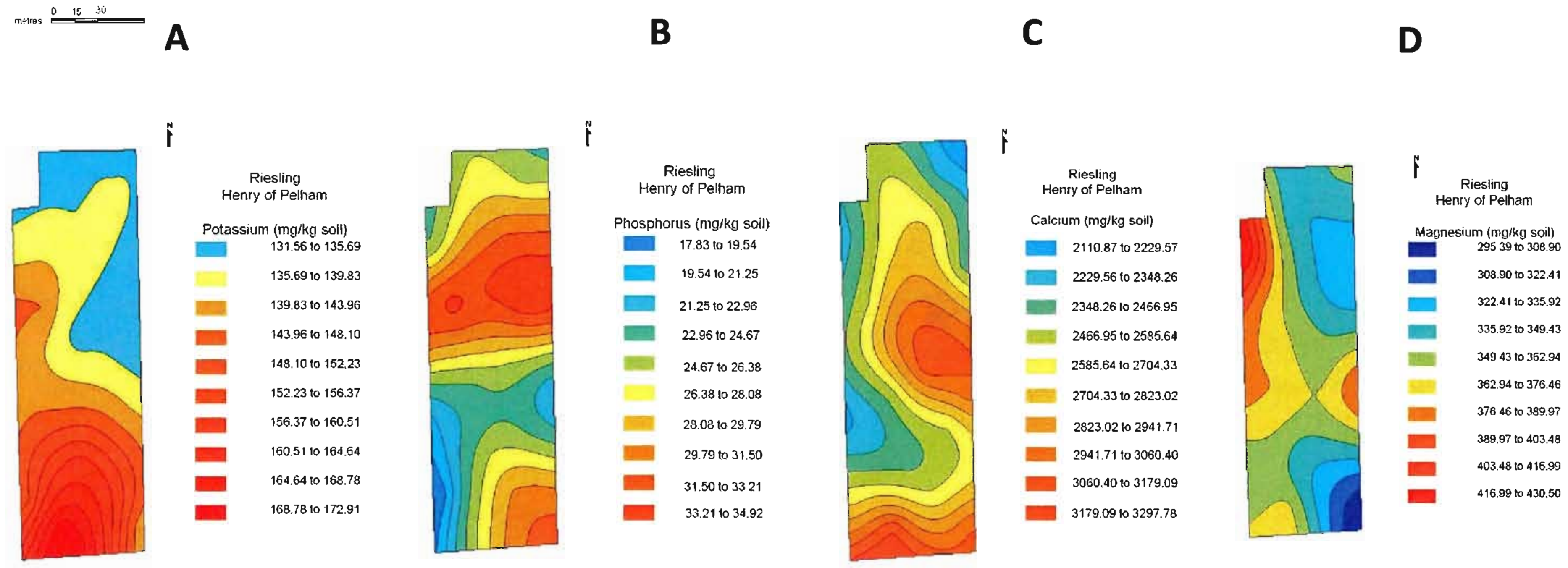
Supplemental Figure 3.5f. Spatial distribution of berry weight (g), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.



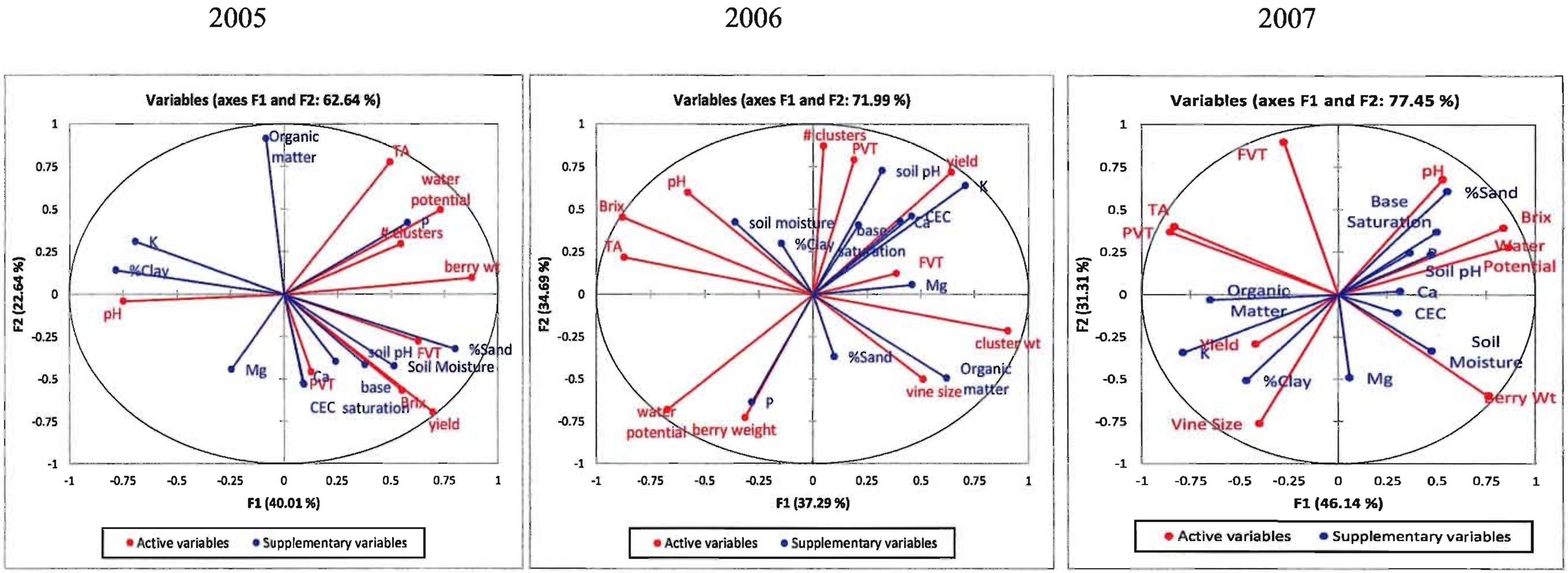
Supplemental Figure 3.6f. Spatial distribution of soil texture, Henry of Pelham, St. Catharines, ON; A: sand (%); B: clay (%).



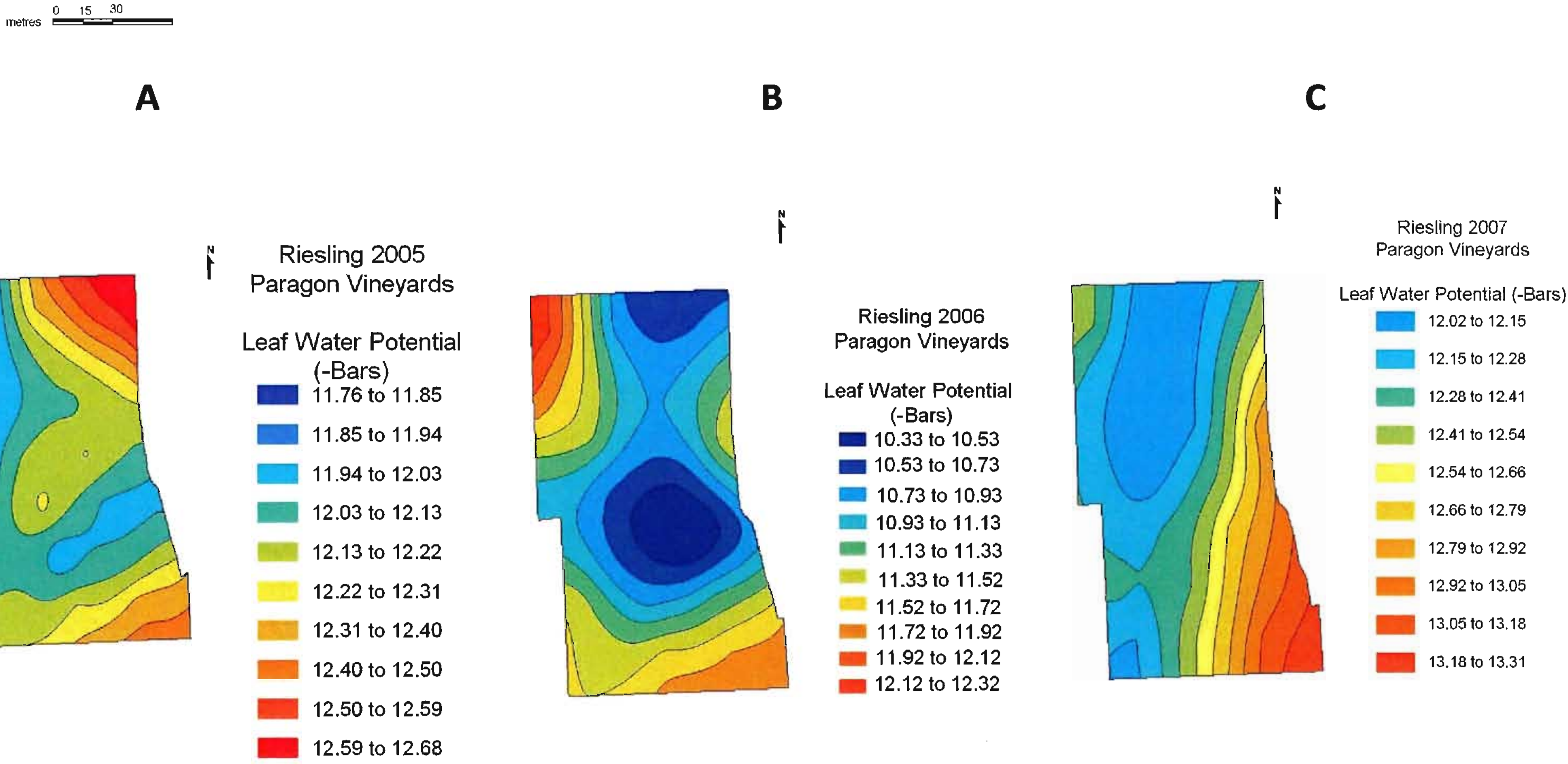
Supplemental Figure 3.7f. Spatial distribution of soil physical properties, Henry of Pelham, St. Catharines, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).



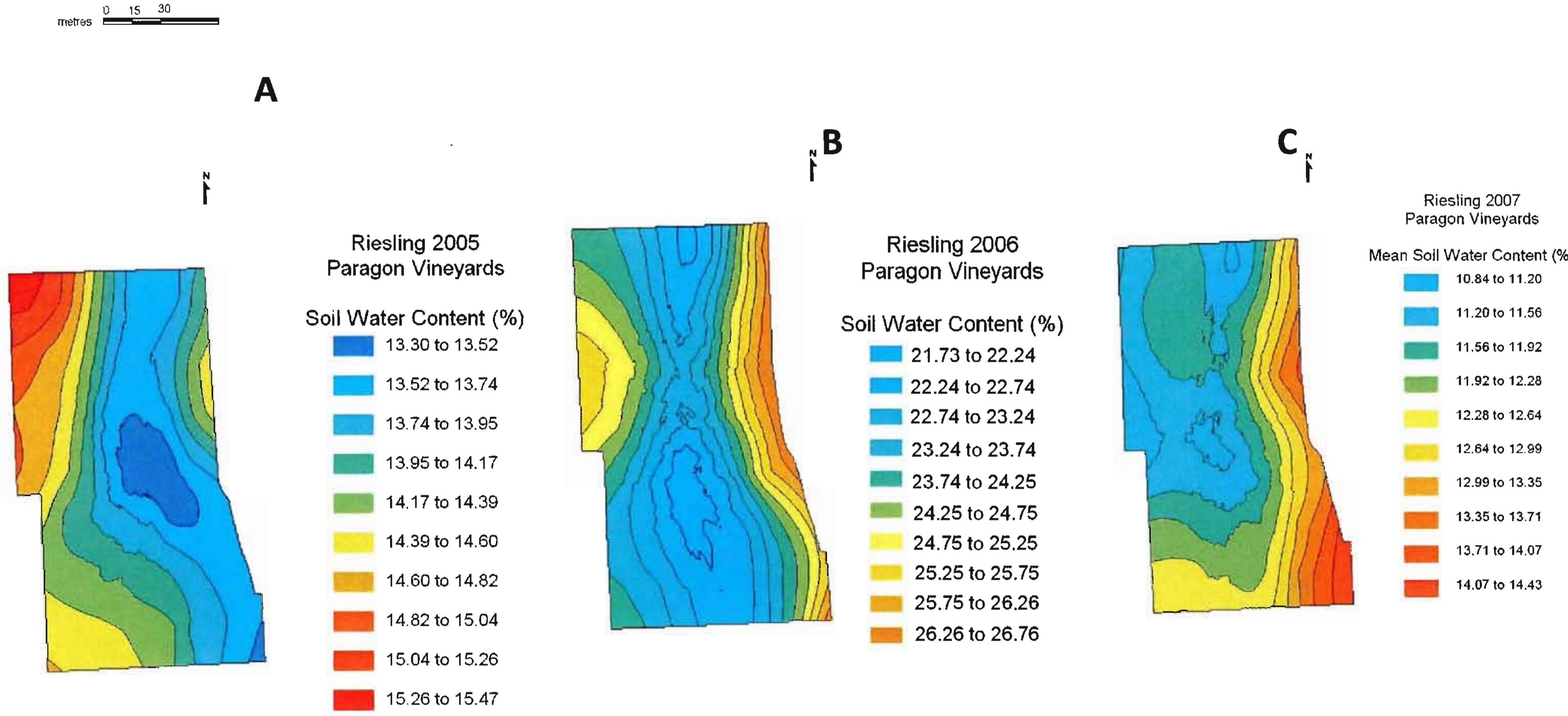
Supplemental Figure 3.8f. Spatial distribution of soil composition, Henry of Pelham, St. Catharines, ON; A: K; B: P; C: Ca; D: Mg


2005 2006 2007

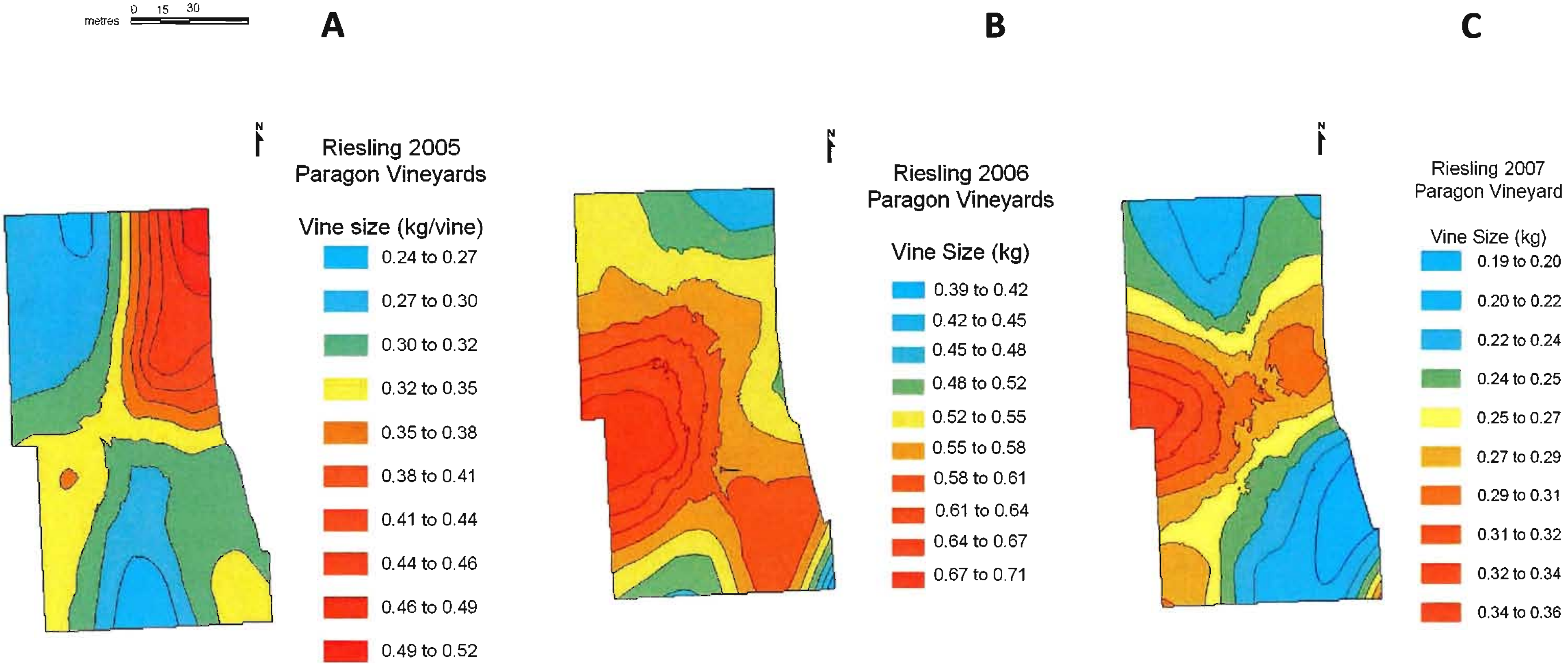
Supplemental Figure 3.9f. Principal component analysis of viticulture and soil variables for Henry of Pelham, 2005-2007. *Supplementary variables in blue are soil variables.*



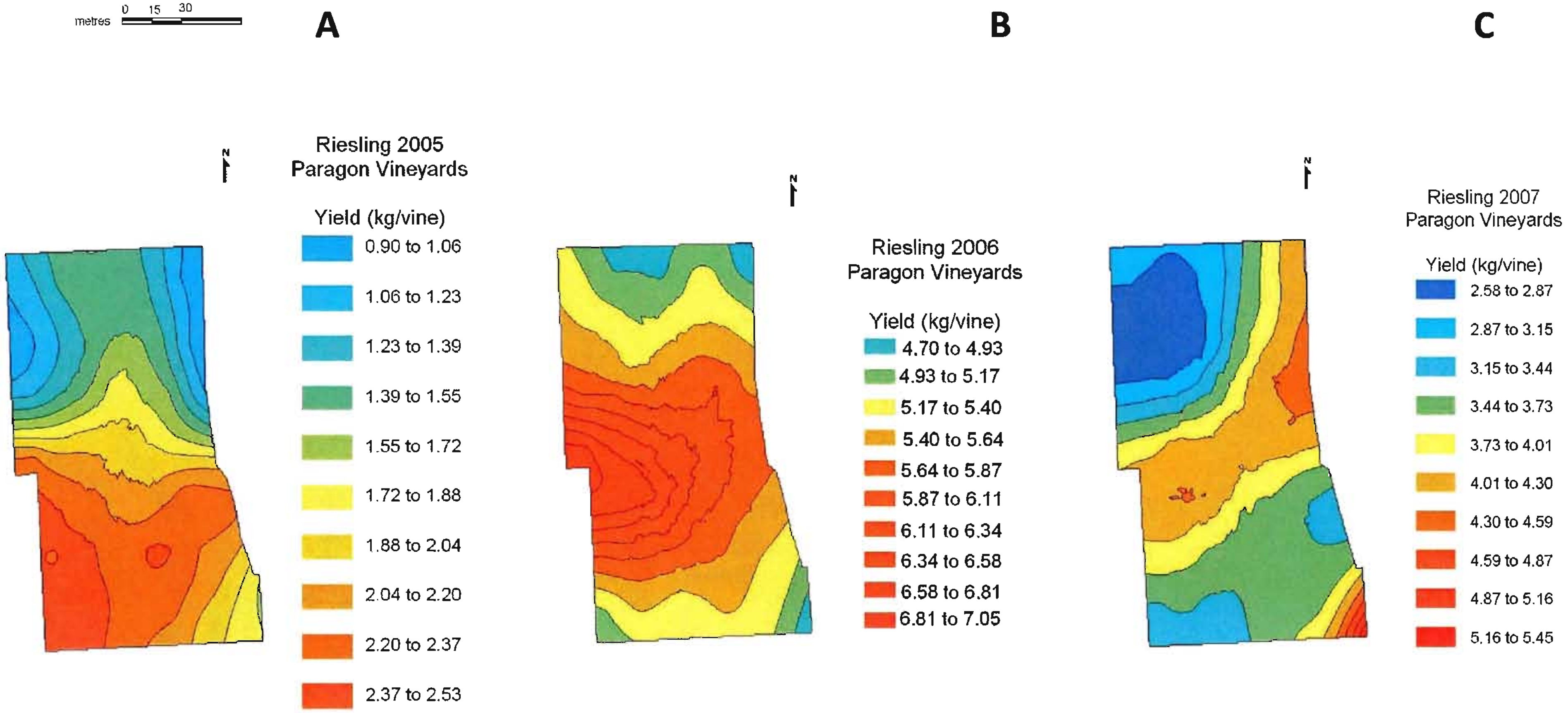
Supplemental Figure 3.1g. Spatial distribution of leaf water potential (-bars), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.



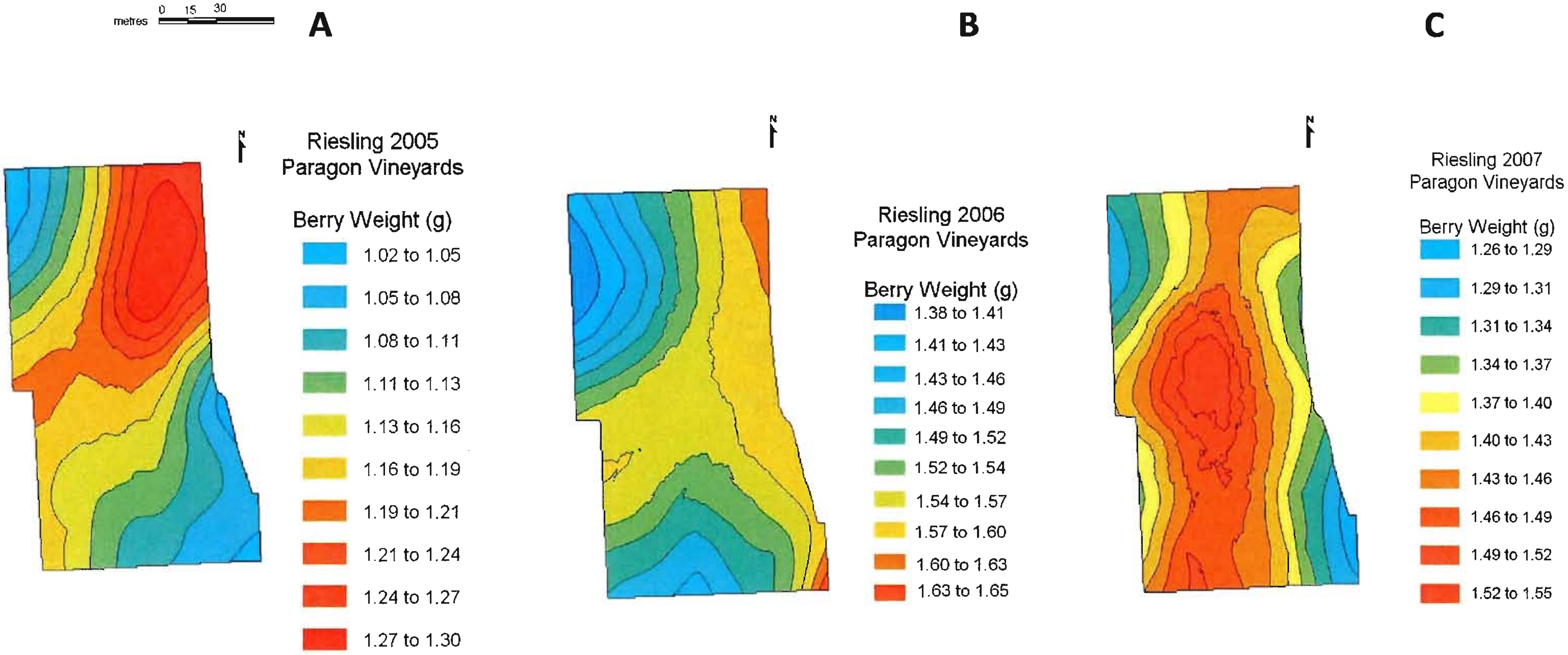
Supplemental Figure 3.2g. Spatial distribution of soil moisture (%), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.



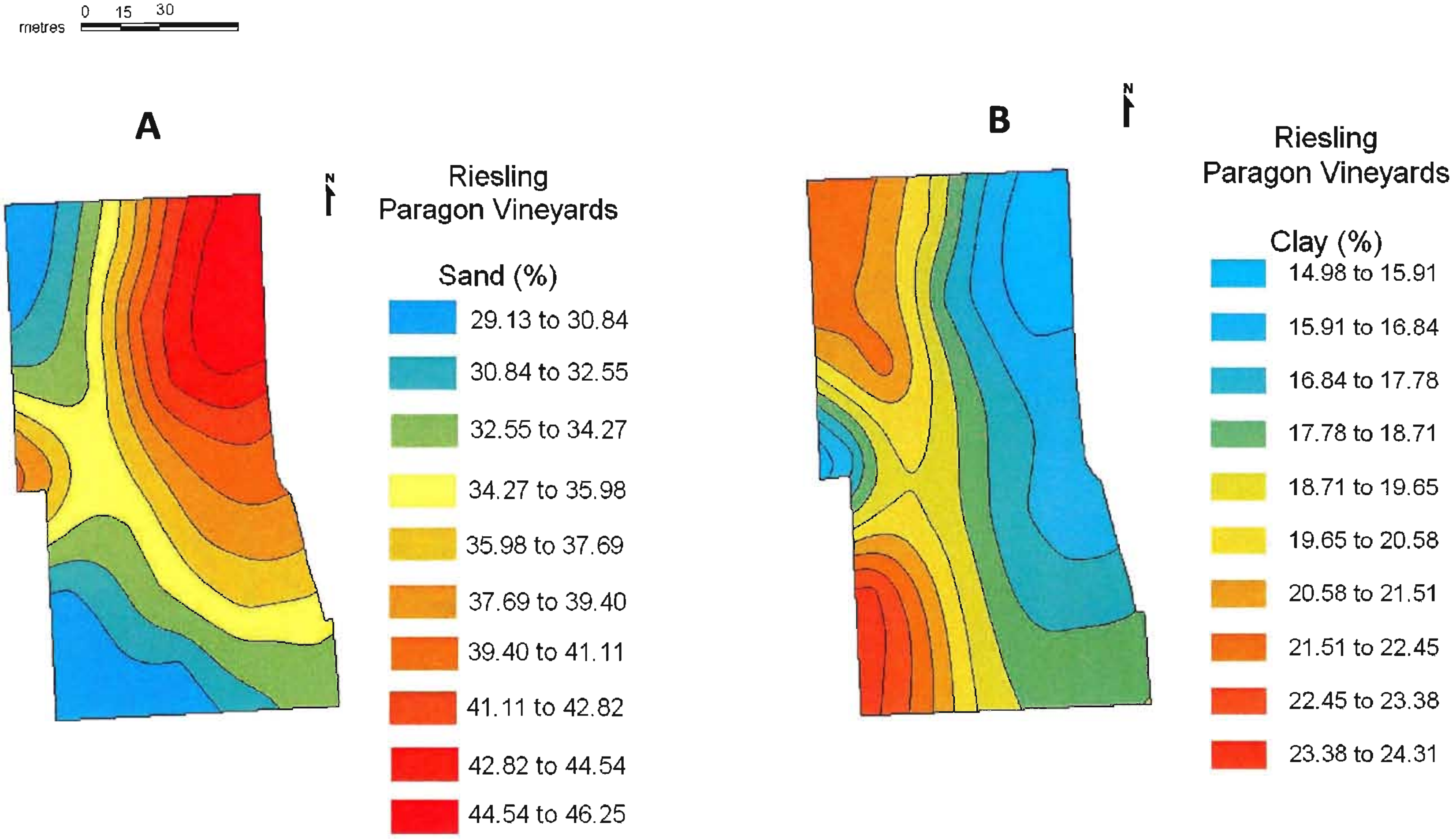
Supplemental Figure 3.3g. Spatial distribution of vine size (kg/vine), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.



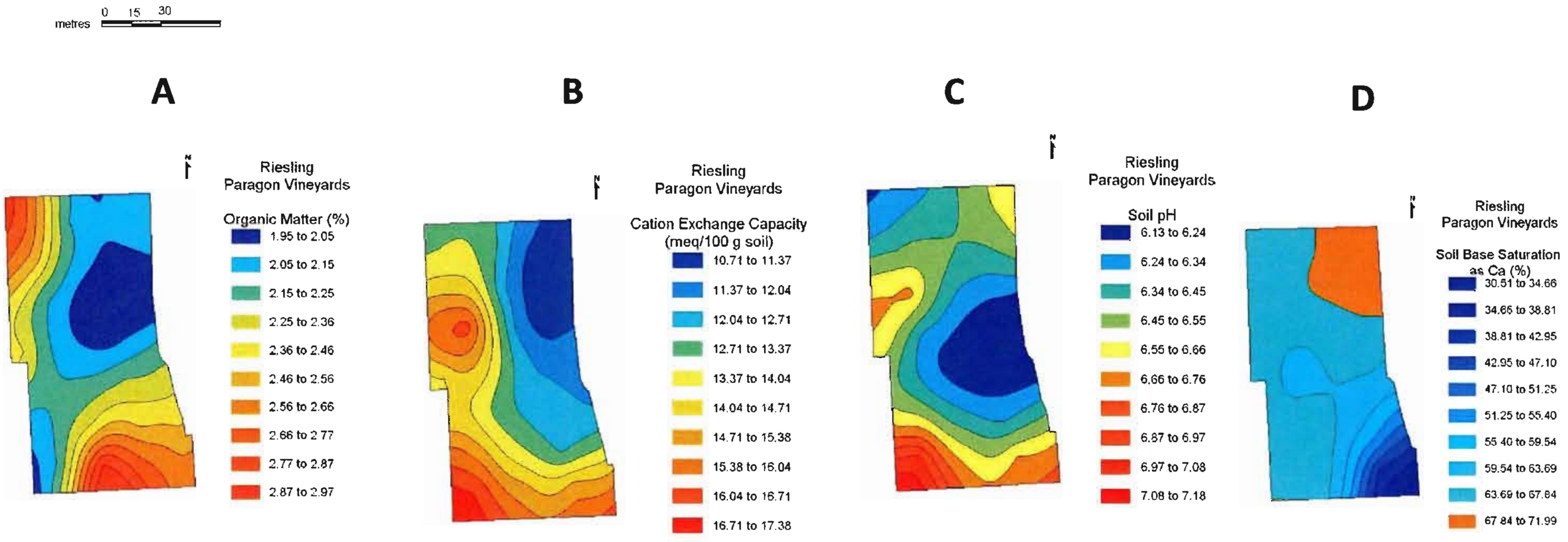
Supplemental Figure 3.4g. Spatial distribution of yield (kg/vine), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.



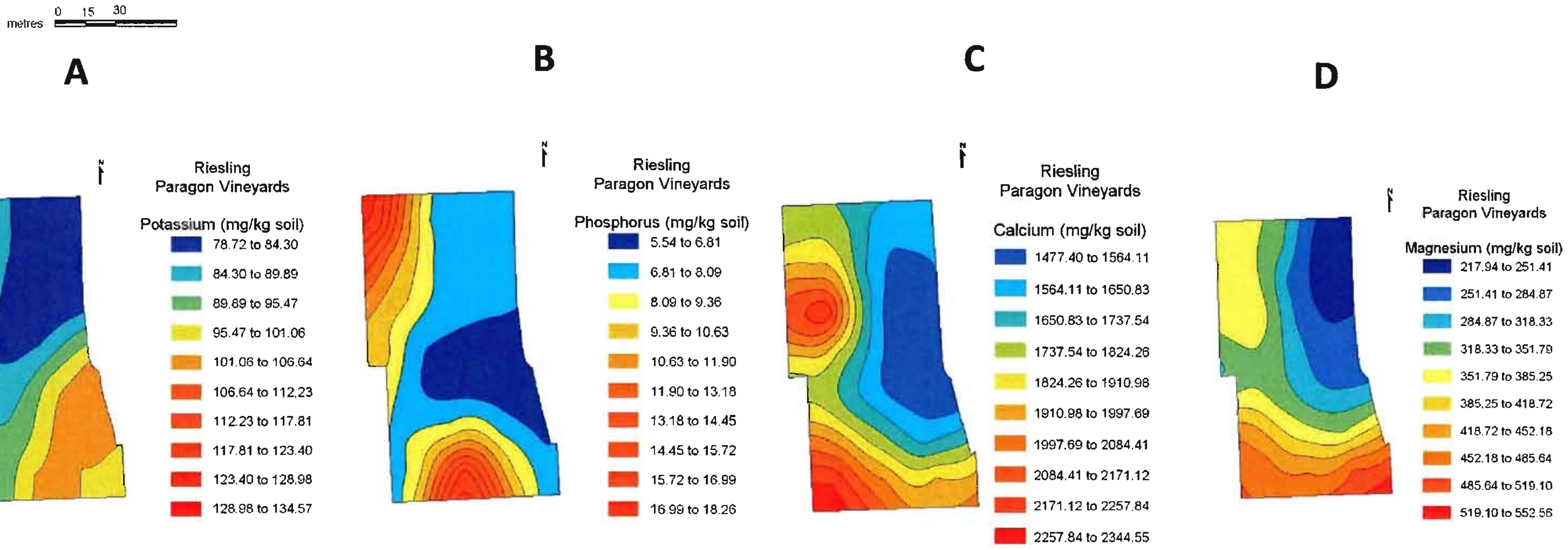
Supplemental Figure 3.5g. Spatial distribution of berry weight (g), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.



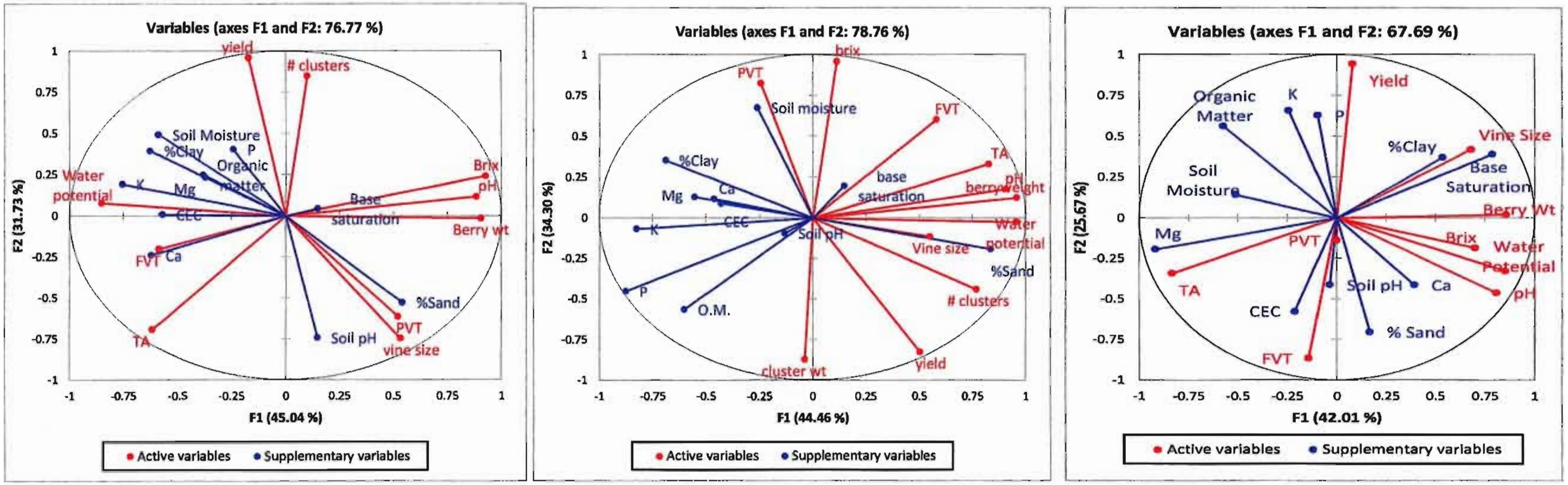
Supplemental Figure 3.6g. Spatial distribution of soil texture, Paragon Vineyards, Jordan, ON; A: sand (%); B: clay (%).



Supplemental Figure 3.7g. Spatial distribution of soil physical properties, Paragon Vineyards, Jordan, ON; A: Organic matter (%); B: Cation exchange capacity (meq/100 g soil); C: soil pH; D: soil base saturation as Ca (%).



Supplemental Figure 3.8g. Spatial distribution of soil composition, Paragon Vineyards, Jordan, ON; A: K; B: P; C: Ca; D: Mg


2005

2006

2007

Supplemental Figure 3.9g. Principal component analysis of viticulture and soil variables for Paragon Vineyards, 2005-2007. *Supplementary variables in blue are soil variables.*

Chapter 4: Spatial Variation of Berry Composition within Riesling Vineyards in the Niagara Peninsula

JAMES J. WILLWERTH and ANDREW G. REYNOLDS

Abstract

Spatial variability of berry composition was studied over a 3 year period within ten commercial Riesling vineyards in the Niagara Peninsula. These vineyards were delineated using global positioning systems (GPS) and 75 to 80 sentinel vines were georeferenced within a sampling grid for data collection. During the 2005 to 2007 growing seasons, vine water status measurements [midday leaf water potential (ψ)] were collected bi-weekly from a subset of these sentinel vines. Data were collected on soil texture and composition, soil moisture, vine water status, and fruit composition. These variables were mapped using GIS software and relationships between them were elucidated. Temporal stability in the spatial patterns of soil texture and composition, soil moisture, vine water status, soluble solids (Brix), titratable acidity and monoterpenes was examined. Spatial trends in terms of vine water status and/or soil moisture were temporally stable in most vineyards. Fruit composition variables were not as stable over a three year period. Brix and potentially volatile terpenes (PVT) were temporally stable in seven vineyards over the course of the study [Chateau des Charmes, Flat Rock, Glenlake (Brix only), Henry of Pelham, Myers, Paragon, Lambert (Brix only), Cave Spring (PVT only) and Vailmont (PVT only)]. Spatial trends in free volatile terpenes were only temporally stable in three vineyards (Chateau des Charmes, Glenlake, Myers). In general, the spatial distribution of fruit composition was not as consistent on a year to year basis as vine water status or vine performance.

Keywords: Terroir, precision viticulture, vine water status, fruit composition

Introduction

The terroir concept can be defined as an interactive ecosystem, in a given place, including climate, soil, and the vine (van Leeuwen and Seguin 2006). The main influence of soil on wine quality seems to be based on physical properties and soil water holding capacity and/or drainage characteristics (Seguin 1986). Studies of soil physical properties, such as soil texture and their relationship with vine performance, have demonstrated that significant variations may exist within single vineyards (Hall et al. 2002). Precision agriculture techniques have been used to study variation in countless instances involving many crops including grapes. Spatial variability in soil, climatic conditions, pests, and disease, has been associated with yield and some fruit composition variables (Bramley and Hamilton 2004, Cortell et al. 2005, Hall et al. 2002). Greenspan and O'Donnell (2001) investigated the spatial variability within two vineyard blocks. They were able to distinguish between high and low vigour zones and found that these "management zones" had significantly different means of yield, Brix, and water status. Cortell et al. (2007, 2008) studied a number of yield and fruit quality indices in Oregon Pinot noir vineyards and found that vine vigour associated with soil and water availability had an impact on fruit composition, particularly phenolics. Bramley (2005) found that Cabernet Sauvignon vineyards in Coonawarra varied in a number of fruit quality parameters and there was some consistency from year to year. Intra-annual variation was greater for some quality indices, such as phenols, than, for others such as Brix (Bramley 2005). Many terroir-related studies indicate that water availability and vine water status are the means by which terroir affects wine style and quality (Koundouras et al. 1999, Penavayre et al. 1991, Peyrot des Gachons et al. 2005, Seguin 1983). Yet, the impact of site and vine water status on grape/wine composition has not been widely addressed, at least not with important environmental factors and cultural practices kept constant, particularly in New World wine regions. Research has indicated that changes in vine water status can impact vine growth, fruit composition, yield and aroma compounds (Tregoat et al. 2002, van Leeuwen and Seguin 2006). Therefore, studying within-site variation in soil, vine water status, and fruit composition variables can help elucidate terroir effects while keeping key environmental factors such as mesoclimate constant.

Precision viticulture techniques, including global positioning systems (GPS) and geographic information systems (GIS), are being utilized to study variations within vineyards in the Niagara Peninsula.

To date, few studies have been conducted to determine how terroir influences wine varietal character in the Niagara Peninsula, ON. Some studies have indicated that vine size and soil texture can have some effects on fruit composition and sensory characteristics of wines, but the findings were not consistent from year to year (Reynolds et al. 2007). Therefore, this study attempted to further understand the basis of terroir in Riesling vineyards within sub-appellations of the Niagara Peninsula. The specific primary objectives of this study were to demonstrate the influences of soil texture, soil water content, and vine water status on fruit composition within vineyard blocks, and to delineate these terroir effects using GPS and GIS. It was hypothesized that consistent water status zones can be identified within vineyard blocks and that vine water status will play a major role in fruit composition, whereas soil will play a role through its water holding capacity and water supply to the vine.

Materials and Methods

Refer to Chapter 3 for detailed methodology. Additional methods concerning fruit composition are described below.

Viticultural data collection. For each sentinel vine, data were collected annually at harvest each season. Fruit was sorted based on vine water status and retained for winemaking. Clusters were counted from each sentinel vine and samples of 100 berries were taken for determination of berry weight and standard fruit composition indices (Brix; titratable acidity; pH), whereas a sample of 250 berries total were taken for monoterpene concentration analyses.

Fruit composition. Each 100-berry and 250-berry sample was weighed to determine the mean berry weight. The frozen berry samples were then heated in 250-mL beakers to an internal temperature of 80 °C in a Fisher Scientific Isotemp 228 water bath (Fisher Scientific, Ottawa, ON) to dissolve any precipitated tartaric acid. The heated berry samples were then cooled, juiced in a laboratory juicer (Omega Products Inc., Harrisburg, PA, model 500), and an approximately 35-mL portion was clarified using a IEC Centra CL2 Centrifuge (International Equipment Co., Needham Heights, MA) to remove large particles that might cause problems with the autotitrator sampling mechanism. Soluble solids (expressed as °Brix) were measured on the unclarified berry juice samples using a temperature-compensated Abbé bench refractometer (American Optical Corp., Buffalo, NY, model 10450). The pH was measured using an Accumet pH/ion meter Model AR50 (Fisher Scientific, Ottawa, ON). Titratable acidity (TA) was measured on 5 mL clarified samples using a Man-Tech PC-Titrate autotitrator (Man-Tech Associates Inc., Guelph, ON, model PC-1300-475). Samples were titrated to a pH 8.2 endpoint with a 0.1 N NaOH solution. Results were expressed as tartaric acid equivalents (g/L). Monoterpenes were analysed for the 250-berry samples using the method developed by Dimitriadis and Williams (1984) as modified by Reynolds and Wardle (1989). The free volatile terpene (FVT) and potentially-volatile terpene (PVT) concentrations were expressed as mg/kg. A large database was compiled annually on these sentinel vines for all yield and berry composition variables.

Statistical analysis. SPSS (Chicago, IL) was used for correlation analyses. Pearson correlation coefficients were determined between soil composition, soil texture, vine water status, soil water content, and fruit composition (Brix, TA, pH, FVT, PVT) for all vintages. Through the use of XLSTAT, principal component analyses were conducted to elucidate relationships among soil, water status, yield, and vine performance variables. Soil variables were used as supplementary variables for PCA. MapInfo and Vertical Mapper (Northwood GeoScience, Ottawa, ON) were used to construct geospatial maps of all variables. These maps, correlation analyses and PCA were used to examine spatial variation for selected variables in each season, and to compare spatial relationships between correlated variables.

Results

General comments. All results shown are from the 2005-2007 growing seasons. Meteorological data depicting temperature and rainfall events for each growing season are depicted in Figure 4.1. There were drought periods in all three growing seasons but this was particularly the case in 2005, and the very hot and dry 2007 vintage. The 2006 growing season was marked by cooler and wetter periods later in the season, particularly in late August, September and October. Through the use of GPS and GIS technologies, the data collected from each vintage were depicted spatially and analysed to examine spatial trends and relationships. Examples of such maps from representative vineyard blocks are depicted in Figures 4.2a through 4.4c. Interpretation of the entire data set was assisted through correlation tables and PCA biplots but the results section is further divided in sections (A-G) detailing the within-site findings from Riesling vineyards used for this study that had three complete years of data collected. Each section is subdivided into geospatial maps depicting spatial relationships of soil, viticulture and fruit composition variables for each site followed by PCA results and interpretations. Tables of point correlations for each vineyard are also included. All of the within-site tables and figures can be found under Supplementary Tables and Figures at the conclusion of this chapter. Soil variables and water potential figures for vineyard sites are found in Chapter 3.

Within-site results. **Section A.** Myers Vineyard (Lincoln Lakeshore sub-appellation), Vineland, ON, 2005-2007.

Consistent water status zones were identified within vineyard sites in 2005, 2006 and 2007. Spatial relationships in vine water status were temporally stable and correlated, despite different weather conditions experienced during each of the growing seasons. Furthermore, from Figures 4.2a to 4.4a and Supplemental Figures 4.1a to 4.4a, it can be seen that many fruit composition variables and spatial relationships were also temporally stable from 2005 to 2007. Spatial trends in Brix (Suppl. Figure 4.1a) were temporally stable over three years of the study. However, there was not much variation within the vineyard. Brix demonstrated good spatial relationships with soil moisture (Fig 4.2 to 4.4a) and vine water status. Berry TA (Suppl. Figure 4.2a) had some areas of temporal stability, particularly from 2006-07. The 2007 season had the lowest TA, which could probably be related to the hot, dry growing season. Some of the inconsistencies observed in 2005 are related to winter injury and the presence of secondary clusters with later development. Some spatial relationships were observed in terms of TA and vine water status. In general, areas of less negative water status had higher TA values. Brix and TA were inversely related spatially. Spatial trends of FVT (Suppl. Figure 4.3a) and PVT (Suppl. Figure 4.4a) were fairly stable over the three year period and there were some relationships with vine water status (Figures 4.2 to 4.5a). Generally, areas of more negative water status had higher concentrations of monoterpenes. Monoterpene concentrations were highest in the 2006 vintage, particularly in the case of PVT (Fig. 4.3a). No clear spatial relationships existed between Brix and flavour compounds.

PCA showed that soil moisture, vine water status, vine size, berry weight and Ca were correlated with TA in all three vintages (Suppl. Figure 4.5a). These same variables were not correlated with Brix in the hotter and drier 2005 and 2007 vintages, and inversely correlated with Brix in 2006. OM was associated with terpenes in 2005 and 2006, as was sand in 2006. In general, yield was inversely related to Brix and terpenes. Brix and flavour compounds were generally highly but inversely correlated with TA. From Supplemental Table 3.1a soil moisture was negatively correlated with pH in 2005 but positively correlated in 2007 at $p<0.05$. Soil moisture was negatively correlated ($p<0.05$) with Brix in 2006. In 2005, organic matter (OM) and cation exchange capacity (CEC) were both positively correlated with TA at $p<0.01$ and $p<0.05$, respectively. Calcium (Ca) was negatively correlated with PVT in both 2005 and 2006 at $p<0.01$. In 2006 soil pH was negatively correlated ($p<0.05$) with Brix and TA in 2007. Also in 2007 phosphorus (P), and OM were correlated with berry pH. Multiple significant correlations ($p<0.05$) were found in respect to monoterpenes in 2007. Clay content, magnesium (Mg), and CEC were all positively correlated with FVT whereas base saturation (BS) was negatively correlated. BS, Ca, and soil pH were all negatively correlated with PVT.

Section B. Glenlake Vineyards (Niagara Lakeshore sub-appellation), Niagara-on-the-Lake, ON, 2005-2007.

Consistent zones of vine water status and soil moisture were found in 2005, 2006, and 2007 despite different weather conditions (Ch. 3). Spatial trends in Brix (Suppl. Figure 4.1b) were inconsistent over the period of this study. There were some spatial relationships with vine water status in some areas of the vineyard (Figures 4.2 to 4.4b). The differences in Brix in 2005 might have been related to winter injury and its impact on vine performance and health. TA (Suppl. Figure 4.2b) and FVT (Suppl. Figure 4.3b) were fairly temporally stable from 2005-07. Some excellent relationships were also found between water status and flavor compounds (Figures 4.2b and 4.4b), particularly in 2005.

Through PCA, some relationships were observed (Suppl. Figure 4.5b). In 2005, water status, soil moisture and vine size were correlated. Water status was highly correlated with fruit composition. More negative water status values were related to higher Brix, terpenes and pH in this vineyard for 2005. As expected, Brix, terpenes, and pH were all highly correlated. In 2006, soil moisture and vine water status were not correlated but water status, Brix, vine size and FVT were correlated. Soil moisture was highly correlated with yield, TA and clay content in the soil. In 2007, many variables were highly correlated. Vine water status and terpenes were highly correlated as were OM and soil pH, while being inversely correlated to TA. Soil moisture, Brix, pH and sand content were also highly positively correlated to each other and inversely correlated to yield.

In 2005, FVT were correlated with vine water status and PVT were highly correlated at $p<0.01$ (Suppl. Table 4.1b). Sand content was also highly correlated ($p<0.01$) to FVT. Soil Mg was correlated with Brix and PVT at $p<0.01$. CEC was negatively correlated with Brix and positively correlated with TA at $p<0.01$. In 2006, many of the correlations did not exist as they did in 2005. Soil calcium was correlated ($p<0.05$) with berry pH and P was correlated ($p<0.01$) to PVT. In 2007, soil moisture was correlated ($p<0.05$) to PVT and soil Mg was correlated to FVT at $p<0.05$. CEC was correlated to berry pH ($p<0.05$). Therefore, in the hotter, drier years of 2005 and 2007, there were more consistent relationships and correlations found between soil moisture and vine water status, and monoterpenes.

Section C. Chateau des Charmes (St. David's Bench sub-appellation), Niagara-on-the-lake, ON, 2005-2007.

This site was one of the vineyards that demonstrated temporal consistency in terms of spatial variability. Many of the variables were temporally stable for this vineyard despite different weather conditions experienced in the 2005, 2006, 2007 growing seasons. These included vine water status (Ch. 3), Brix, TA and both FVT and PVT (Suppl. Figures 4.1 to 4.4c). Vine water status was highly spatially related to both FVT and PVT in both 2005 and 2006 (Figures 4.2 to 4.4). From the geospatial data in chapter 3, water status and berry weight had some excellent spatial relationships with many fruit composition variables including Brix, TA, and terpenes. Therefore, water status may have been impacting these variables indirectly through a higher skin to juice ratio as a result of smaller berries. Many of these findings can be further explained through results of PCA (Suppl. Figure 4.5c). In both 2005 and 2006 water status was shown to be highly positively-correlated with berry weight, Brix and pH. These same variables were also shown to be highly negatively-correlated with FVT and PVT, vine size and yield. The same trends were shown in 2007, except that vine water status was not correlated with yield or pH. Therefore, more negative water status (i.e., water stress) seemed to have a positive impact on fruit composition resulting in higher flavour compound concentrations. Soil moisture was negatively correlated ($p<0.05$) with pH in 2005 and TA in 2006 and 2007 at $p<0.01$ (Suppl. Table 4.1d). Soil moisture was also positively correlated with Brix in both 2006 ($p<0.05$) and 2007 ($p<0.01$). OM was positively correlated with TA in 2005 at $p<0.05$ and FVT and PVT in 2006 at $p<0.01$ and 0.05 respectively. Soil pH, Ca, and CEC were all negatively correlated ($p<0.01$) with Brix in 2005. Soil K was inversely correlated with TA in 2005 and pH and FVT in 2006, while P was related to FVT in 2006 at $p<0.05$ in all cases. In 2007, soil pH, Ca and CEC were all inversely correlated ($p<0.05$) to berry pH.

Section D. Cave Spring Cellars (Beamsville Bench sub-appellation), Beamsville, ON, 2005-2007.

Contrary to other vineyards, this site did not show temporal stability for many of the variables studied. Possible reasons for this are explained in chapter 3 of this dissertation. Only some areas of the vineyard were stable for fruit composition variables. Spatial trends in terms of Brix (Suppl. Figure 4.1d) were not very consistent or stable from 2005-07. TA (Suppl. Figure 4.2d) spatial patterns were stable for 2005 and 2007 but in the wetter 2006 vintage, the patterns were opposite. From Supplemental Figures 4.3 and 4.4d, there were some areas showing temporal stability in terms of monoterpenes, whereas in some regions of the vineyard, flavor compounds were the highest for both years.

Some relationships were depicted through PCA (Suppl. Figure 4.5d). In 2005, water status was highly correlated with PVT, clay soils, CEC, and Ca while showing no correlation with soil moisture. It was also inversely correlated with yield, berry weight, and vine size. Soil moisture, however, was highly correlated with sandy soils, vine size, yield, TA and P. FVT and Brix were correlated with sand and soil pH. In 2006, leaf ψ and soil moisture were both highly correlated as well as yield, vine size, yield, OM, and K. All of these variables were inversely correlated with Brix, TA, and terpenes. In 2007, vine water status was correlated with Brix and pH and inversely correlated to terpenes.

In 2005, FVT were correlated with OM ($p<0.01$) and P ($p<0.05$) (Suppl. Table 4.1d). OM was also negatively correlated ($p<0.05$) with Brix. In both 2005 and 2006 soil BS was inversely correlated with FVT at $p<0.05$. In 2006, sand was negatively correlated ($p<0.05$) with TA. In 2007, both soil moisture and CEC were correlated to PVT at $p<0.05$ and $p<0.01$, respectively.

Section E. Flat Rock Cellars (Twenty Mile Bench sub-appellation), Jordan, ON, 2005-2007.

Results from geospatial maps showed that many variables under study appeared to be temporally stable from year to year despite different weather conditions experienced in each growing season. Vine water status was temporally stable for the most part with consistent water status zones demonstrated in each year as shown in Chapter 3. Some spatial trends in terms of Brix (Suppl. Figure 4.1e) were observed from 2005-07 with only some sections showing inconsistencies. Many of these can be related to areas of poor vine health due to winter injury, particularly in the west end of the vineyard. TA (Suppl. Figure 4.2e) was similar to Brix in terms of spatial variability and temporal stability. Areas of higher Brix had lower TA as expected. Values of Brix were fairly consistent over three years but TA was highest in 2006. Spatial trends in FVT (Suppl. Figure 4.3e) were inconsistent over the course of the study but did not vary tremendously either. Better spatial trends were observed with respect to PVT (Suppl. Figure 4.4e). Trends were generally stable in PVT and were lowest in 2007.

Through PCA (Suppl. Figure 4.5e) it was found that soil moisture and vine water status were not correlated in 2005. However, vine water status was positively correlated with PVT, K, and sand content, while being negatively correlated with vine size and berry pH. Soil moisture, on the other hand, was more correlated with TA and yield. In 2006, leaf ψ and soil moisture were more closely related, showing a higher positive correlation. From PCA factor loadings (data not shown); vine water status was negatively correlated with yield, TA and terpenes. In 2007, leaf ψ, soil moisture, sand percentage, and OM were highly correlated with Brix and TA and inversely related to berry weight and terpenes, therefore indicating that more negative water status and less moisture resulted in wines with lower TA and higher flavour compounds.

From Supplemental Table 4.1e, vine water status was highly correlated with PVT in 2005 and correlated with pH ($p<0.01$) in 2006 and Brix and TA in 2007 at $p<0.05$. Soil moisture was correlated with Brix in 2007 and negatively correlated to pH in 2005 at $p<0.05$. Soil Ca and CEC were inversely correlated ($p<0.05$) to Brix in 2005. OM was negatively correlated with TA in 2005 but correlated in 2007 at $p<0.05$. OM was correlated with both FVT and PVT in 2006 but negatively correlated with FVT in 2007 at $p<0.05$. Soils with higher clay content were negatively correlated ($p<0.05$) with FVT and PVT in 2006. Percent sand, OM and K ($p<0.01$) were correlated with TA in 2007 whereas soil pH and Ca were inversely correlated at $p<0.05$.

Section F. Henry of Pelham (Short Hills Bench sub-appellation), St. Catharines, ON, 2005-2007.

Spatial trends in Brix (Suppl. Figure 4.1f) were temporally stable from 2005-2007 and the values were also consistent from year to year, despite differences in growing seasons. TA (Suppl. fig. 4.2f) was transient in nature, whereby in 2005 and 2007 it was spatially similar, but in 2006 the trend was completely the opposite within the vineyard. FVT (Suppl. Figure 4.3f) and PVT (Suppl. fig. 4.4f) demonstrated some stability in terms of their spatial trends within the vineyard. Little variation was observed with respect to FVT but there was more variation in PVT. Monoterpene concentrations were highest in 2006 as shown in Suppl. Figures 4.3 and 4.4f. PCA (Suppl. Figure 4.5f) demonstrated that leaf ψ was positively correlated with TA and inversely correlated with percent clay and pH. In 2006, vine water status was non-correlated to Brix, pH, and TA but correlated to monoterpenes. In 2007, monoterpenes were inversely correlated to soil moisture, and Brix and TA were correlated to leaf ψ and percent sand.

From Suppl. Table 4.1f, OM was correlated ($p<0.05$) with TA as well as FVT in 2005. PVT were negatively correlated ($p<0.05$) with percent clay in 2005 but non-correlated in 2006. Soil P was correlated ($p<0.05$) with pH in 2005 and TA, Brix, and pH in 2006, albeit negatively in terms of pH. PVT were negatively correlated ($p<0.05$) with soil P. In 2007, leaf ψ was correlated ($p<0.01$) with Brix and inversely correlated ($p<0.05$) with pH. Soil moisture was correlated with both berry pH ($p<0.05$) and FVT ($p<0.01$). Soil K was correlated with PVT in 2007 at $p<0.01$.

Section G. Paragon Vineyards (Creek Shores sub-appellation), Jordan, ON, 2005-2007.

Spatial trends in Brix (Suppl. fig. 4.1g) were fairly temporally stable from 2005-2007. In general, areas of higher Brix corresponded to areas of lower water status. TA (Suppl. Figure 4.2g) had similar spatial trends to Brix but inversely related. Similarly, vine water status seemed to have some relationships in that areas of more positive water status also had higher TA. In general, FVT (Suppl. Figure 4.3g) and PVT (Suppl. Figure 4.4g) both had some areas of temporal stability but were inconsistent in from year to year. Many relationships were found through PCA (Fig. 4.5g). In 2005, soil moisture and vine water status were positively correlated with clay content, TA and FVT, whereas berry weight, vine size, sand content, and Brix were negatively correlated. In 2006, vine water status was positively correlated with vine size, berry weight, berry pH, TA and FVT and negatively correlated with OM, P and K. Soil moisture was positively correlated with FVT, PVT, and Brix, while being negatively correlated with yield. In 2007, vine water status was correlated with Brix and pH and negatively correlated with OM, K, and P.

As shown in Supplemental Table 4.1g, vine water status was correlated ($p<0.01$) with berry pH in 2006. A number of soil variables were correlated with fruit composition variables. Soil K was highly correlated with FVT in 2005 ($p<0.05$). In 2006, soil pH was correlated ($p<0.05$) with TA, berry pH, and inversely correlated ($p<0.05$) with PVT. OM, sand, Mg, Ca, and CEC were all correlated ($p<0.05$) with berry pH. Soil P was negatively correlated ($p<0.01$) with FVT. In 2007, soil pH was correlated ($p<0.05$) with Brix, and K was inversely correlated ($p<0.01$) with FVT.

Correlation analysis. 2005-2007. (See Tables 4.2-4.4) Through analysis of the entire data set including all sites, leaf ψ was correlated with TA in both 2005 and 2007. FVT and PVT were correlated with leaf ψ in 2006 and 2007, respectively but inversely correlated with FVT in 2007. Soil moisture was correlated with FVT in both 2006 and 2007 (Figures 4.3 and 4.4). Other fruit composition variables did not exhibit consistent trends with soil moisture. Brix, TA and pH were often correlated with soil moisture but not in a consistent fashion with some years being positively correlated and other vintages being inversely correlated. However, in the hotter, drier years of 2005 and 2007, soil moisture was found to be inversely correlated with TA whereas in the wetter 2006 vintage they were positively correlated. As expected, Brix and TA were inversely correlated. FVT and PVT were correlated with each other and in some years correlated with Brix and generally inversely correlated with TA (Figures 4.2 and 4.4).

Principal component analysis. 2005-2007. (See Figures 4.5 to 4.7) Principal component analysis was used to help interpret the full data set from all the vineyard sites to elucidate relationships between soil, vine water status, and fruit composition. In 2005 (Figure 4.5), Brix was inversely correlated to leaf ψ and correlated with vine size, soil moisture and yield. TA was correlated with sand percentage and was inversely correlated to FVT and PVT and non-correlated with Brix. From Figure 4.6, in 2006, Brix was inversely correlated with soil moisture, yield, vine size and sand percentage whereas TA was correlated to those variables including leaf ψ. PVT and PVT were non-correlated with Brix and TA but correlated with leaf ψ, soil moisture, OM, soil P and K. In 2007 (Figure 4.7), Brix, FVT and PVT were correlated with soil moisture, OM, and soil P and non-correlated with leaf ψ. TA was correlated with sand, yield and inversely related to Brix and monoterpenes.

Discussion

Soluble solids. Spatial variability in Brix was found in every vineyard site (Figs. 4.2a to 4.4c, Suppl. Figures 4.1a to g). However, in general, large variation in Brix did not exist. They varied in the range of 1.5-3 Brix within sites. This is in agreement with research performed in Australia (Bramley 2005) as well as Washington, USA, where Brix varied in Concord vineyards (Davenport et al. 2001).. Soluble solids were temporally stable in seven vineyards over the three year period of the study [Chateau des Charmes, Flat rock, Glenlake, Henry of Pelham, Myers, Paragon, Lambert (data not included)] (Suppl. Figures 4.1a, b, c, e, f, g). Through correlation analysis and PCA, there were often associations between soil moisture and Brix in many of the vineyard sites. However, they were not always consistent in terms of their relationship or from year to year. In general, areas of lower soil moisture had higher Brix levels but this was not always the case and some sites (Chateau des Charmes) consistently demonstrated the opposite effect (Figures 4.2 to 4.4c).

Vine water status was more consistent in its relationship with Brix. Vine water status was found to have an impact on Brix mainly through spatial interpolation maps and PCA. In general, areas of vines with "lower water status" had higher sugar concentrations than areas of "higher water status". This also corresponds to lower soil moisture content. This can be explained mainly due to the indirect impact of vine water status on vegetative growth resulting in less vigorous vines (as shown in Chapter 3) as well as through PCA analysis (Figures 4.5 to 4.7 and Suppl. Figures 4.5a-g). Therefore, it appears that variation in Brix is a result of soil moisture and vine water status and their impact on vine size and berry weight, as shown in Chapter 3.

Vine size and yield components were found to be closely related to sugar concentrations. Some studies indicate that water stress can advance maturity (McCarthy and Coombe 1985) and increase sugar levels (Kliewer et al. 1983). These increases in sugar can be due to a concentration effect resulting from water loss; lower yields (Smart 1974) from water deficit which reduces carbohydrate sinks in the vine; and better fruit exposure due to less vegetative growth (Smart 1974, Smart 1985, Smart et al. 1990). Koundouras et al. (2006) found that lower water potential decreased shoot growth and that water deficit accelerated sugar accumulation and malic acid breakdown. Soluble solid concentrations were also related to berry weight on a number of occasions. These may be a result of a concentration effect. Some studies have shown that water stress can lead to higher final sugar concentrations in the fruit not through gains in sugar production but associated with reductions in berry weight (Hardie and Considine 1976). The findings of this study support that notion. In a few vineyards, such as Chateau des Charmes, low water status vines had lower sugar concentrations (Figures 4.2 to 4.4c). Under water deprivation, the decrease in photosynthesis and sugar export from the leaves can lead to this reduction in berry sugar accumulation (Quick et al. 1992, Rogiers et al. 2004). Esteban et al. (1999) found that higher water availability increased sugar levels due to increased photosynthetic activity or increased leaf area (Carbonneau et al. 1983).

Sugar levels were the highest in 2005 and lowest in 2006, which is indicative of those growing seasons. The 2006 vintage was cooler and wetter (Figure. 4.1) with more vegetative growth (see Chapter 3) that generally resulted in lower sugar levels. The 2005 growing season was very hot and dry and the crop levels were very low due to bud damage caused by the winter of 2004/05. The combination of both of these factors resulted in fruit with higher sugar levels than the other two vintages. This finding is supported through the work published by Jackson and Lombard (1994) and Reynolds (1993) on Brix through the impact of climate and crop level, respectively. There was however, a large variation in Brix in some vineyards due to individual vine variation caused by cold injury, as shown in Figure 4.6b where Brix were as low as 16 in some areas and much higher Brix in subsequent years. The 2007 yield was larger due to a lack of winter injury, but the season was hot and dry, resulting in higher than normal sugar levels in general. The variation was not as great in this particular vintage because there was ample sunshine, heat units and extended dry periods.

No consistent findings were found in terms of soil variables on Brix levels within sites. Soil texture played a minor role in its impact on berry sugar levels. Sand content was inversely related to Brix in a few vineyards, as were Ca, soil pH, and OM. Soil K, P, and Mg also showed few relationships. The findings of this study are in agreement with those of van Leeuwen et al. (2004) who studied the impact of different soil textures on grape maturation of Bordeaux varieties in France. Sandy soils resulted in large berries, low sugars but high acidity. The authors also found that clay soils resulted in berries with the highest sugars and that these soil effects were influenced through vine water status. It was concluded that mineral nutrient uptake by the vine or availability in the soil did not have a significant impact on fruit quality (van Leeuwen et al. 2004).

Titratable acidity. TA was highly variable within vineyard sites. It also was shown to be very transient and spatial trends within vineyards often varied from year to year. As a result, spatial trends in TA were temporally stable in only some vineyards. In a number of cases, spatial trends in TA were consistent in two out of the three vintages. It was generally found that the 2005 and 2007 vintages were consistent which each other. This makes sense because they were similar growing seasons. In other cases, 2006 and 2007 vintages demonstrated consistent spatial trends in TA. This is a result of individual vine variation due to cold injury suffered during the winter of 2004/05. Some damaged areas of vineyards that were affected by winter damage had a number of secondary clusters on the vine that matured later than fruit formed from primary buds and thus had higher TA values. As individual vines became less variable (due to better vine health), more consistent spatial trends were observed. Many of the relationships involving TA were similar to Brix. Soil moisture and vine water status had an impact in some vineyards as shown through spatial interpolation maps, correlation analysis and PCA. In general, areas of higher soil moisture and vines with higher vine water status also had higher TA, similar to a study by Koundouras et al. (Koundouras et al. 1999). Similarly to Brix, this is a result of more vegetative growth and poorer fruit development. A more vigorous canopy results in more shading of the fruit, that can decrease malic acid degradation in the fruit (Kliewer and Lider 1968). TA was generally inversely related to Brix (e.g. Figures 4.2 to 4.4a) but in some cases it was non-correlated. There were few consistent relationships between soil variables and TA. Soil texture seemed to impact TA in only a few cases and it was more of a result of larger vines (more vigour), as shown in Chapter 3. TA was often correlated with percent sand, larger vines and higher yields. These findings are in agreement with those of van Leeuwen et al. (2004) who found that sandy soils in Bordeaux had larger berries and higher acidity.

Monoterpenes. Monoterpenes are an important measurement of fruit composition because they play a major role in the varietal character of Riesling wines. As in the case of Brix and TA, monoterpenes varied spatially within vineyard sites. FVT concentrations were variable within vineyards. However, spatial trends within vineyards concerning FVT were not very temporally stable, partly due to how consistently low their levels were in most of the vineyard sites. Spatial trends in FVTs were only temporally stable in three vineyards (Chateau des Charmes, Glenlake, Myers) (Suppl. Figures 4.3a, b, c). The lack of temporal stability is similar to what Reynolds et al. (2007) found in a Niagara Riesling vineyard where monoterpene spatial distribution varied across different vintages. PVT also varied spatially within vineyards. However, the spatial trends of these monoterpenes were more temporally stable in vineyards than FVT, as temporal stability was found in seven vineyards [Chateau des Charmes, Flat Rock, Henry of Pelham, Myers, Paragon, Cave Spring, Vailmont (data not included)] (Suppl. Figures 4.4a, c, d, e, f, g). Some vineyards showed a remarkable amount of temporal stability for monoterpenes as shown in Supplemental Figures 4.3d and 4.4d. One of the resounding findings was that in every vineyard site, monoterpenes were the highest in the 2006 vintage. The 2005 and 2007 vintages were much hotter and drier than the 2006 vintage. These vintages had vines with lower water status (Fig. 4.2a to 4.4c). This suggests that periods of drought and resultant low vine water status have negative effects on monoterpene concentrations. However, regions within vineyard sites (i.e., Myers) with smaller berry weights seemed to have higher concentrations of FVT and PVT, reflecting the impact of skin-to-juice ratio (Figs. 4.2 to 4.4a). Therefore, it appears from these findings that either high (lack of any deficit) or very low water status can be detrimental to concentration in monoterpenes.

This is a highly interesting finding of this research study. Peyrot des Gachons et al. (2005) found similar results pertaining to vine water status and volatile thiols in Sauvignon blanc grapes, and reported that mild water deficits resulted in higher grape quality. In other studies, limited water availability also increased glycoconjugates of aroma compounds and increased wine quality (Koundouras et al. 2006). McCarthy and Coombe (1985) found that reducing irrigation led to increased concentrations of monoterpenes, but results from Reynolds and Wardle (1997) and Reynolds et al. (2006) indicated that prolonged irrigation deficits reduced these flavour compounds in berries. In the 2006 study, decreasing the duration of water stress increased FVT and PVT at harvest in Gewürztraminer grapevines. Therefore, our research further supports the importance of vine water status and its impact on aroma potential in white wine cultivars, and suggests that mild water deficits appear to maximize aroma potential. No consistent relationships were shown between soil variables and monoterpene concentrations. It should be noted that in some instances OM, P and K were correlated with either FVT or PVT in multiple vineyards and vintages. Nutrient differences have been noted to possibly impact fruit composition. These results are not consistent enough to make any reasonable explanations, however Reynolds et al. (2007) found similar relationships with PVT being correlated with P, and K in Riesling, which is interesting and may require some elucidation through further research. Soluble solids were generally correlated with monoterpene concentrations, which is an indication of general maturity. At times, TA was related to monoterpenes but no consistent trends were found.

Fruit composition variables were not as consistent as vine water status, vine size and yield components, which supports other precision viticulture studies such as Bramley (2005) who found that fruit quality at harvest was considerably less variable than yield (Bramley and Hamilton 2004). While there were some good spatial relationships between vine water status and fruit composition, these relationships were not as strong as those between vine water status and other factors like berry weight and vine vigour (as shown in Chapter 3).

Through the use of precision viticulture techniques, it was found that many viticultural variables could be related to vine water status and vine size in many of the vineyard sites examined. Since water deficits in vines have been shown to reduce shoot growth (Kliewer et al. 1983) and canopy density (Smart 1974), low water status may have altered the canopy characteristics of the vine, ultimately leading to better leaf and fruit exposure and improved fruit composition. Furthermore, many of the relationships between vine size and vine water status demonstrate that water status is greatly influenced by water supply coupled with evaporative demand of the canopy. Total leaf area and exposed leaf area measurements are therefore relevant. Carbonneau (1999) has shown that the ratio of exposed leaf area: yield is an important measurement in relation to vine vigour and that this can impact fruit quality due to sink competition. Similar to this study, Cortell et al. (2007) studied different vigour zones within vineyards and found that vine vigour impacted berry weight, Brix and TA. They attributed variation between vigour zones to soil depth and water holding capacity. Greenspan and O'Donnell (2001) investigated the spatial variability within different vineyard blocks and they were able to distinguish between high and low vigour zones and found that these "management zones" had different yield, Brix, and water status.

Variability is an important concept to understand for vineyard managers to produce consistent premium grapes in all wine producing regions. In Ontario, there is an extreme amount of variability due to direct and indirect effects (i.e., cold injury) of our climate, and therefore there is a critical need to have the necessary tools to study variation of vineyards. Variability in sugar levels is important to understand in situations where grapes are priced based on sugar levels, such as in Ontario. Large variability can have negative economic consequences as one area of low sugars reduces overall sugar levels and can impact the quality and price of the grapes. Therefore, through precision viticulture a better understanding of grape maturity can be used to make wise harvesting decisions.

Conclusions

Vineyards were variable in terms of soil, vine water status and fruit composition. Our hypotheses were upheld in that consistent water status zones can be identified within vineyard sites across the Niagara Peninsula and that these regions are temporally stable despite different climatic conditions. Furthermore, results indicate that some soil variables, and vine water status, may contribute significantly to wine quality through their effects on vine size and fruit composition. For some vineyards, many viticulture and fruit composition variables were also temporally stable. Although, there were some good spatial relationships between vine water status and fruit composition, these relationships were not as strong as those between vine water status and other factors like berry weight and vine vigour. Through the use of precision viticulture technology, it was found that many viticultural variables could be related to vine water status and vine size in most of the vineyard sites examined. Many of these relationships are site-specific. Therefore, this further supports the importance for research on Niagara's unique terroir within vineyard sites, as well as between its sub-appellations.

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Table 4.2 Overall correlations of soil, water status and fruit composition variables for all vineyard sites. Niagara Peninsula, ON. 2005.

Table 4.3 Overall correlations of soil, water status and fruit composition variables for all vineyard sites. Niagara Peninsula, ON. 2005.

Table 4.1. Overall correlations of soil, vine water status and fruit composition variables for all vineyard sites. Niagara Peninsula, ON. 2005.

Variables	Water Potential	Brix	TA	pH	FVT	PVT	Soil Moisture	%Sand	%Clay	soil pH	OM	P	K	Mg	Ca	CEC	BS
Water Potential	**1**	-0.161	**0.199**	0.087	-0.246	-0.183	0.046	0.141	-0.150	0.027	-0.124	0.021	**-0.184**	-0.099	-0.088	-0.147	0.074
Brix		**1**	**-0.474**	0.080	**0.165**	0.089	**0.300**	-0.112	0.129	0.011	-0.090	-0.066	0.025	0.147	0.105	0.080	0.014
TA	*	***	**1**	**0.188**	**-0.364**	**-0.539**	**-0.208**	**0.349**	**-0.317**	**-0.178**	0.040	**0.259**	-0.057	**-0.372**	**-0.233**	**-0.184**	-0.145
pH			***	**1**	-0.056	**-0.364**	**-0.280**	**0.533**	**-0.432**	**-0.293**	**-0.188**	0.079	-0.158	**-0.318**	**-0.354**	**-0.366**	**-0.290**
FVT		*	***		**1**	**0.429**	-0.088	-0.264	**0.403**	0.041	-0.032	-0.232	0.107	**0.454**	0.074	0.106	0.027
PVT			***	***	***	**1**	-0.128	**-0.417**	**0.344**	0.247	-0.033	-0.205	0.202	0.255	**0.302**	**0.330**	0.202
Soil Moisture		***	***	***			**1**	**-0.171**	0.085	**0.338**	0.101	0.146	0.065	0.051	**0.314**	**0.288**	**0.310**
%Sand			***	***		**	*	**1**	**-0.881**	**-0.397**	**-0.239**	0.113	**-0.173**	**-0.495**	**-0.631**	**-0.632**	**-0.307**
%Clay			***	***	**	*		***	**1**	**0.297**	0.092	**-0.207**	0.090	**0.556**	**0.570**	**0.584**	**0.237**
soil pH			*	***			***	***	***	**1**	0.004	0.082	0.002	0.096	**0.799**	**0.662**	**0.833**
OM				*				**			**1**	**0.497**	**0.692**	**0.190**	0.073	0.151	-0.019
P			**						**		***	**1**	**0.556**	**-0.189**	-0.003	0.068	0.072
K	*							*			***	***	**1**	-0.010	0.071	**0.170**	-0.023
Mg			***	***	**			***	*		*	*		**1**	0.114	**0.162**	-0.050
Ca			**	***		*	***	***	***	***					**1**	**0.920**	**0.688**
CEC			**	***		*	***	***	***	***			*	*	***	**1**	**-0.302**
BS				***			***	***	**	***					***	***	**1**

*, **, ***: Significant r values at p<0.05, 0.01, 0.001, respectively.

Table 4.2. Overall correlations of soil, vine water status and fruit composition variables for all vineyard sites. Niagara Peninsula, ON. 2006.

Variables	Water potential	Brix	TA	pH	FVT	PVT	Soil Moisture	%Sand	%Clay	soil pH	OM	P	K	Mg	Ca	CEC	BS
Water potential	**1**	0.015	0.012	0.026	**0.194**	0.055	**0.256**	**0.167**	**-0.198**	**-0.233**	0.067	**0.269**	-0.004	**-0.189**	**-0.289**	**-0.250**	-0.079
Brix		**1**	**-0.168**	**0.521**	-0.065	0.070	**-0.159**	0.052	-0.063	-0.077	**-0.174**	0.018	-0.055	-0.058	-0.059	0.002	-0.005
TA		***	**1**	0.045	**0.199**	-0.078	**0.192**	0.068	-0.094	**-0.218**	0.091	0.017	**0.231**	-0.108	**-0.188**	-0.091	**-0.175**
pH		***		**1**	0.035	-0.030	**-0.248**	0.149	-0.149	-0.053	0.016	**0.239**	**0.200**	**-0.190**	-0.032	0.025	-0.017
FVT	*		*		**1**	**0.570**	**0.365**	-0.152	0.040	-0.012	**0.560**	**0.481**	**0.637**	-0.014	0.038	0.102	0.002
PVT					***	**1**	0.140	**-0.278**	0.152	0.064	**0.365**	**0.294**	**0.334**	0.042	0.163	**0.225**	0.059
Soil Moisture	**	***	***	***	***		**1**	**-0.230**	**0.222**	**-0.175**	**0.448**	**0.157**	**0.331**	**0.371**	-0.095	-0.125	-0.046
%Sand	*					**	**	**1**	**-0.881**	**-0.397**	**-0.239**	0.113	**-0.173**	**-0.495**	**-0.631**	**-0.632**	**-0.307**
%Clay	*						**	***	**1**	**0.297**	0.092	**-0.207**	0.090	**0.556**	**0.570**	**0.584**	**0.237**
soil pH	**		**				*	***	***	**1**	0.004	0.082	0.002	0.096	**0.799**	**0.662**	**0.833**
OM		*			***	***	***	**			**1**	**0.497**	**0.692**	**0.190**	0.073	0.151	-0.019
P	**			**	***	***	*		**		***	**1**	**0.556**	**-0.189**	-0.003	0.068	0.072
K			**	*	***	***	***	*			***	***	**1**	-0.010	0.071	**0.170**	-0.023
Mg	*			*			***	***	*		*	*		**1**	0.114	**0.162**	-0.050
Ca	***		*					***	***	***					**1**	**0.920**	**0.688**
CEC	**					**		***	***	***			*	*	***	**1**	**-0.302**
BS			*					***	**	***					***	***	**1**

*, **, ***: Significant r values at p<0.05, 0.01, 0.001, respectively.

Table 4.3. Overall correlations of soil, vine water status and fruit composition variables for all vineyard sites. Niagara Peninsula, ON. 2007.

Variables	Water potential	Brix	TA	pH	FVT	PVT	Soil moisture	%Sand	%Clay	soil pH	OM	P	K	Mg	Ca	CEC	BS
Water potential	1	0.085	**0.148**	**0.231**	**-0.214**	**0.264**	**0.172**	**0.497**	**-0.416**	**-0.226**	-0.057	**0.267**	-0.009	**-0.324**	**-0.341**	**-0.322**	**-0.175**
Brix		1	**-0.392**	**0.272**	0.021	**0.165**	0.006	0.119	-0.031	-0.072	**-0.154**	-0.034	-0.137	0.046	-0.103	-0.108	-0.023
TA	*	***	1	**-0.354**	**-0.304**	-0.050	**-0.109**	-0.055	0.109	**-0.149**	0.059	0.055	0.121	-0.010	-0.125	-0.078	**-0.164**
pH	**	***	***	1	**0.277**	**0.180**	**0.401**	0.000	-0.047	**0.187**	**0.223**	**0.409**	**0.430**	**-0.160**	0.146	**0.169**	**0.183**
FVT	**		***	***	1	**0.164**	**0.464**	**-0.399**	**0.387**	**0.418**	0.124	0.142	**0.183**	0.085	**0.527**	**0.526**	**0.353**
PVT	***	*		*	*	1	0.112	0.149	-0.048	0.051	**-0.159**	0.140	-0.076	-0.137	0.011	0.030	0.002
Soil moisture	*		**	***	***		1	**-0.226**	**0.234**	**0.246**	**0.259**	**0.375**	**0.305**	0.136	**0.269**	**0.303**	**0.223**
%Sand	***				***		**	1	**-0.881**	**-0.397**	**-0.239**	0.113	**-0.173**	**-0.495**	**-0.631**	**-0.632**	**-0.307**
%Clay	***				***		**	***	1	**0.297**	0.092	**-0.207**	0.090	**0.556**	**0.570**	**0.584**	**0.237**
soil pH	**		*	*	***		**	***	***	1	0.004	0.082	0.002	0.096	**0.799**	**0.662**	**0.833**
OM		*		**		*	***	**			1	**0.497**	**0.692**	**0.190**	0.073	0.151	-0.019
P	**			***			***		**		***	1	**0.556**	**-0.189**	-0.003	0.068	0.072
K				***	*		***	*			***	***	1	-0.010	0.071	**0.170**	-0.023
Mg	***			*				***	*		*	*		1	0.114	**0.162**	-0.050
Ca	***				***		***	***	***	***					1	**0.920**	**0.688**
CEC	***			*	***		***	***	***	***			*	*	***	1	**-0.302**
BS	*		*	*	***		**	***	**	***					***	***	1

*, **, ***: Significant r values at $p<0.05$, 0.01, 0.001, respectively.

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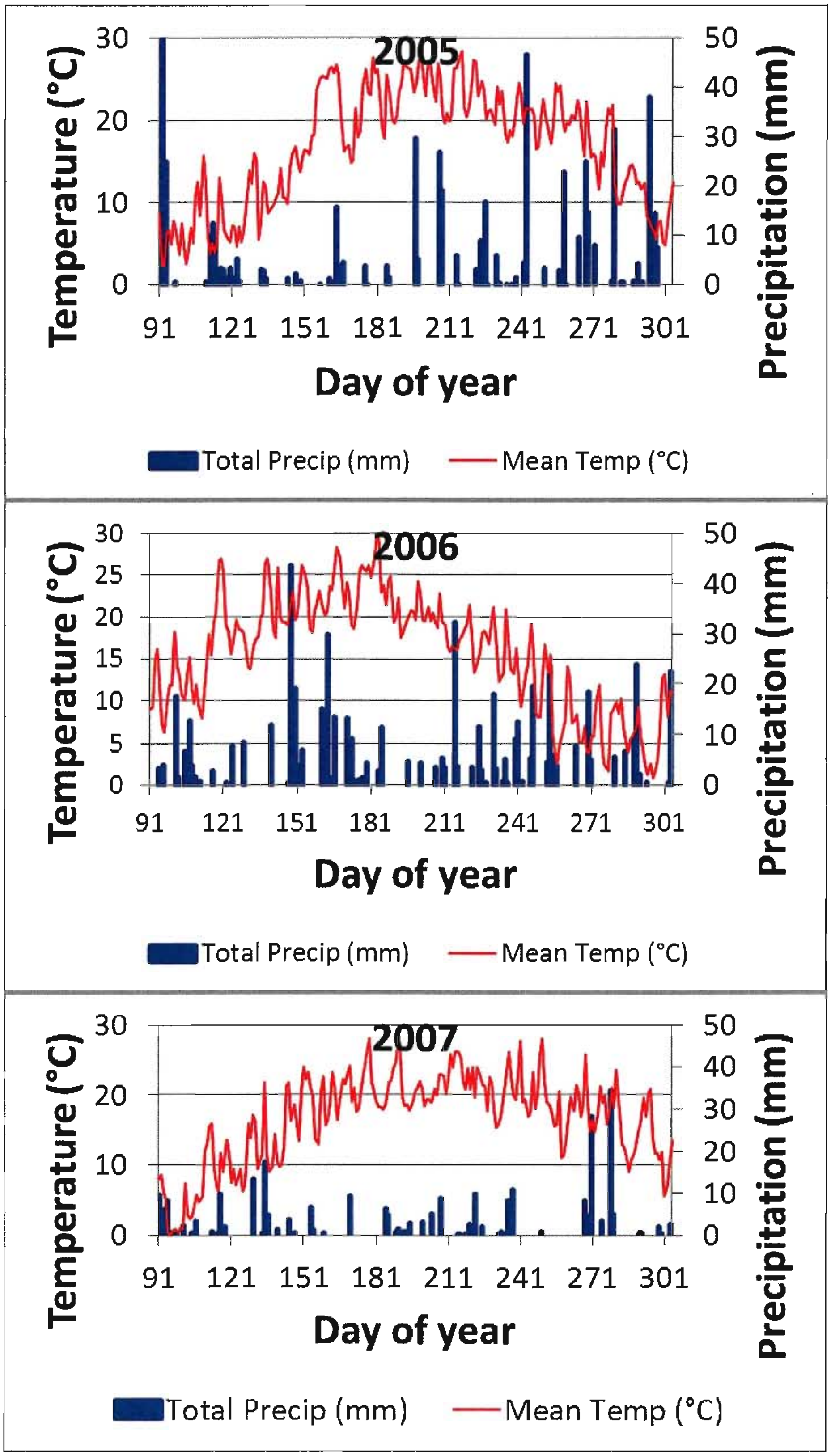

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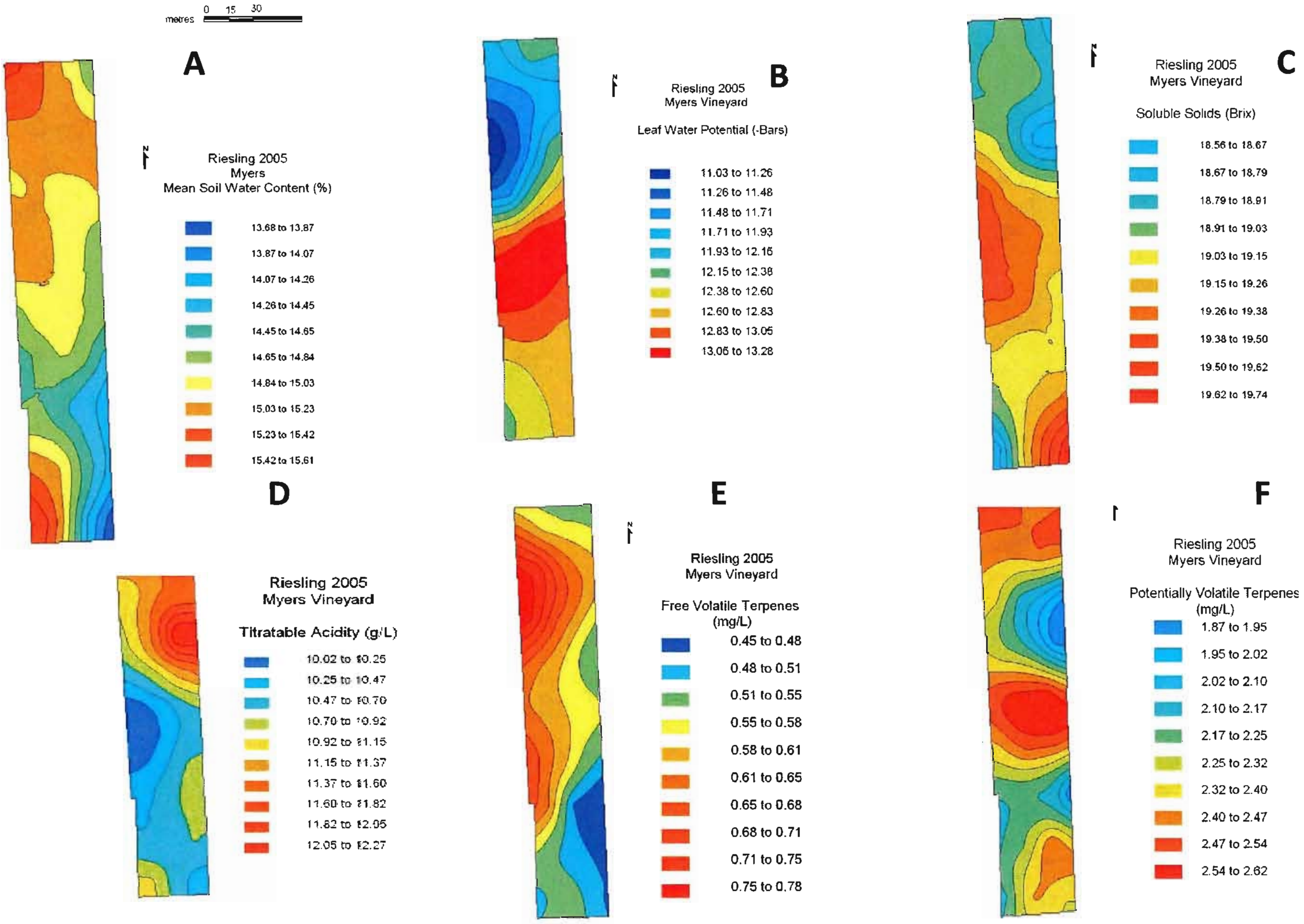

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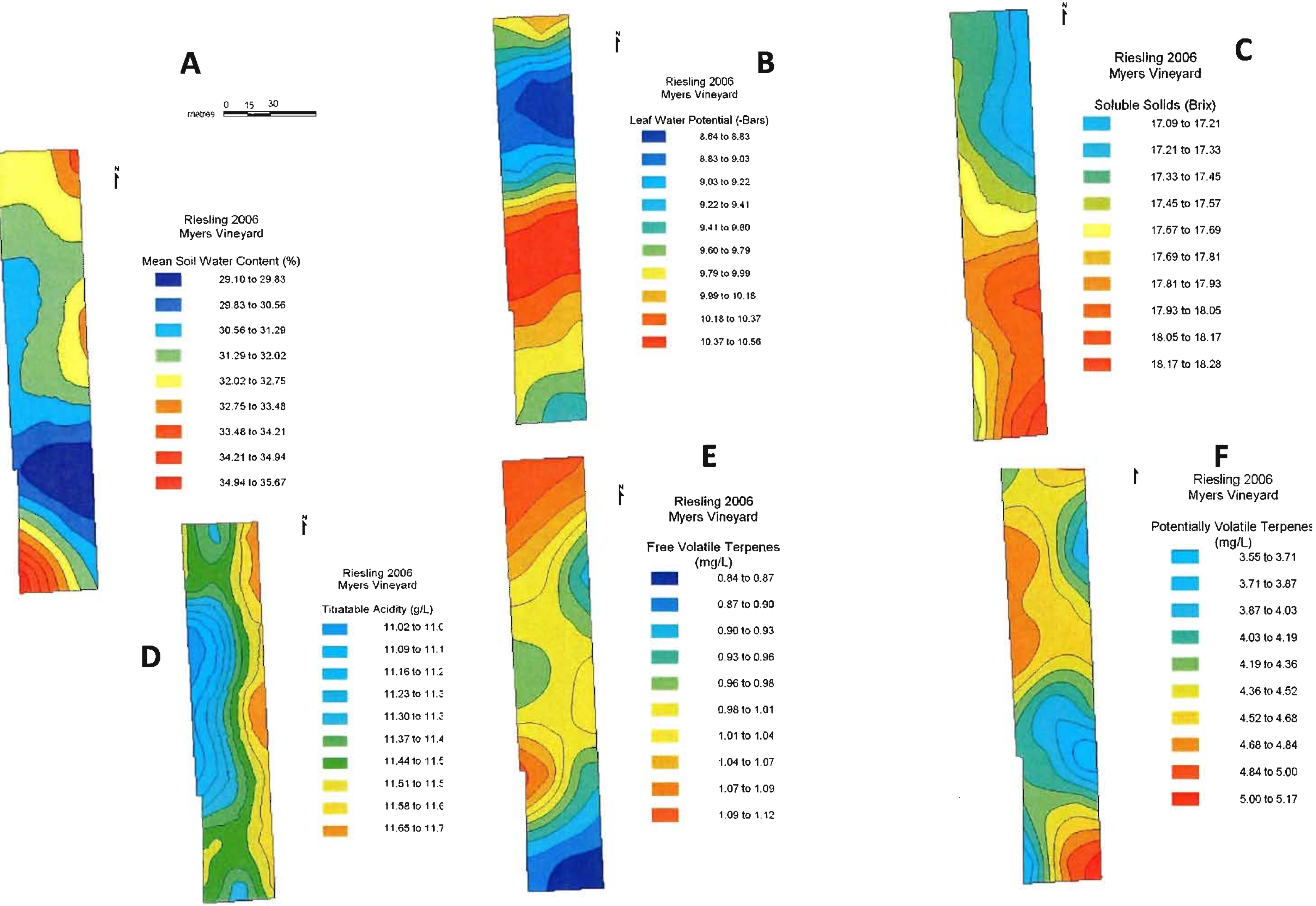

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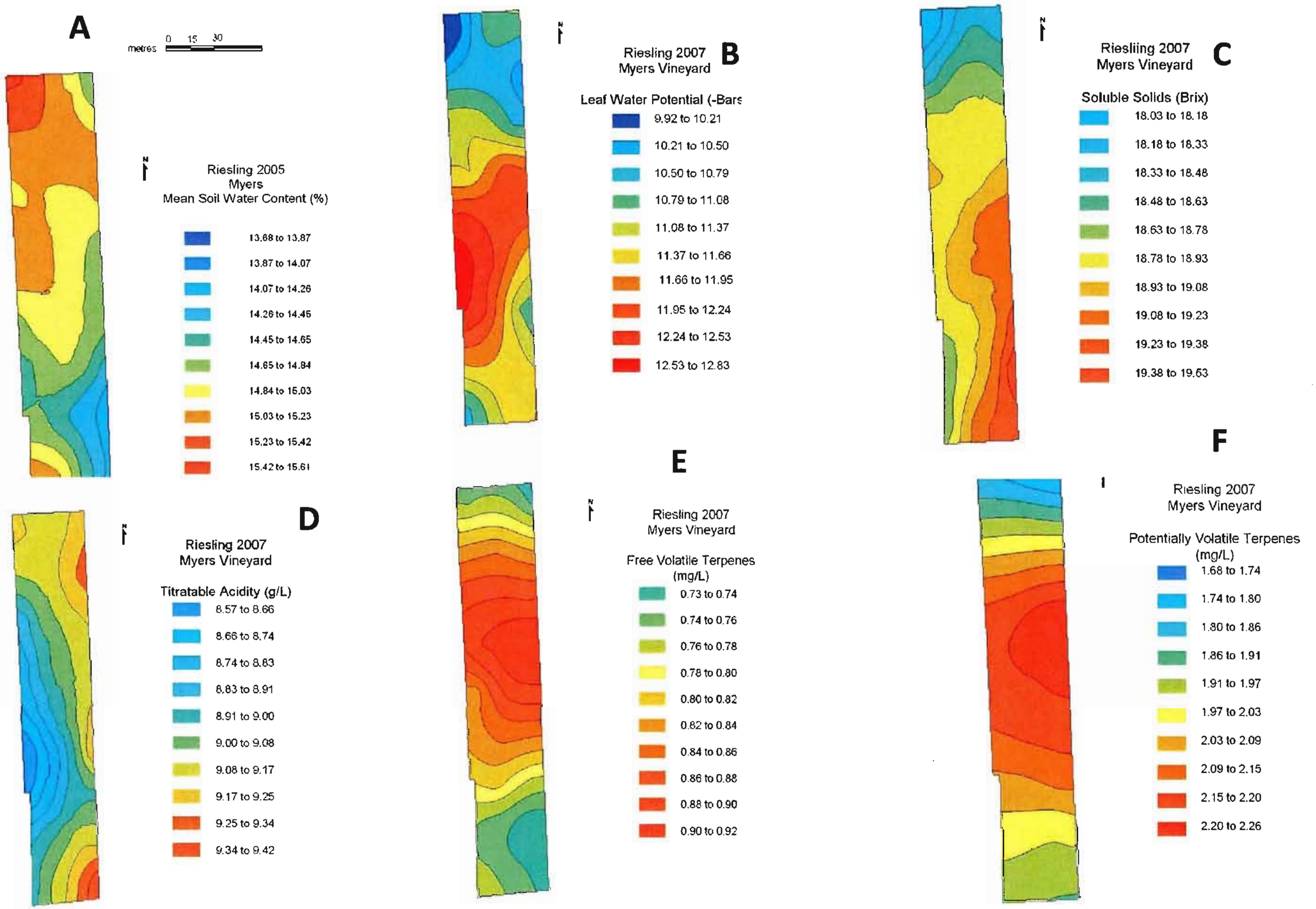

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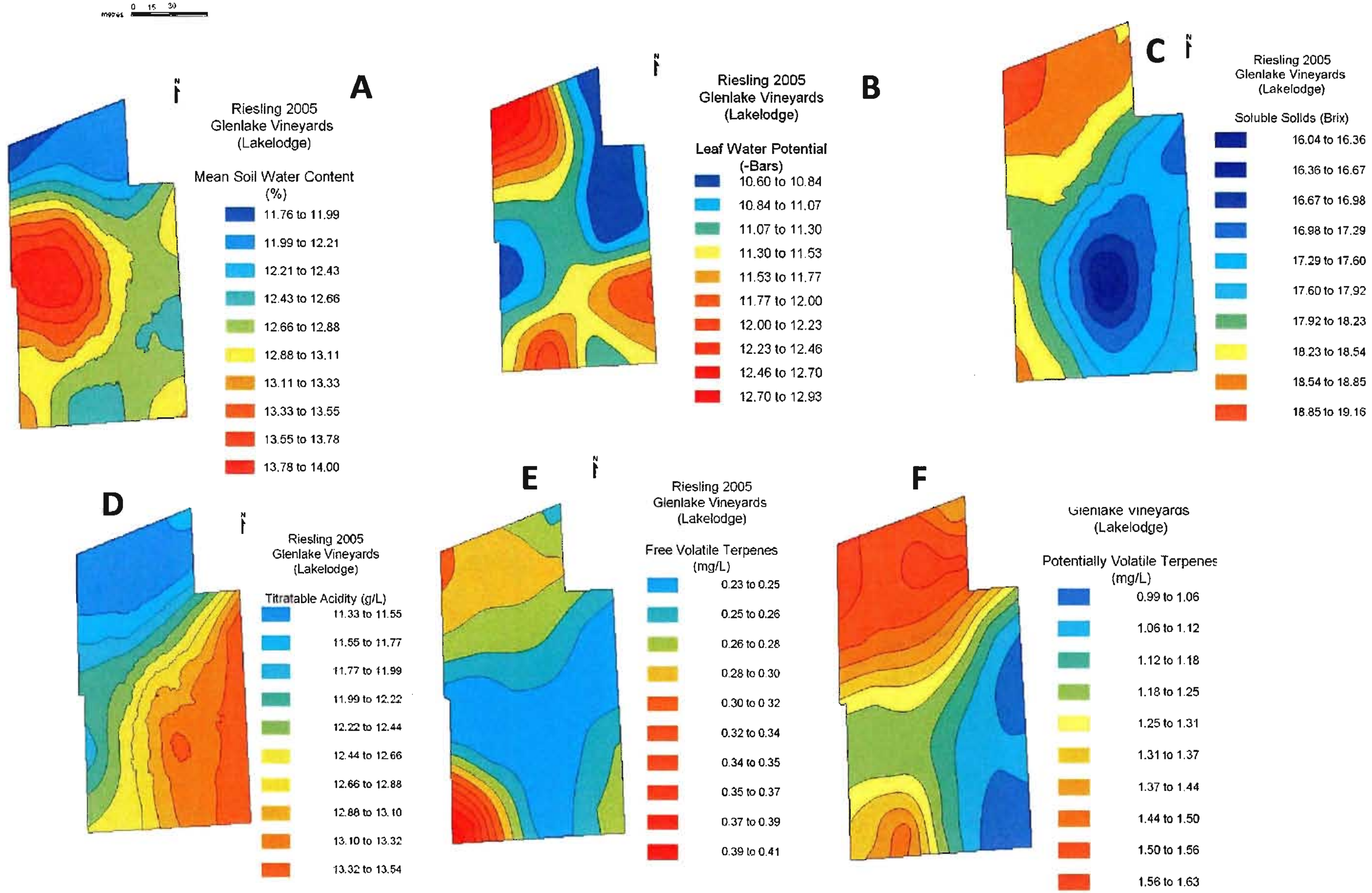

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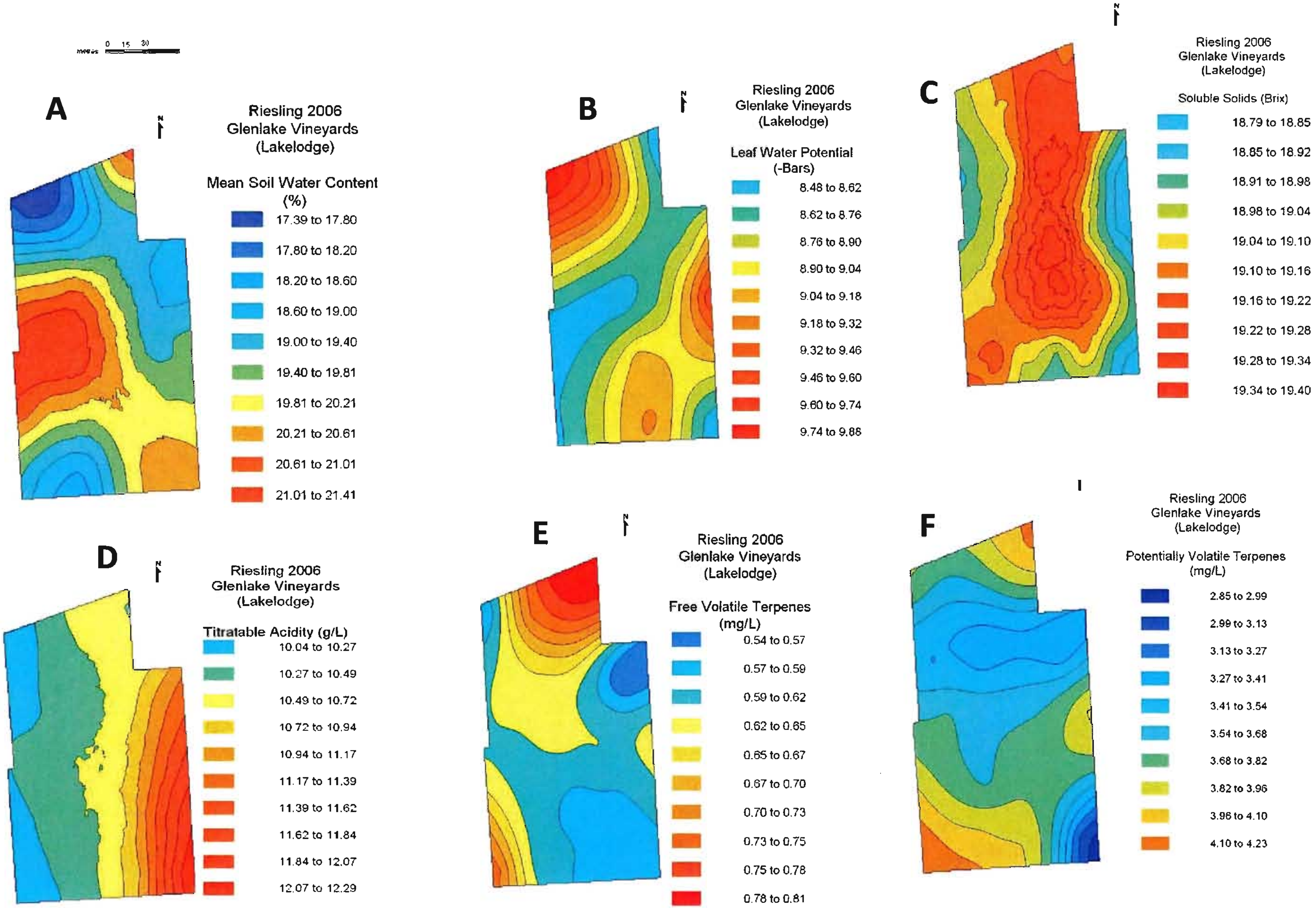

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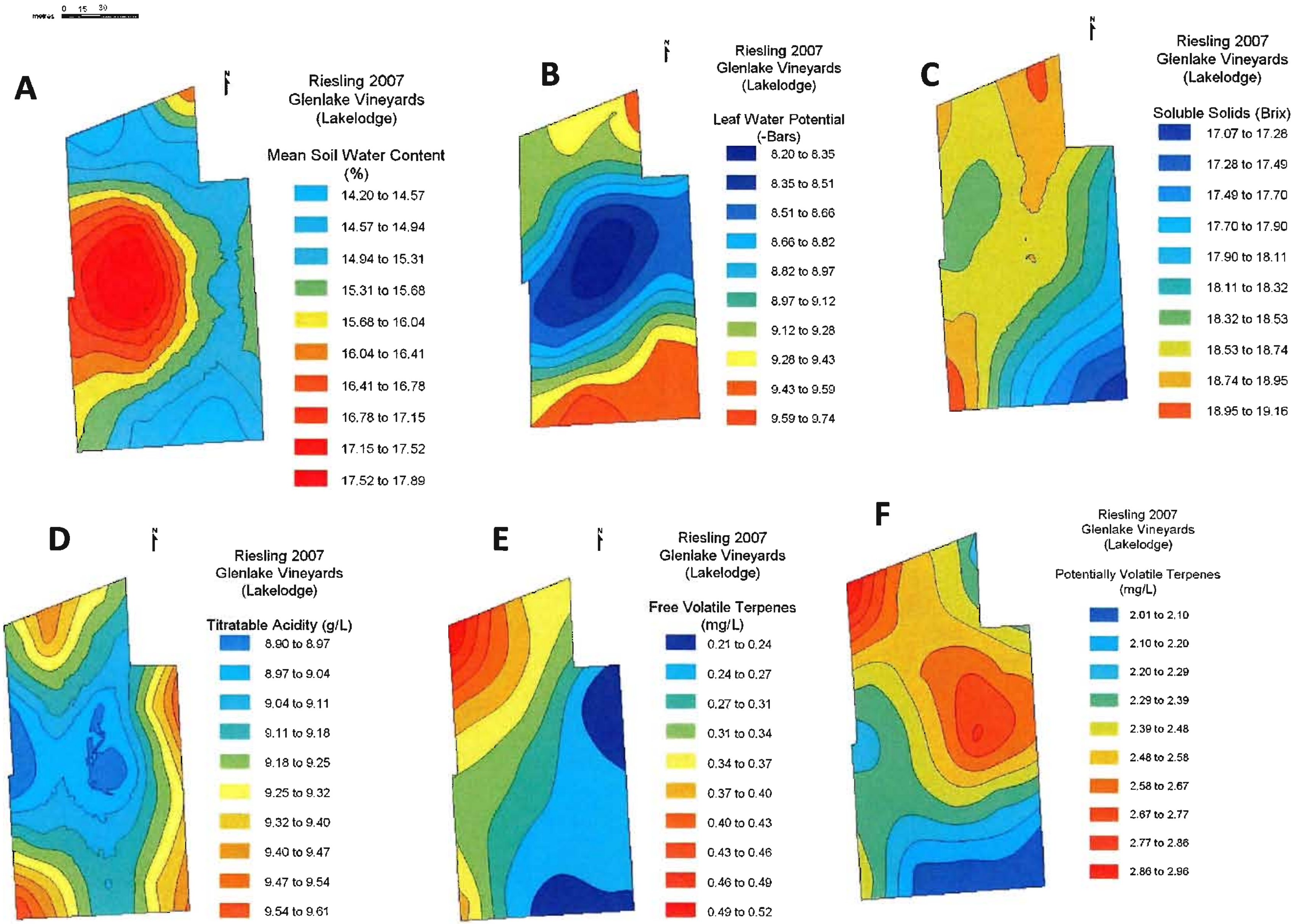

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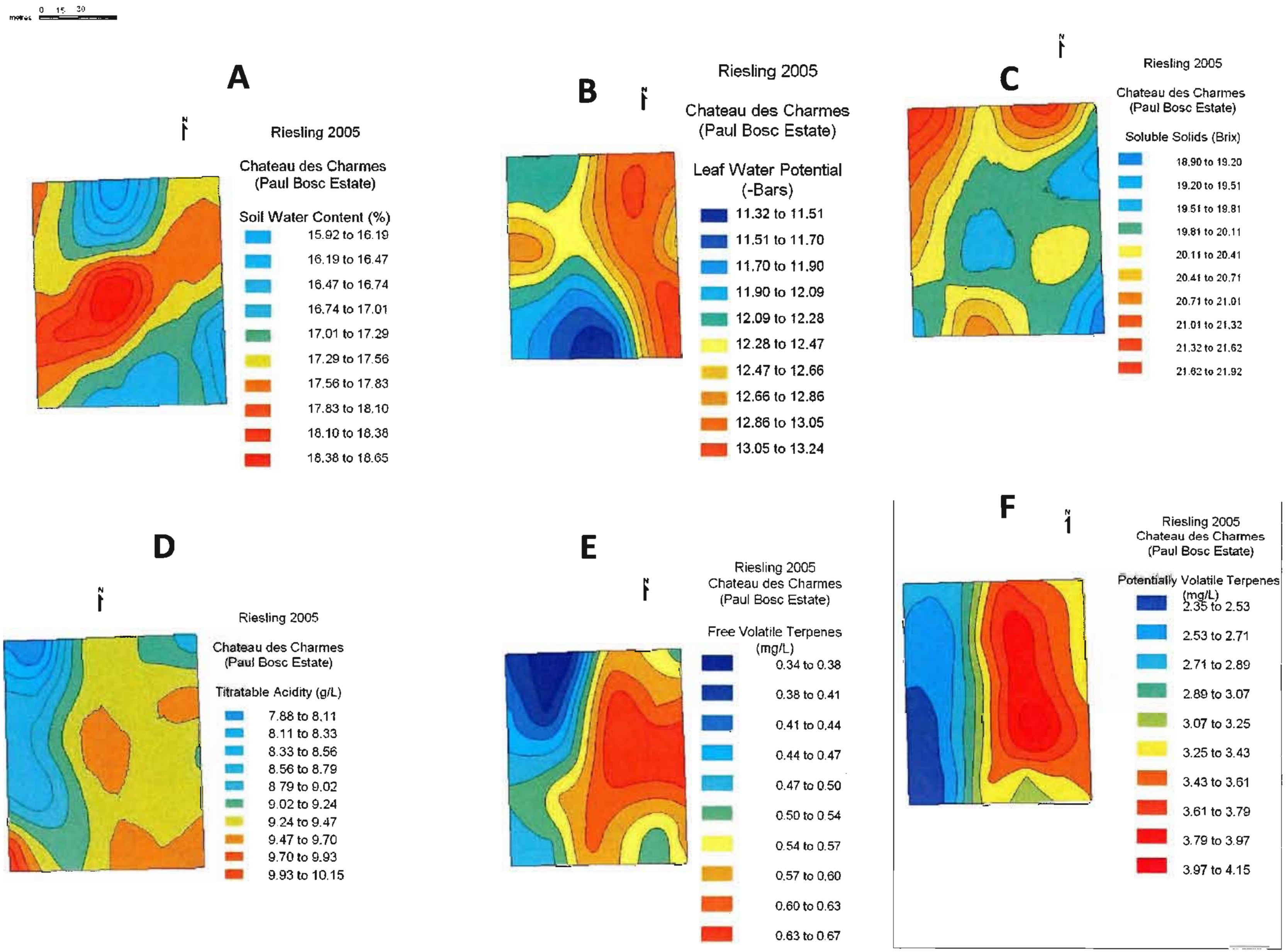

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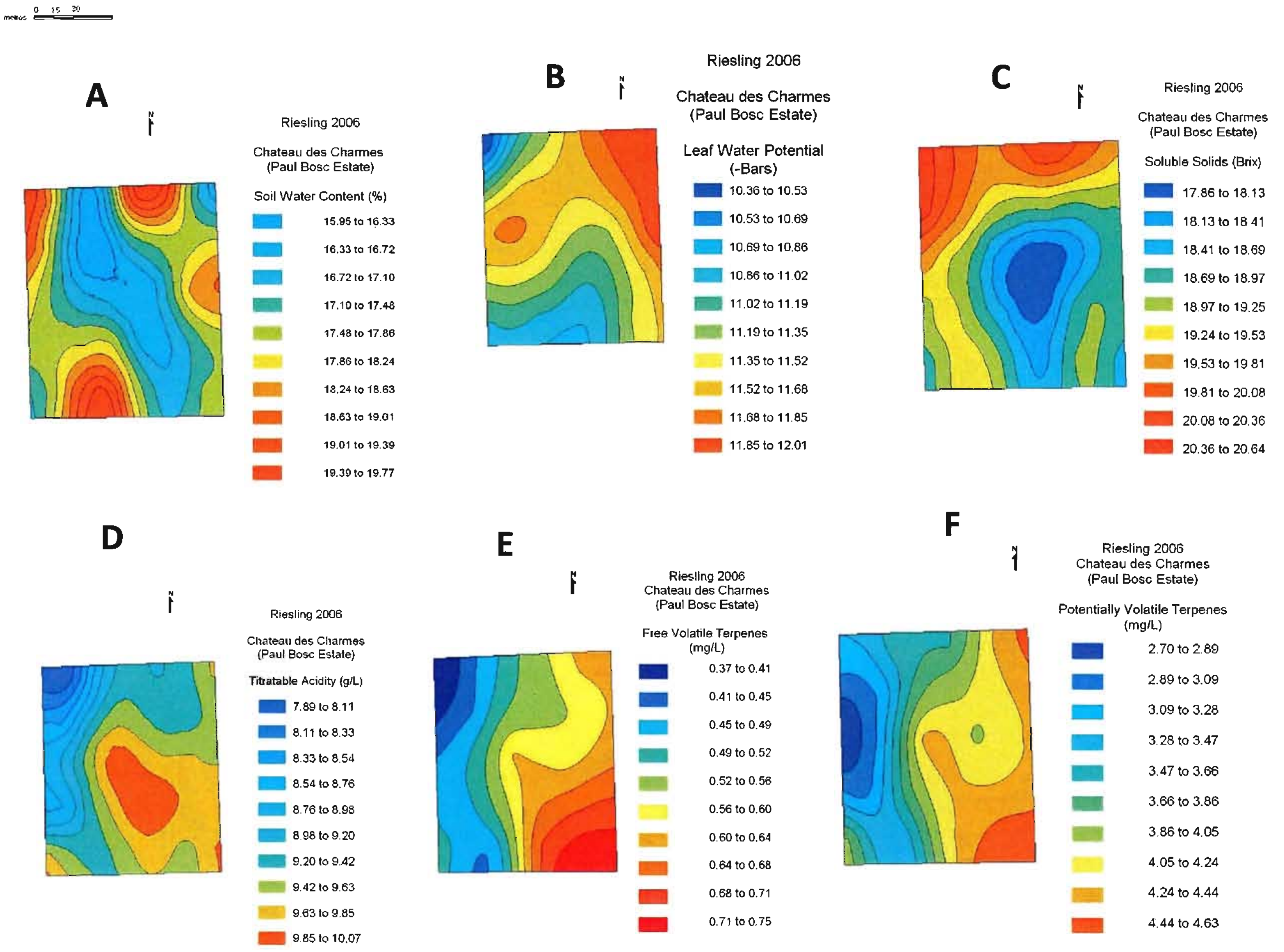

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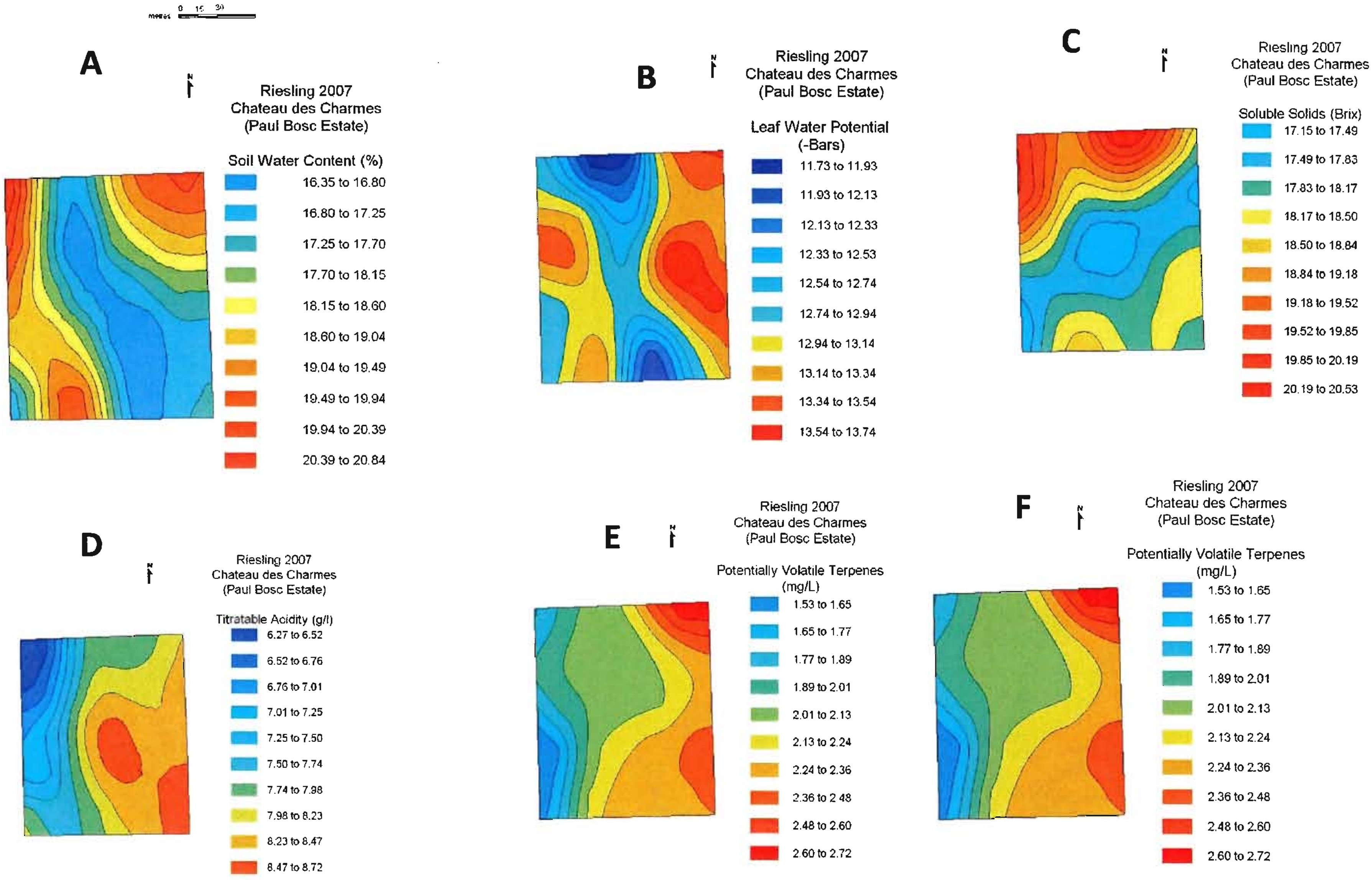

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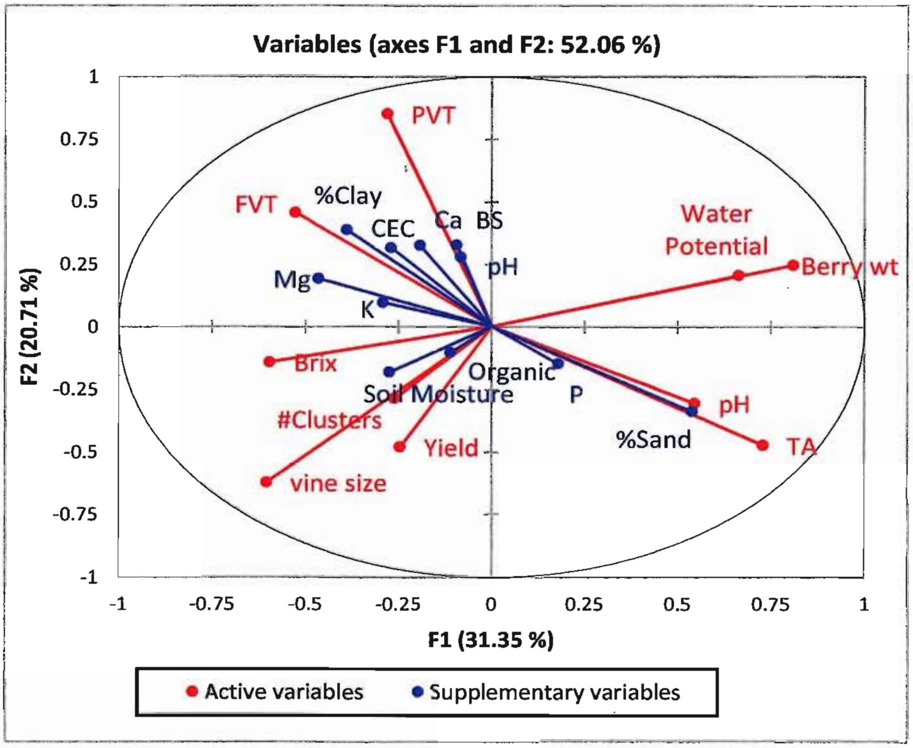

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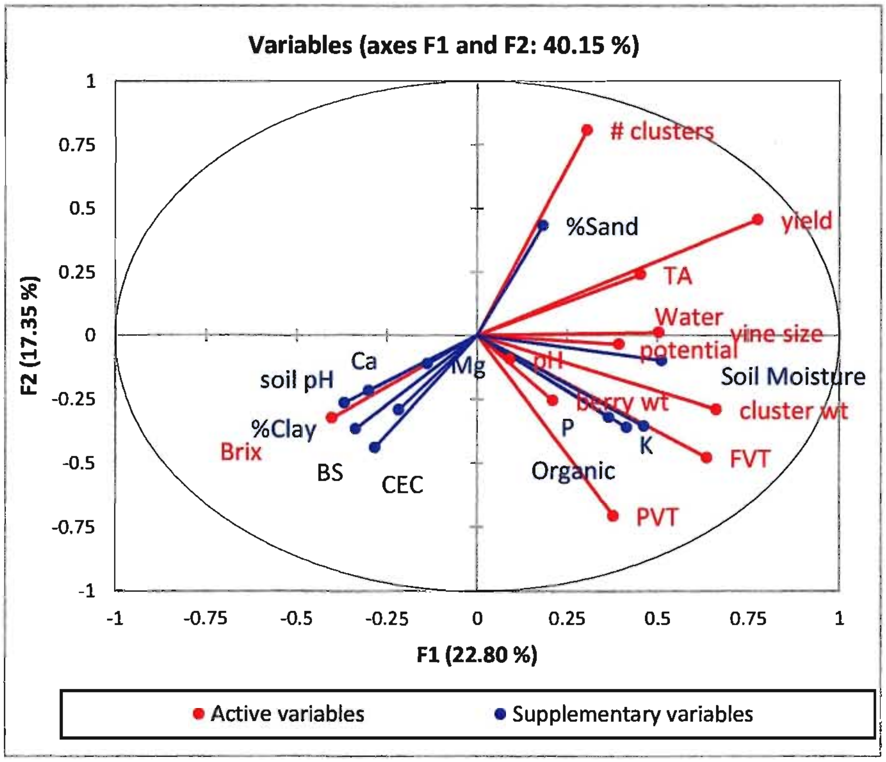

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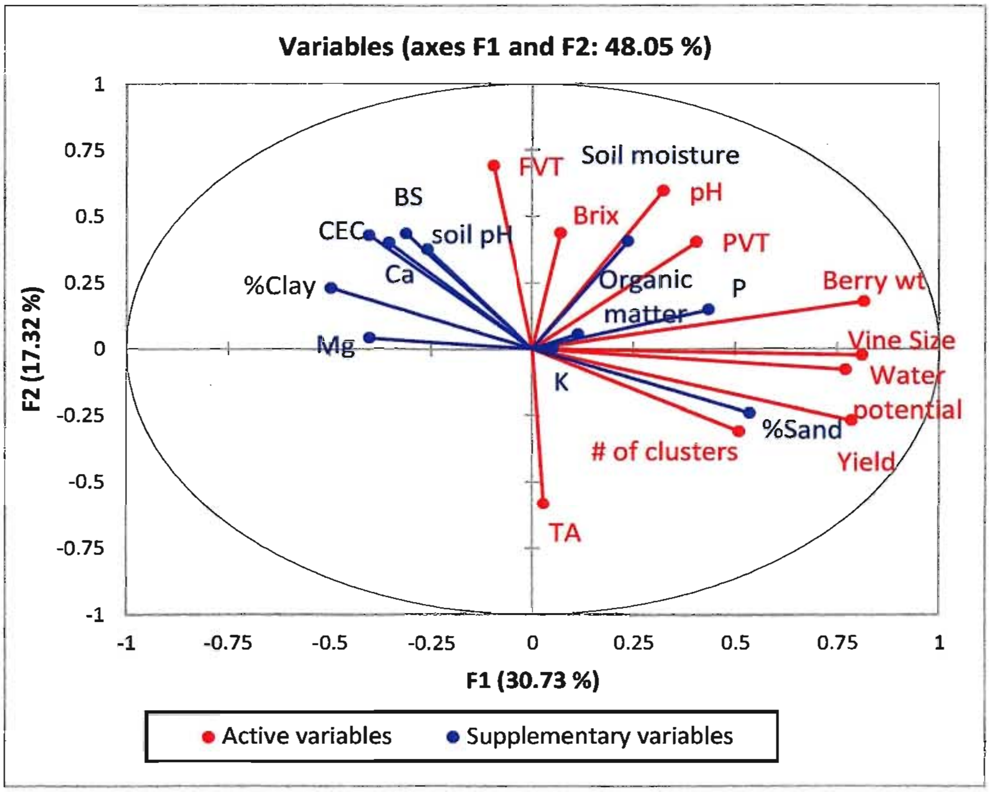

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Yield Variable	**Water Status Variable**		**Soil Variable**									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (Ca)**
Brix	0.035	-0.060	-0.174	0.241	-0.141	-0.371	-0.096	-0.254	-0.115	-0.287	-0.104	-0.163
TA	0.329	0.204	0.403	-0.179	0.744**	-0.133	0.468	0.453	0.168	0.227	0.532*	-0.250
pH	0.142	-0.253*	-0.152	-0.044	0.020	0.343	-0.020	-0.391	0.218	0.279	0.131	0.088
FVT	0.037	0.159	0.607	0.013	0.563	-0.277	0.501	-0.190	0.084	-0.196	0.097	-0.313
PVT	-0.478	0.136	0.813	-0.751	0.412	-0.553	-0.030	0.281	-0.824	-0.899*	-0.873	-0.080
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (Ca)**
Brix	-0.190	-0.254*	0.214	0.045	-0.108	-0.534*	0.129	-0.015	-0.182	-0.399	0.005	-0.342
TA	0.169	0.196	0.078	-0.111	0.207	-0.146	-0.038	0.339	-0.421	-0.241	-0.185	-0.101
pH	0.232	0.097	-0.194	0.227	-0.171	0.144	-0.112	-0.074	0.370	0.174	0.241	-0.045
FVT	-0.326	-0.202	0.130	-0.141	0.385	0.057	0.319	0.062	0.039	0.313	0.371	-0.023
PVT	-0.252	-0.109	0.061	0.183	-0.255	-0.278	-0.039	-0.125	0.001	-0.083	0.180	-166
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (Ca)**
Brix	-0.264	-0.182	-0.124	0.395	-0.163	-0.428	0.021	-0.301	0.106	-0.338	-0.038	-0.290
TA	0.151	-0.098	0.095	-0.110	0.317	-0.471*	0.359	0.354	-0.073	-0.126	0.243	-0.329
pH	0.275	0.403**	0.163	-0.260	0.489*	0.403	0.539*	0.308	0.258	0.385	0.219	0.127
FVT	-0.121	0.301	-0.184	0.459*	0.049	-0.217	0.027	-0.181	0.511*	-0.018	0.516*	-0.473*
PVT	-0.201	-0.273	-0.003	0.269	0.009	-0.527*	-0.137	0.138	0.056	-0.531*	0.222	-0.683**

*, **: Significant r values at $p<0.05$, 0.01, respectively.

Supplemental Table 4.1b. Correlations between soil and berry composition variables for Glenlake Vineyards (Lakelodge), 2005-2007.

Yield Variable	Water Status Variable		Soil Variable									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (Ca)**
Brix	0.281	-0.111	0.236	0.218	0.418	-0.116	0.035	0.009	0.611**	0.036	-0.553*	-0.136
TA	-0.170	0.128	0.098	-0.389	-0.353	0.167	0.322	0.043	-0.526	0.042	0.661**	0.097
pH	0.200	0.076	-0.023	0.102	0.117	0.073	0.053	0.136	0.455	0.168	-0.253	0.009
FVT	0.751	-0.155	0.877**	-0.478	0.294	0.418	0.437	0.122	0.616	0.264	0.705	-0.126
PVT	0.941**	-0.306	0.576	-0.023	0.644	0.401	0.610	0.432	0.820*	0.332	0.314	0.169
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (Ca)**
Brix	0.042	0.047	-0.027	-0.415	-0.017	-0.253	0.402	-0.009	-0.396	-0.179	0.310	-0.219
TA	0.013	0.047	-0.326	-0.107	-0.290	0.074	-0.319	0.247	-0.529	-0.036	0.072	0.007
pH	-0.049	0.049	-0.145	0.05	-0.040	0.439	0.059	-0.206	0.165	0.531*	0.347	0.450
FVT	0.177	0.068	0.314	-0.232	-0.372	0.081	0.260	0.054	-0.166	0.108	0.019	0.195
PVT	-0.248	-0.108	0.223	-0.207	0.346	-0.415	0.717**	0.128	0.004	-0.376	0.065	-0.349
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (Ca)**
Brix	-0.150	0.430	0.055	-0.219	-0.100	0.112	0.235	0.053	0.020	0.210	0.324	0.000
TA	-0.033	-0.263	-0.284	0.053	0.158	0.048	0.073	0.179	0.014	0.097	0.032	-0.087
pH	0.243	0.329	0.260	-0.311	-0.067	0.466	0.365	0.053	0.221	0.482	0.555*	0.341
FVT	0.325	0.024	-0.188	0.023	0.135	0.240	-0.082	-0.176	0.573*	0.427	-0.064	0.113
PVT	0.207	0.558*	0.312	-0.128	-0.305	0.206	-0.313	0.176	0.116	0.135	-0.105	0.144

*, **: Significant r values at $p<0.05$, 0.01, respectively.

Supplemental Table 4.1c. Correlations between water status, soil and berry composition variables for Chateau des Charmes (Paul Bosc Estate), 2005-2007.

Yield Variable	**Water Status Variable**		**Soil Variable**									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (Ca)**
Brix	0.295	0.069	-0.207	0.341	-0.068	-0.560*	-0.134	-0.124	0.339	-0.563*	-0.570*	-0.425
TA	0.259	0.172	-0.369	0.306	-0.526*	0.170	-0.106	-0.493*	-0.349	0.353	0.277	0.446
pH	-0.055	-0.318*	0.124	-0.111	0.017	0.054	0.070	0.028	-0.206	-0.135	-0.192	0.059
FVT	-0.363	0.240	0.444	-0.799	0.716	-0.85	0.153	0.542	0.561	-0.822	-0.830	-0.752
PVT	0.568	-0.090	-0.793	0.771	0.526	0.526	-0.808	-0.735	-0.511	0.402	0.306	0.544
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (Ca)**
Brix	0.001	0.275*	-0.174	0.241	-0.372	0.046	-0.362	-0.071	0.123	-0.002	-0.021	0.018
TA	0.213	-0.309**	0.288	-0.177	0.109	0.060	0.041	-0.058	-0.119	0.121	0.257	-0.201
pH	-0.172	0.205	-0.115	0.082	-0.291	0.199	0.406	0.478*	0.221	-0.373	-0.284	0.149
FVT	-0.233	0.136	0.097	-0.025	0.684**	-0.009	0.522*	0.585*	0.160	-0.139	-0.081	-0.257
PVT	-0.029	0.002	0.085	0.022	0.543*	0.01	0.362	0.360	0.162	0.006	0.050	-0.081
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (Ca)**
Brix	-0.265	0.445**	-0.398	-0.355	-0.425	0.189	-0.295	0.013	-0.089	0.072	0.058	0.138
TA	0.072	-0.431**	0.212	-0.083	0.329	0.197	0.343	0.376	-0.088	0.189	0.238	0.113
pH	-0.365	0.204	0.055	-0.105	-0.066	-0.617*	0.089	0.034	0.249	-0.468*	-0.478*	-0.411
FVT	-0.338	0.071	-0.407	0.286	-0.070	0.066	-0.195	0.274	0.008	0.116	0.161	-0.059
PVT	-0.274	-0.198	-0.274	0.337	-0.048	0.404	0.166	0.301	0.062	0.160	0.209	0.120

*, **: Significant r values at $p<0.05$, 0.01, respectively.

Supplemental Table 4.1d. Correlations between water status, soil and berry composition variables for Cave Spring Cellars (Home Block), 2005-2007.

Yield Variable	**Water Status Variable**		**Soil Variable**									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (%Ca)**
Brix	0.394	0.174	-0.415	0.419	-0.483*	0.154	-0.330	-0.168	0.167	0.189	0.205	0.190
TA	-0.119	-0.148	0.223	-0.121	0.069	-0.127	-0.193	-0.374	-0.049	0.106	0.084	0.176
pH	0.446	0.163	0.011	-0.115	0.356	-0.266	0.308	0.009	0.011	-0.035	-0.061	-0.011
FVT	-0.333	-0.023	-0.567	0.487	0.892**	-0.437	0.874*	0.659	0.570	-0.656	-0.578	-0.763*
PVT	-0.414	-0.100	-0.102	0.105	0.371	0.115	0.630	0.537	0.131	-0.141	-0.073	-0.187
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (%Ca)**
Brix	-0.268	-0.132	-0.334	-0.004	-0.159	-0.041	-0.405	-0.327	-0.062	-0.091	-0.216	0.026
TA	-0.253	0.001	-0.526*	0.439	-0.118	-0.287	-0.008	0.158	0.314	-0.134	0.179	-0.358
pH	0.379	-0.098	-0.099	-0.092	0.106	-0.416	-0.287	-0.134	-0.405	-0.168	-0.089	-0.084
FVT	-0.162	-0.413	-0.203	-0.087	-0.060	-0.414	-0.402	-0.063	0.199	-0.437	-0.106	-0.518*
PVT	-0.089	-0.682**	-0.381	-0.006	-0.052	-0.023	-0.409	-0.235	0.246	-0.136	-0.102	-0,145
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (%Ca)**
Brix	-0.175	0.103	-0.213	-0.139	0.029	0.177	-0.374	-0.211	-0.116	0.113	-0.153	0.281
TA	-0.007	-0.131	0.085	-0.026	-0.054	-0.389	0.075	0.220	-0.163	-0.346	-0.216	-0.286
pH	0.046	0.191	-0.277	0.042	-0.054	0.125	0.204	0.015	-0.133	0.173	-0.045	0.237
FVT	0.388	0.132	0.291	-0.108	0.012	0.355	0.290	0.109	0.378	0.234	0.194	0.170
PVT	0.018	0.498*	-0.292	0.410	-0.339	0.194	0.349	-0.267	0.226	0.433	0.649**	-0.028

*, **: Significant r values at $p<0.05$, 0.01, respectively.

Supplemental Table 4.1e. Correlations between water status, soil and berry composition variables for Flat Rock Cellars (Nadja's Vineyard), 2005-2007.

Yield Variable	**Water Status Variable**		**Soil Variable**									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (Ca)**
Brix	0.295	0.069	-0.207	0.341	-0.068	-0.560	-0.134	-0.124	0.339	-0.563*	-0.570*	-0.425
TA	0.259	0.172	-0.369	0.306	-0.526*	0.170	-0.106	-0.493*	-0.349	0.353	0.277	0.446
pH	-0.055	-0.318*	0.124	-0.111	0.017	0.054	0.070	0.028	-0.206	-0.135	-0.192	0.059
FVT	-0.363	0.240	0.444	-0.799	0.716	-0.850	0.153	0.542	0.561	-0.822	-0.830	-0.752
PVT	0.568	-0.090	-0.793	0.771	-0.854	0.526	-0.808	-0.735	-0.511	0.402	0.306	0.544
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (Ca)**
Brix	0.386	0.022	0.358	-0.289	0.335	-0.087	0.405	0.166	-0.237	-0.135	-0.184	0.024
TA	-0.101	0.062	-0.280	0.221	-0.235	-0.294	-0.348	-0.042	0.388	-0.190	-0.145	-0.306
pH	0.621**	0.040	0.147	-0.131	0.196	-0.019	0.232	0.258	-0.097	-0.136	-0.160	-0.037
FVT	0.091	-0.286	0.397	-0.419*	0.428*	0.117	0.410	0.401	-0.159	0.050	0.058	0.053
PVT	-0.056	-0.364	0.359	-0.581*	0.481*	0.047	0.205	0.362	-0.217	-0.128	-0.158	-0.055
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (Ca)**
Brix	0.477*	0.289*	-0.020	0.220	-0.389	-0.322	-0.178	-0.152	0.070	-0.222	-0.230	-0.119
TA	0.538*	-0.048	0.444*	-0.359	0.463*	-0.466*	0.078	0.683**	0.293	-0.455*	-0.422	-0.565*
pH	0.035	-0.089	0.004	-0.081	-0.169	-0.226	-0.066	-0.115	-0.210	-0.180	-0.229	0.010
FVT	0.166	0.056	-0.436	0.348	-0.518*	0.174	-0.026	-0.392	-0.373	0.401	0.339	0.458*
PVT	-0.264	-0.257	-0.026	-0.191	-0.095	0.353	-0.207	-0.057	-0.191	0.222	0.224	0.214

*, **: Significant r values at $p<0.05$, 0.01, respectively.

Supplemental Table 4.1f. Correlations between water status, soil and berry composition variables for Henry of Pelham, 2005-2007.

Yield Variable	**Water Status Variable**		**Soil Variable**									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (Ca)**
Brix	0.335	0.192	0.164	-0.298	-0.256	0.164	-0.043	-0.249	-0.316	0.180	0.147	0.234
TA	0.105	-0.207	-0.277	0.135	0.449*	-0.297	0.053	0.397	-0.045	-0.388	-0.377	-0.357
pH	-0.028	-0.018	0.149	-0.057	-0.030	0.240	0.504*	-0.027	-0.355	0.299	0.239	0.395
FVT	0.032	0.044	0.223	-0.014	0.869*	-0.357	0.432	-0.102	-0.745	0.822	0.772	0.956*
PVT	-0.560	-0.101	0.775	-0.887*	0.347	-0.009	-0.268	-0.465	0.834	0.054	0.143	-0.180
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (Ca)**
Brix	0.194	0.172	0.021	-0.095	-0.128	-0.201	-0.475*	0.033	0.073	-0.049	-0.037	-0.088
TA	0.221	0.065	-0.015	-0.055	-0.051	-0.199	-0.457*	0.103	0.032	-0.069	-0.058	-0.108
pH	0.170	0.110	-0.042	-0.033	-0.065	-0.249	-0.483*	0.100	0.099	-0.091	-0.075	-0.145
FVT	-0.247	0.121	0.345	-0.306	-0.312	0.182	-0.199	-0.221	-0.009	0.087	0.071	0.091
PVT	-0.009	0.399	-0.094	0.007	-0.166	0.248	-0.454*	-0.250	-0.360	0.207	0.159	0.374
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (Ca)**
Brix	0.604**	0.121	-0.070	-0.016	0.024	-0.002	0.044	-0.074	0.016	0.070	0.068	0.038
TA	0.111	-0.140	0.100	-0.096	-0.036	-0.130	-0.014	0.241	0.093	-0.049	-0.051	-0.161
pH	-0.557*	0.224*	-0.111	0.206	-0.397	0.428	0.125	0.177	-0.381	0.338	0.292	0.470*
FVT	0.330	0.562**	0.139	-0.079	-0.103	0.240	-0.020	-0.002	-0.237	0.203	0.152	0.264
PVT	0.122	0.162	-0.216	0.171	0.339	-0.024	-0.088	0.559*	0.062	-0.049	-0.043	-0.139

*, **: Significant r values at $p<0.05$, 0.01, respectively.

Supplemental Table 4.1g. Correlations between water status, soil and berry composition variables for Paragon Vineyards, 2005-2007.

Yield Variable	Water Status Variable		Soil Variable									
2005	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base Saturation (Ca)**
Brix	-0.303	-0.141	-0.121	0.225	-0.335	0.168	-0.136	-0.220	0.202	0.244	0.227	0.018
TA	0.181	0.095	-0.058	0.046	0.239	-0.105	0.023	0.047	-0.088	-0.086	-0.093	0.093
pH	-0.365	-0.185	0.269	-0.182	-0.428	0.131	-0.333	-0.285	-0.048	0.029	0.031	-0.184
FVT	0.738	0.127	-0.442	0.499	0.105	-0.762	0.367	0.929*	0.119	0.129	0.127	-0.391
PVT	0.381	0.365	-0.194	-0.130	0.714	0.010	0.746	0.720	0.028	0.169	0.072	0.056
2006	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (Ca)**
Brix	-0.079	0.072	-0.225	0.308	-0.294	0.136	-0.258	-0.086	0.090	0.250	0.211	0.358
TA	0.114	0.126	0.267	-0.173	-0.074	0.560*	-0.149	0.000	0.144	0.352	0.253	-0.140
pH	-0.579**	0.008	0.525*	-0.350	-0.508*	-0.458*	-0.466*	-0.228	-0.603**	-0.453*	-0.512*	0.360
FVT	-0.133	0.113	0.195	-0.017	-0.468	-0.324	-0.666**	-0.327	-0.378	-0.312	-0.254	0.246
PVT	0.019	0.082	-0.167	0.176	-0.074	-0.576*	-0.197	0.038	-0.184	-0.356	-0.274	0.107
2007	**Leaf Water Potential**	**Soil Moisture**	**Sand**	**Clay**	**OM**	**pH**	**P**	**K**	**Mg**	**Ca**	**CEC**	**Base saturation (Ca)**
Brix	0.238	-0.069	0.241	-0.228	0.009	0.473*	0.080	-0.148	0.023	0.251	0.049	0.132
TA	-0.134	0.082	-0.200	0.217	0.071	-0.054	0.040	0.140	0.214	0.042	0.072	-0.014
pH	0.323	-0.130	0.261	-0.269	-0.151	0.342	-0.180	-0.148	-0.128	0.160	0.071	0.217
FVT	0.297	-0.157	0.453	-0.366	-0.230	0.003	-0.277	-0.606**	-0.292	0.180	-0.243	0.041
PVT	-0.144	0.103	-0.101	0.158	0.137	-0.160	0.127	0.231	-0.030	-0.050	-0.082	0.061

*, **: Significant r values at $p<0.05$, 0.01, respectively.

Supplementary Figures

Supplemental Figure 4.1a. Spatial distribution of berry Brix, Myers Vineyard, Vineland ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.2a. Spatial distribution of berry titratable acidity (g/L), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.3a. Spatial distribution of berry Free Volatile Terpenes (mg/L), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.4a. Spatial distribution of berry Potentially Volatile Terpenes (mg/L), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.5a. Principal component analysis of viticulture and soil variables for Myers Vineyard, ON (a) 2005; (b) 2006; (c) 2007.

Supplemental Figure 4.1b. Spatial distribution of berry Brix, Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.2b. Spatial distribution of berry titratable acidity (g/L), Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.3b. Spatial distribution of berry Free Volatile Terpenes (mg/L), Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.4b. Spatial distribution of berry Potentially Volatile Terpenes (mg/L), Glenlake Vineyard (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.5b. Principal component analysis of viticulture and soil variables for Glenlake Vineyard (Lakelodge), (a) 2005; (b) 2006; (c) 2007.

Supplemental Figure 4.1c. Spatial distribution of berry Brix, Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.2c. Spatial distribution of berry titratable acidity (g/L), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.3c. Spatial distribution of berry Free Volatile Terpenes (mg/L), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.4c. Spatial distribution of berry Potentially Volatile Terpenes (mg/L), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.5c. Principal component analysis of viticulture and soil variables for Chateau des Charmes (Paul Bosc Estate); (a) 2005; (b) 2006; (c) 2007.

Supplemental Figure 4.1d. Spatial distribution of berry Brix, Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.2d. Spatial distribution of berry titratable acidity (g/L), Cave Spring Vineyards (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.3d. Spatial distribution of berry Free Volatile Terpenes (mg/L), Cave Spring Vineyards (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.4d. Spatial distribution of berry Potentially Volatile Terpenes (mg/L), Cave Spring Vineyards (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.5d. Principal component analysis of viticulture and soil variables for Cave Spring Vineyards (Home Block), (a) 2005; (b) 2006; (c) 2007.

Supplemental Figure 4.1e. Spatial distribution of berry Brix, Flat Rock Cellars (Nadja's Vineyard), Jordan; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.2e. Spatial distribution of berry titratable acidity (g/L), Flat Rock Cellars (Nadja's Vineyard), ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.3e. Spatial distribution of berry Free Volatile Terpenes (mg/L), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.4e. Spatial distribution of berry Potentially Volatile Terpenes (mg/L), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.5e. Principal component analysis of viticulture and soil variables for Flat Rock Cellars (Nadja's Vineyard), (a) 2005; (b) 2006; (c) 2007.

Supplemental Figure 4.1f. Spatial distribution of berry Brix, Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.2f. Spatial distribution of berry titratable acidity (g/L), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.3f. Spatial distribution of berry Free Volatile Terpenes (mg/L), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.4f. Spatial distribution of berry Potentially Volatile Terpenes (mg/L), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.5f. Principal component analysis of viticulture and soil variables for Henry of Pelham, (a) 2005; (b) 2006; (c) 2007.

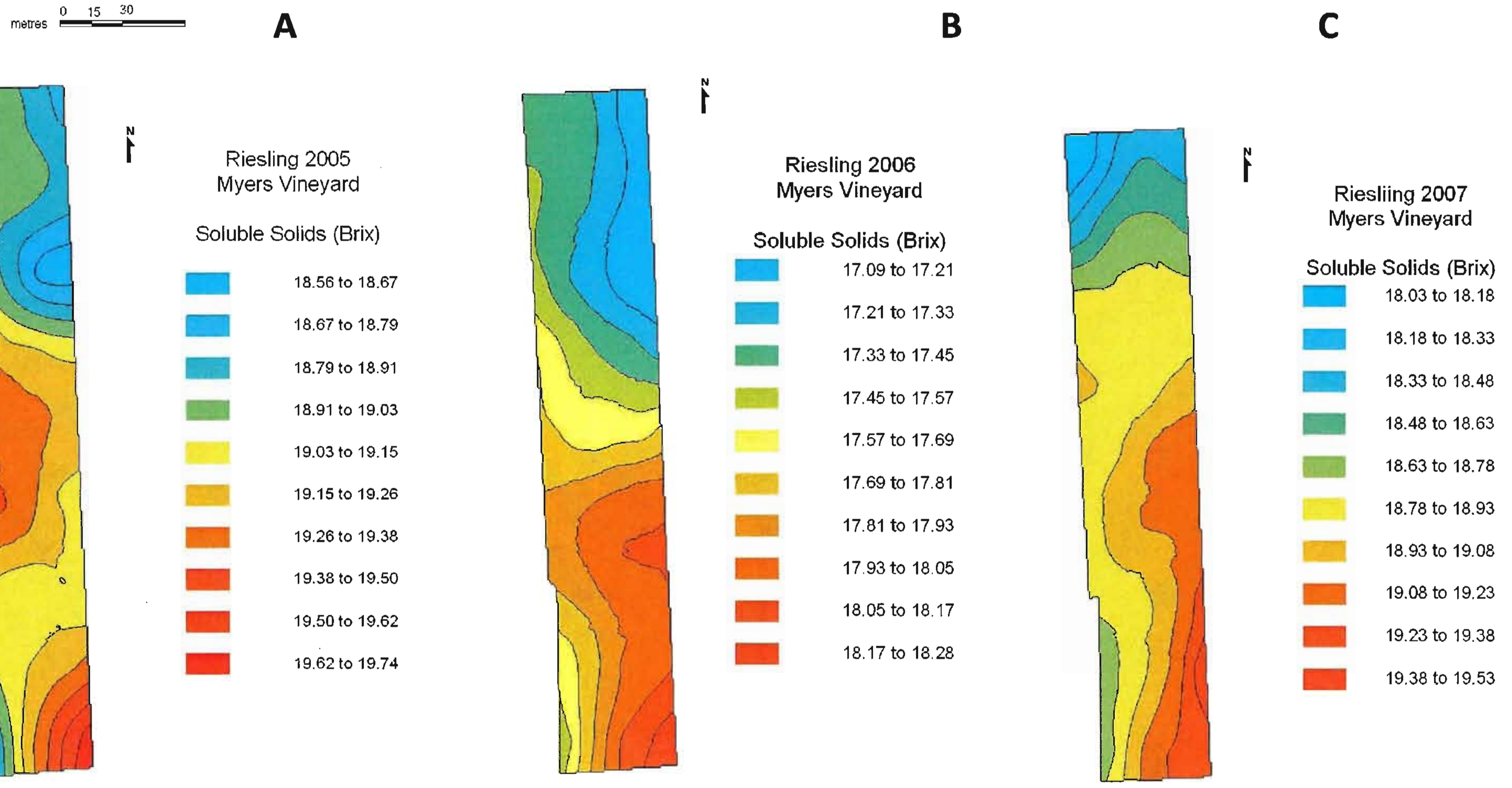
Supplemental Figure 4.1g. Spatial distribution of berry Brix, Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.2g. Spatial distribution of berry titratable acidity (g/L), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.

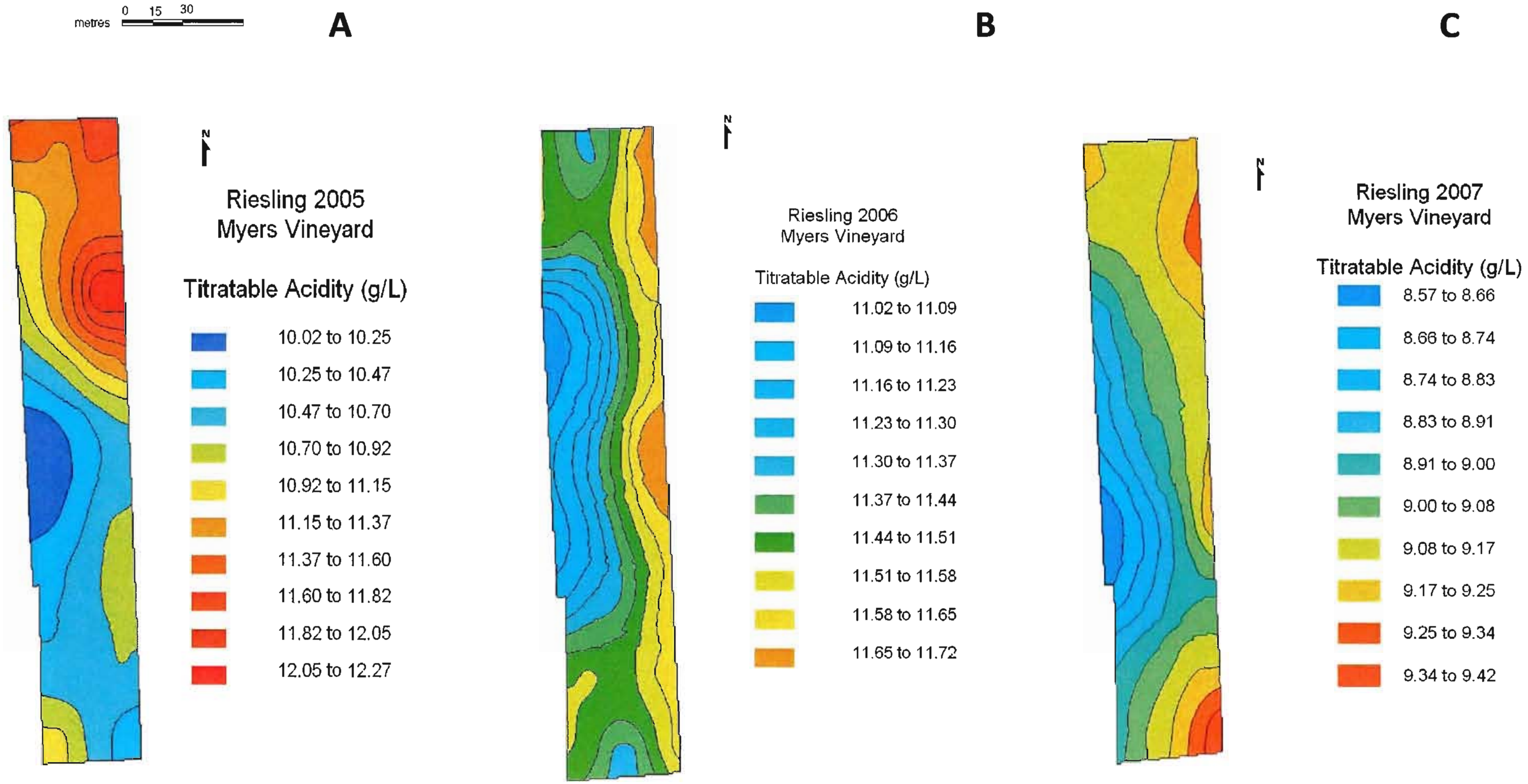
Supplemental Figure 4.3g. Spatial distribution of berry Free Volatile Terpenes (mg/L), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.4g. Spatial distribution of berry Potentially Volatile Terpenes (mg/L), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.

Supplemental Figure 4.5g. Principal component analysis of viticulture and soil variables for Paragon Vineyard, (a) 2005; (b) 2006; (c) 2007.



Supplemental Figure 4.1a. Spatial distribution of berry Brix, Myers Vineyard, Vineland ON; A: 2005; B: 2006; C: 2007.



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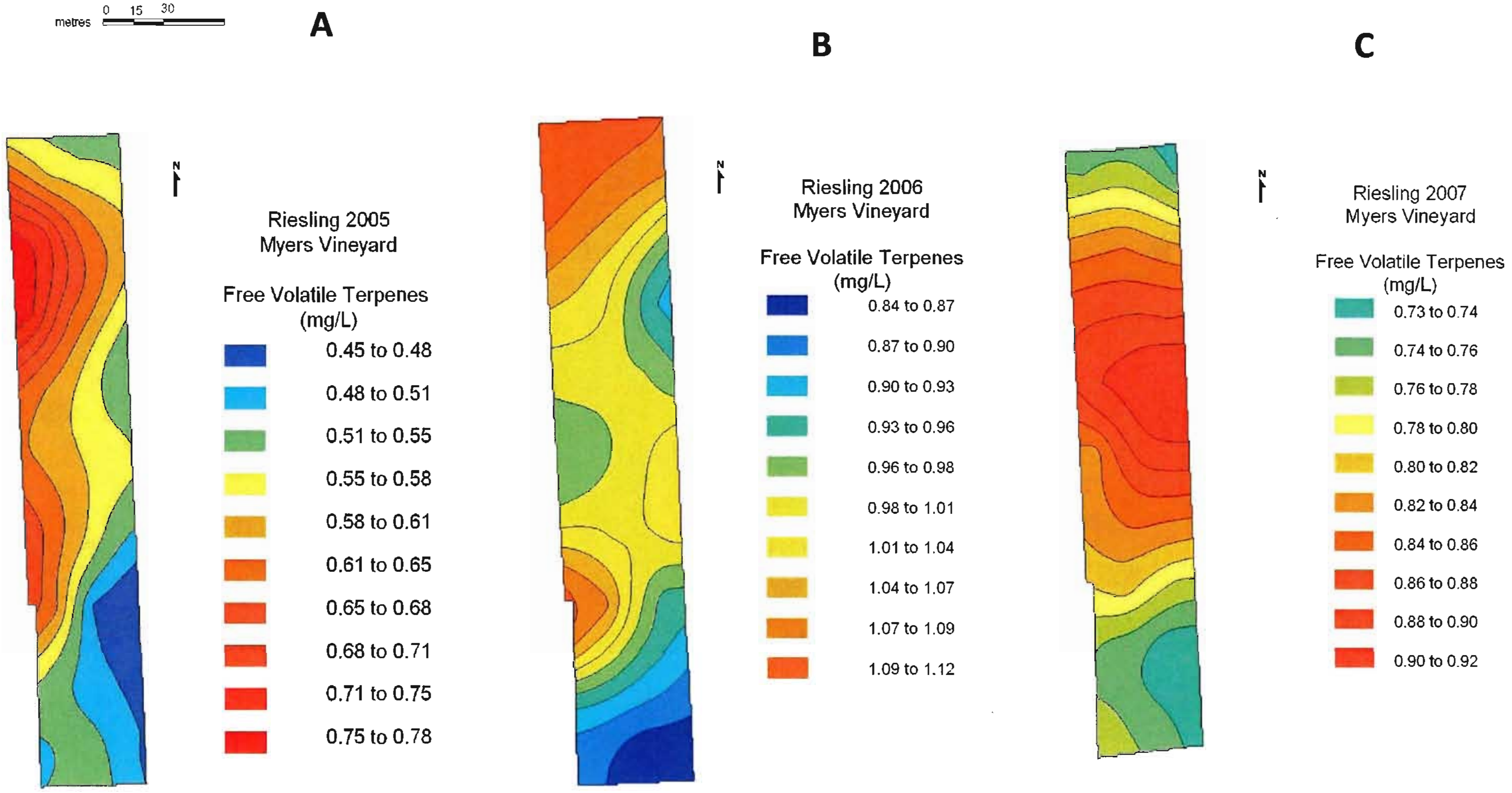
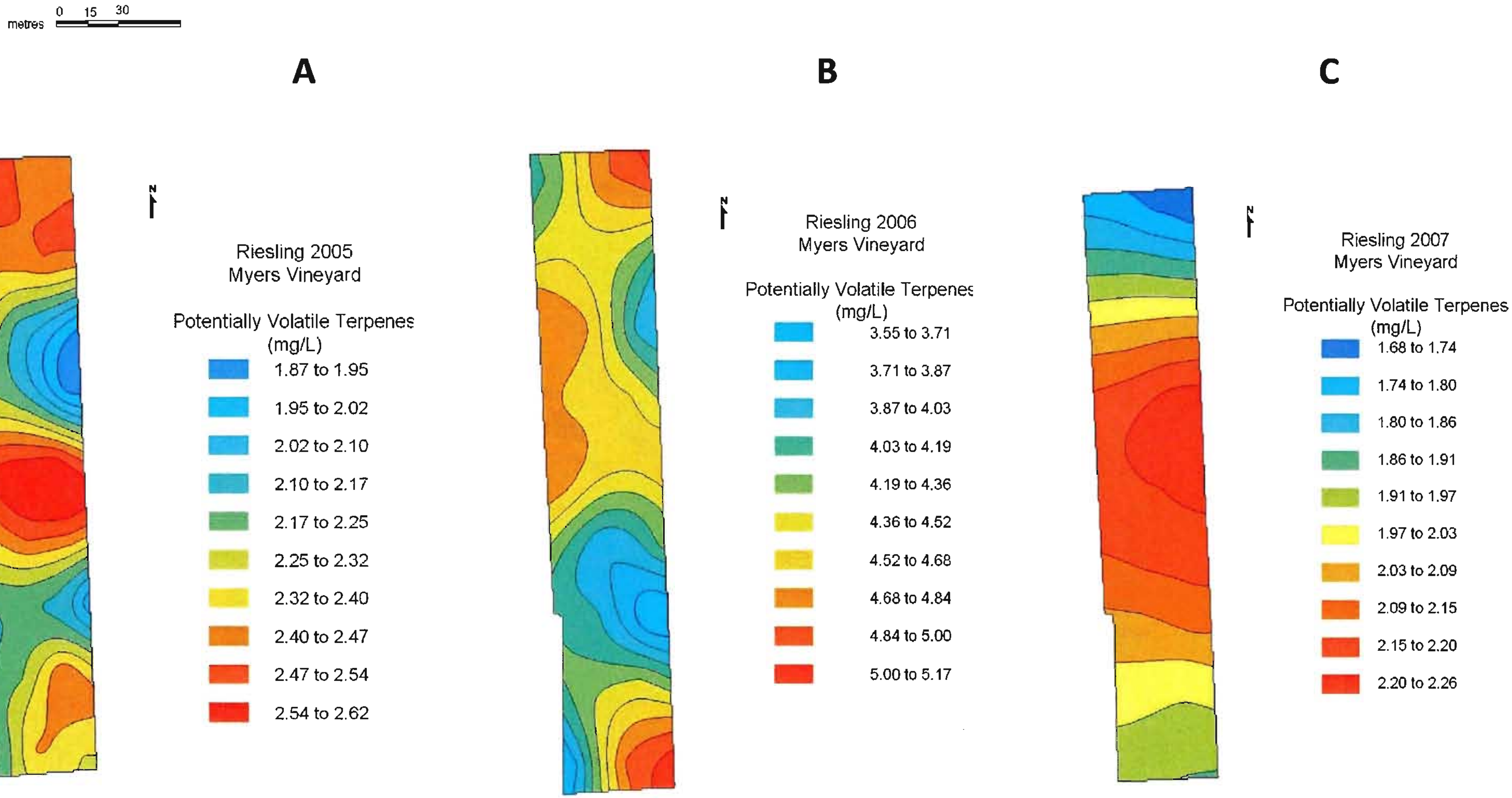


Supplemental Figure 4.3a. Spatial distribution of berry Free Volatile Terpenes (mg/L), Myers Vineyard, Vineland, ON; A: 2005; B: 2006; C: 2007.



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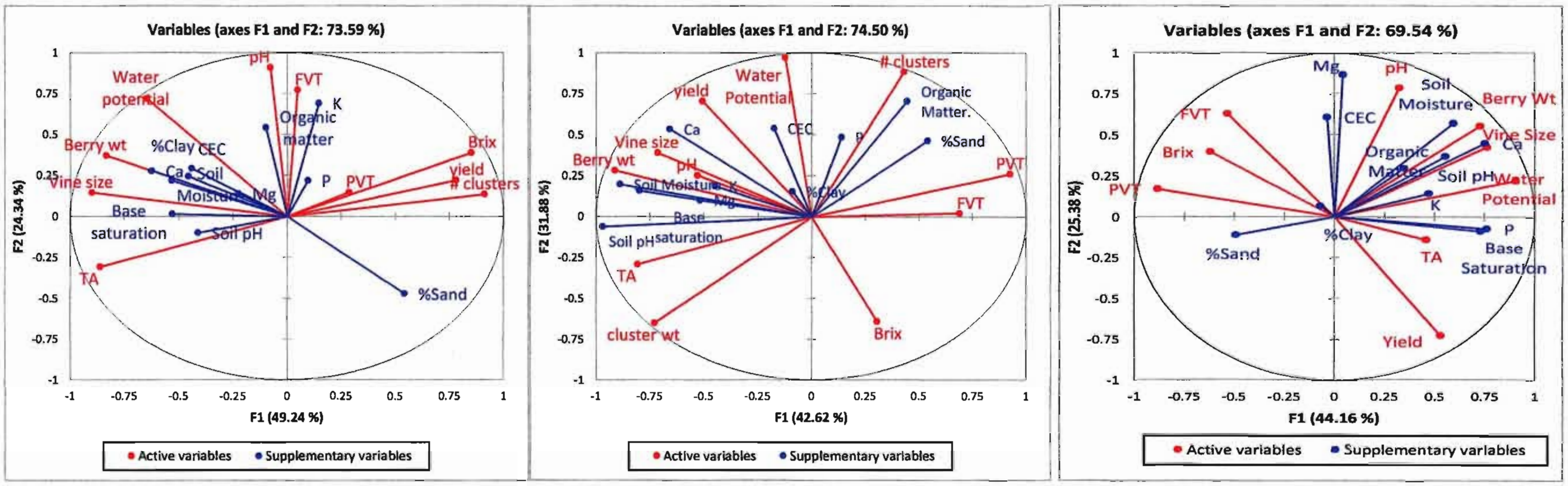
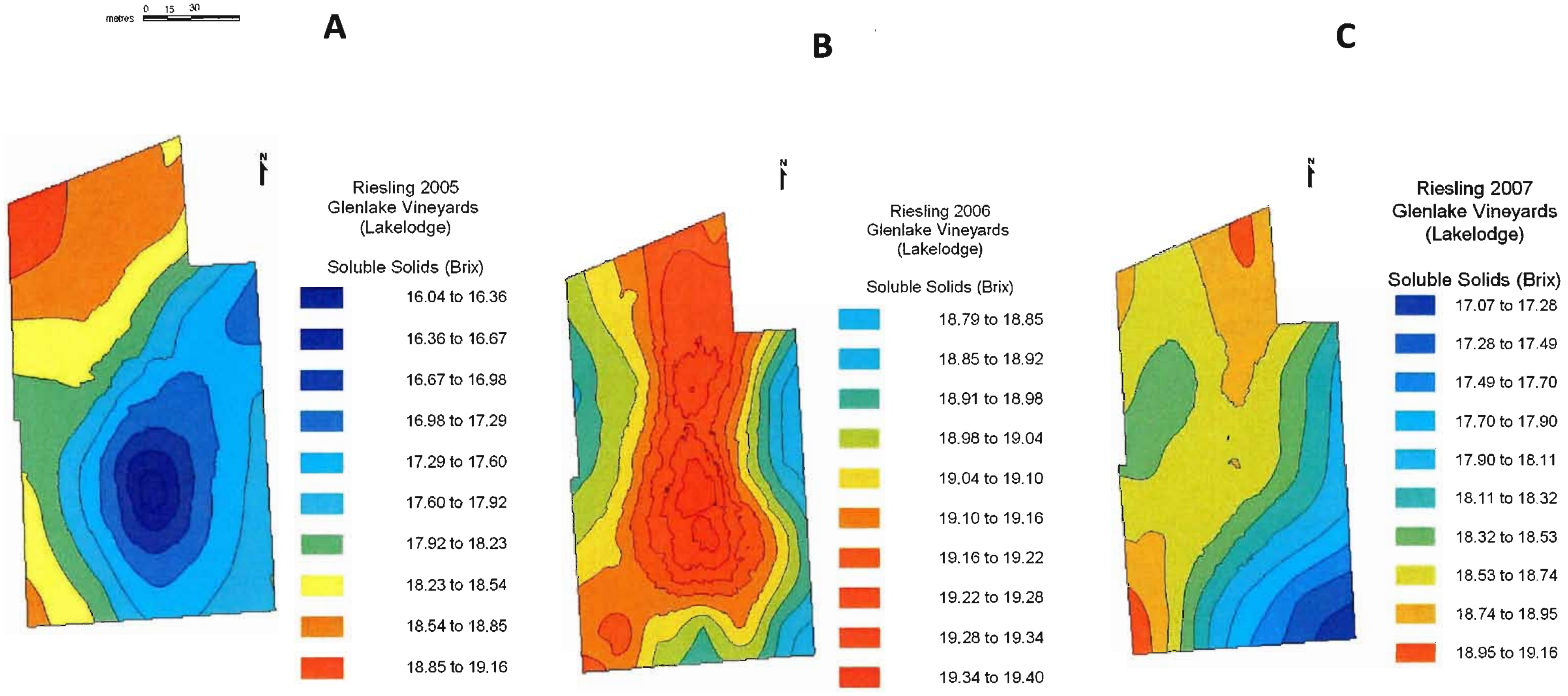
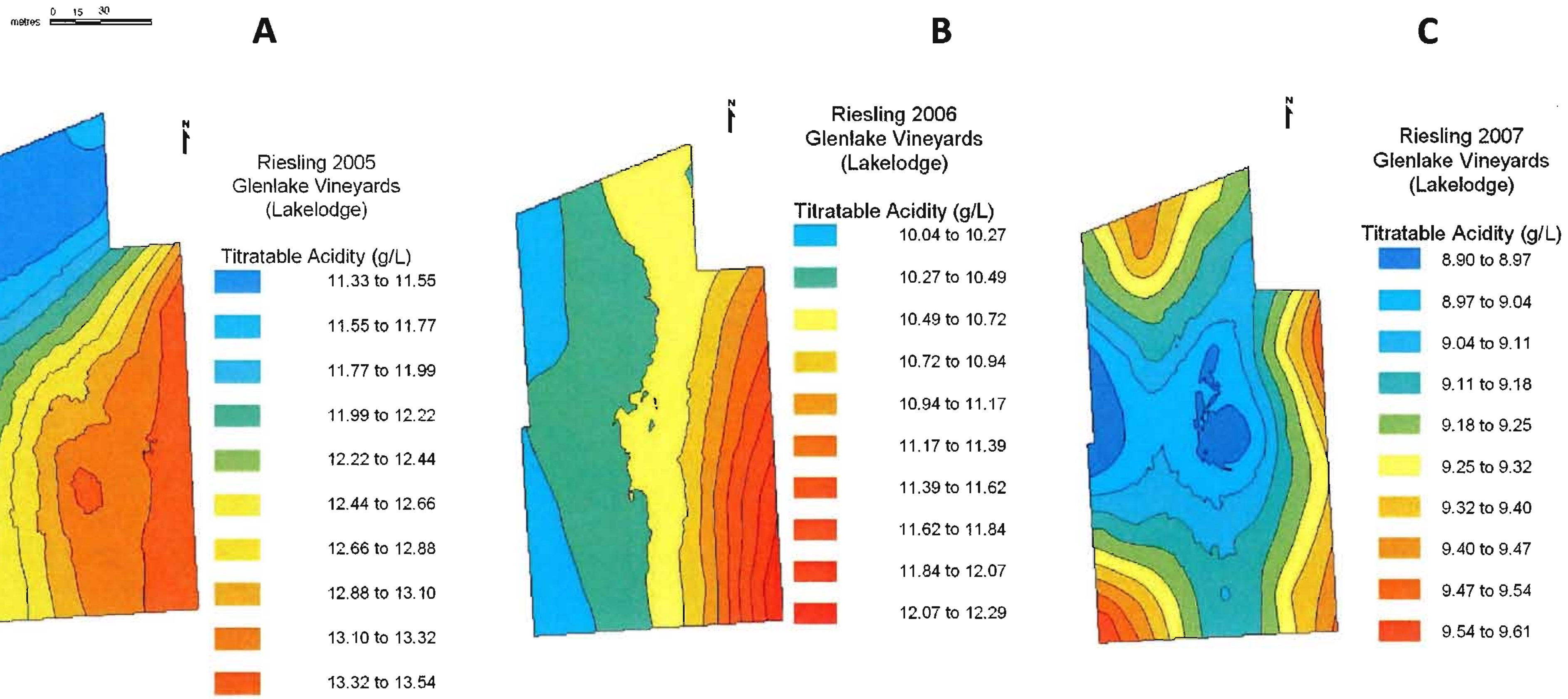

2005 2006 2007

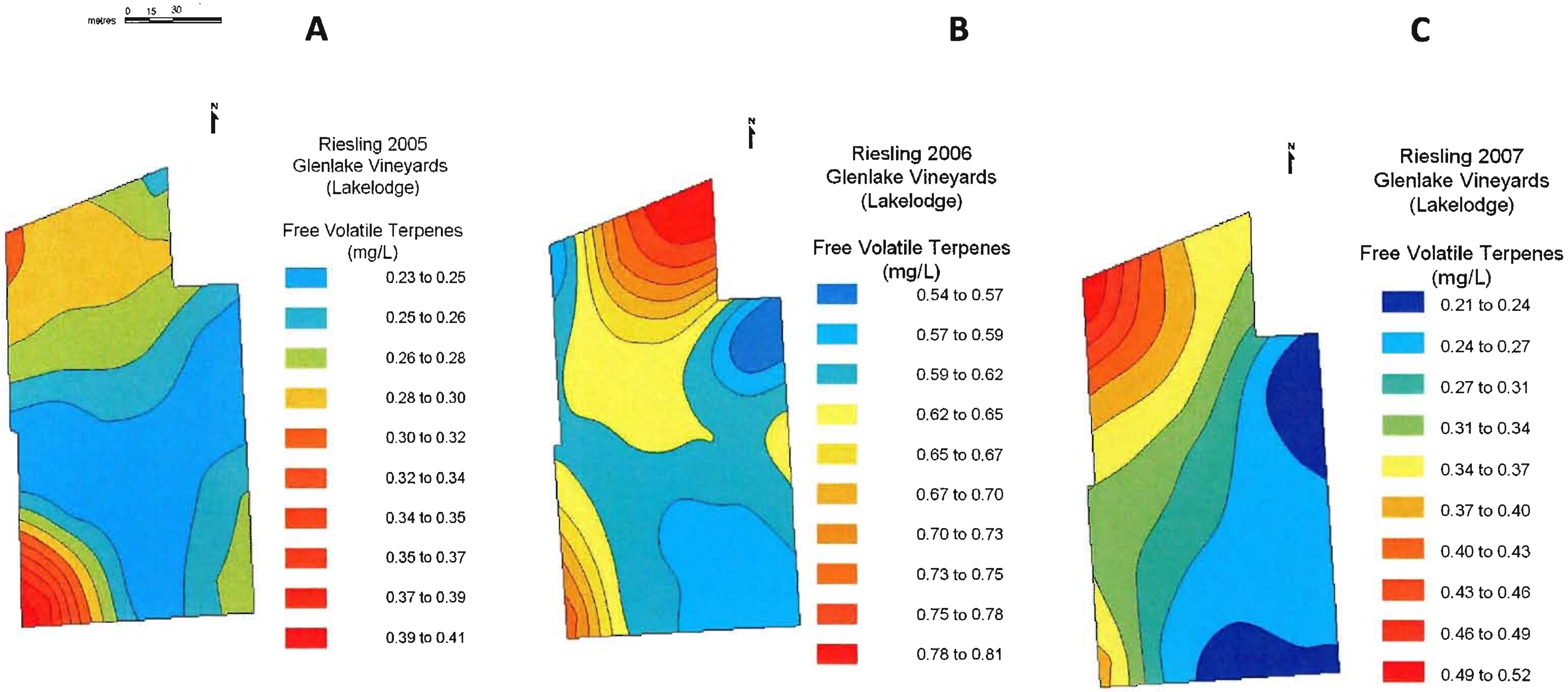
Supplemental Figure 4.5a. Principal component analysis of viticulture and soil variables for Myers Vineyard, 2005-2007. *Supplementary variables in blue are soil variables.*



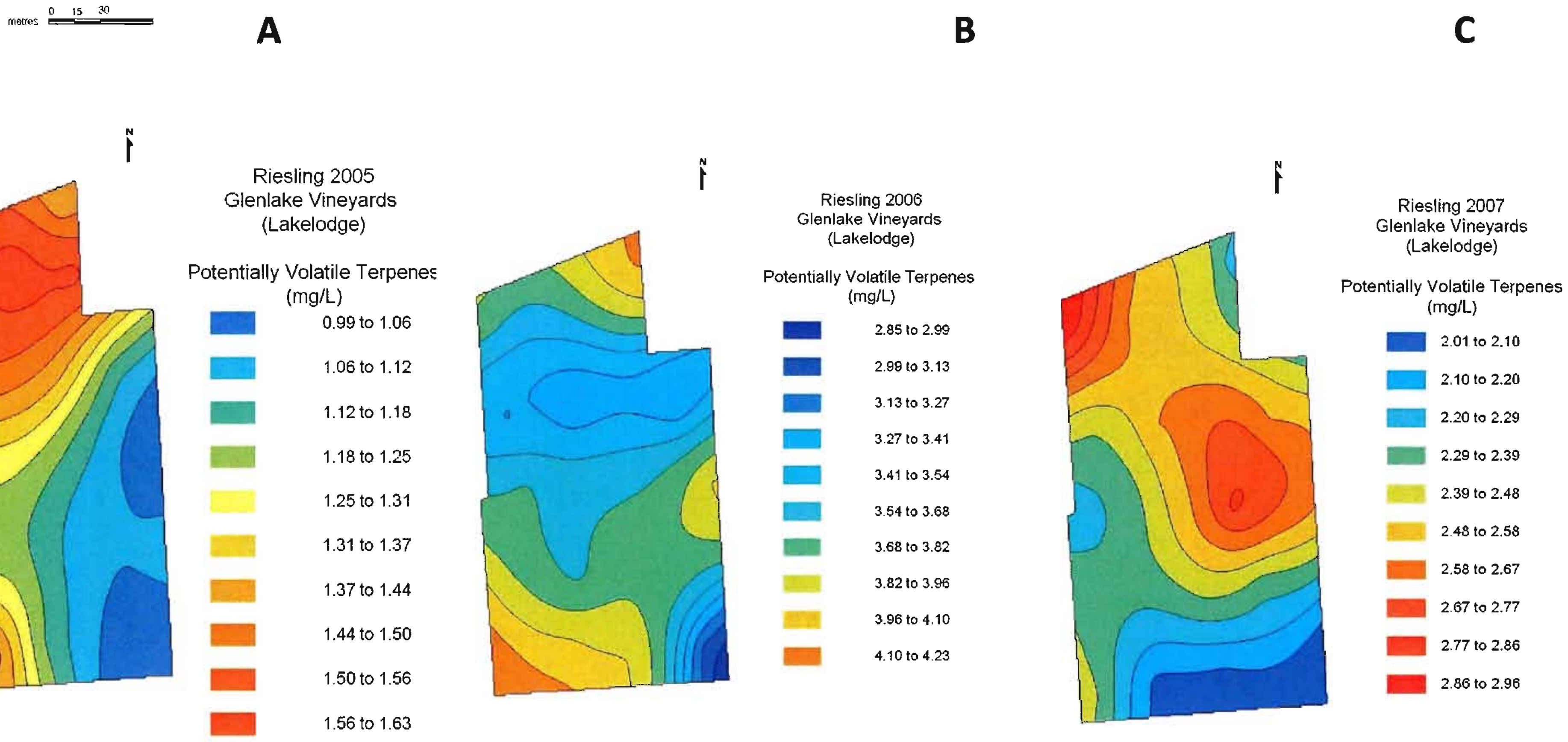
Supplemental Figure 4.1b. Spatial distribution of berry Brix, Glenlake Vineyards (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.



Supplemental Figure 4.2b. Spatial distribution of berry titratable acidity (g/L), Glenlake Vineyards (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006; C: 2007.



Supplemental Figure 4.3b. Spatial distribution of berry Free Volatile Terpenes (mg/L), Glenlake Vineyards (Lakelodge), Niagara-on-the-lake, ON; A: 2005; B: 2006: C: 2007.



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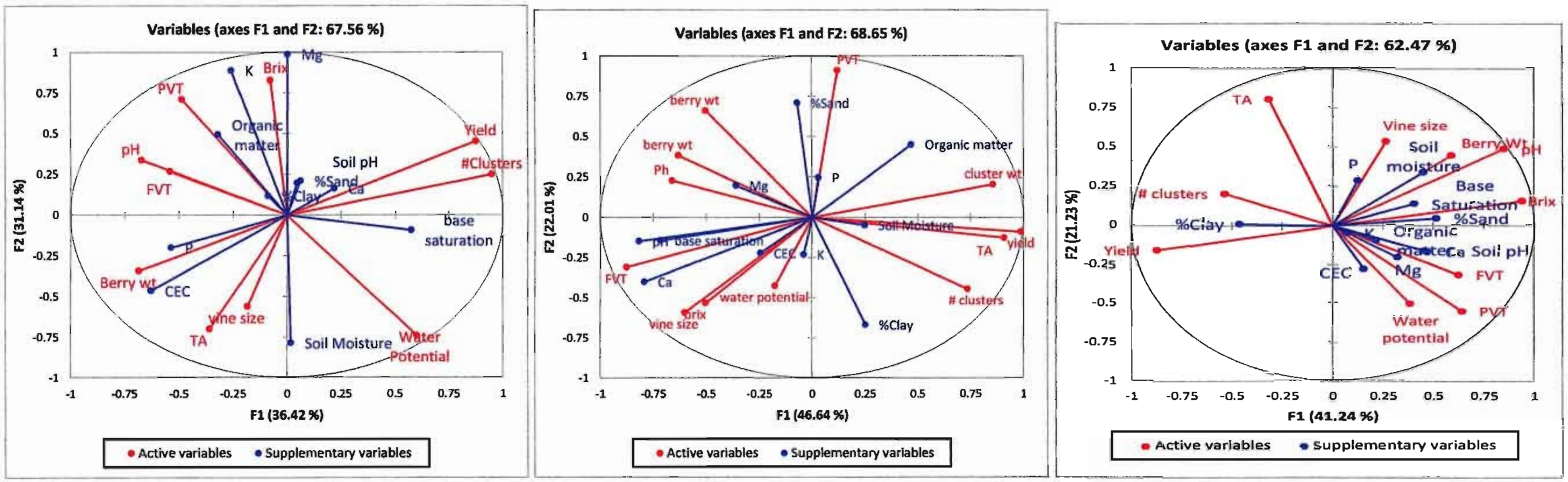
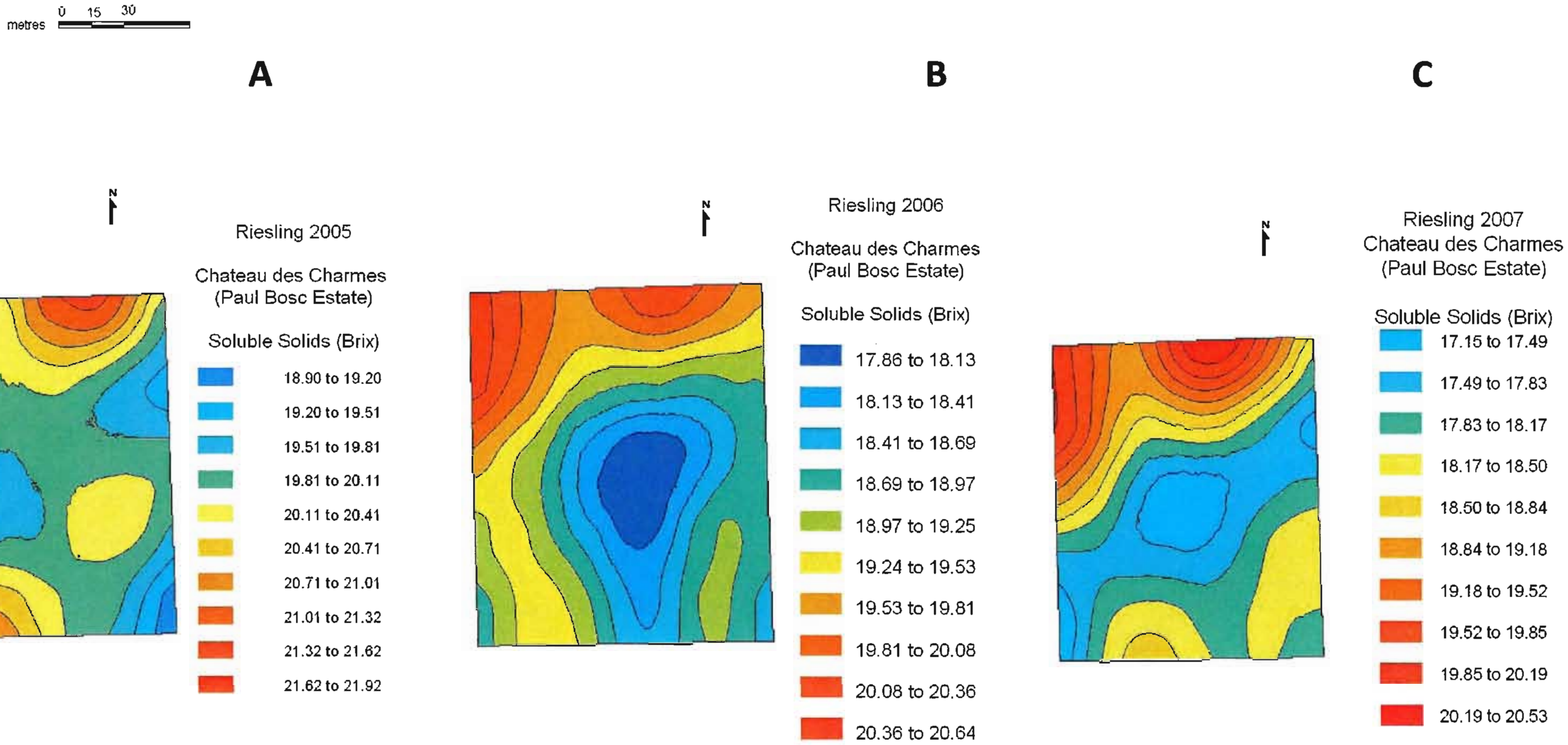


2005

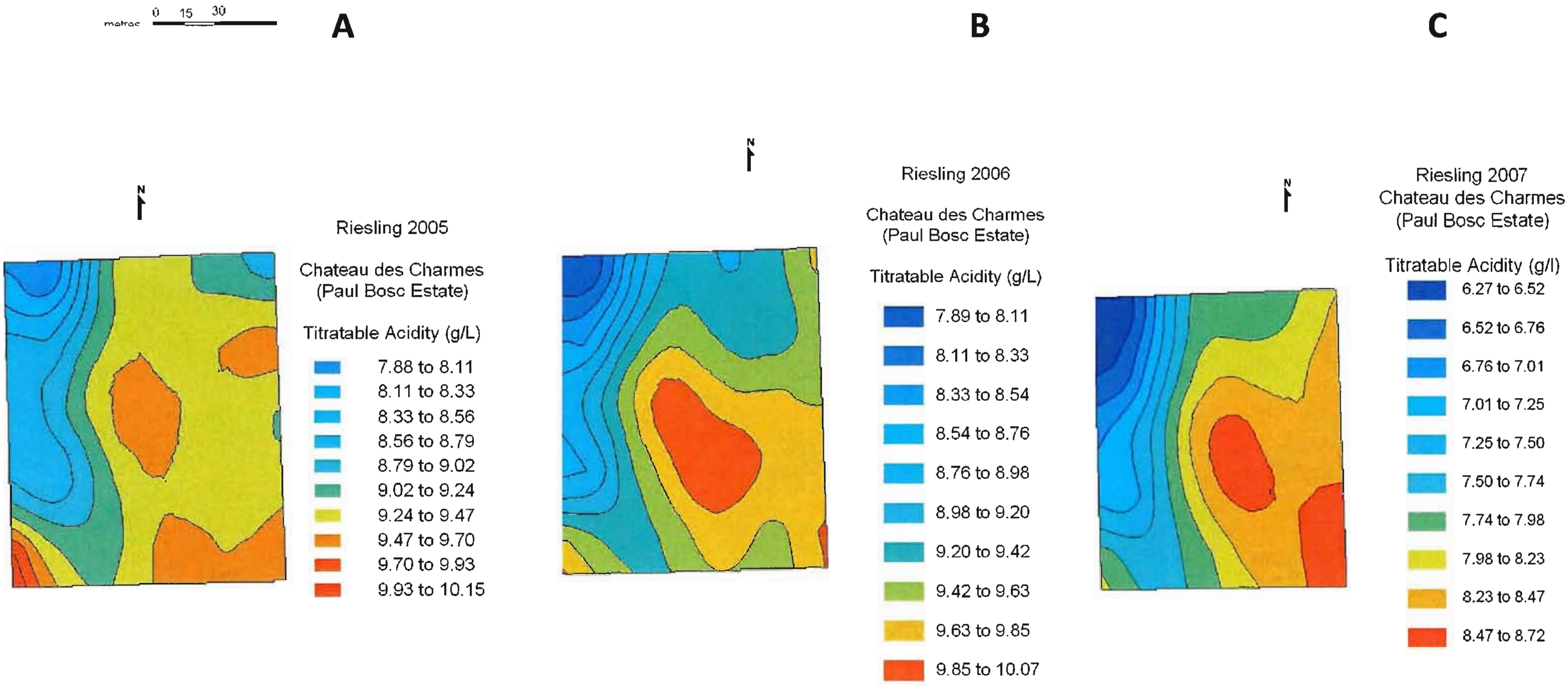
2006

2007

Supplemental Figure 4.5b. Principal component analysis of viticulture and soil variables for Glenlake Vineyards (Lakelodge), 2005-2007. *Supplementary variables in blue are soil variables.*



Supplemental Figure 4.1c. Spatial distribution of berry Brix, Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-Lake, ON; A: 2005; B: 2006; C: 2007.



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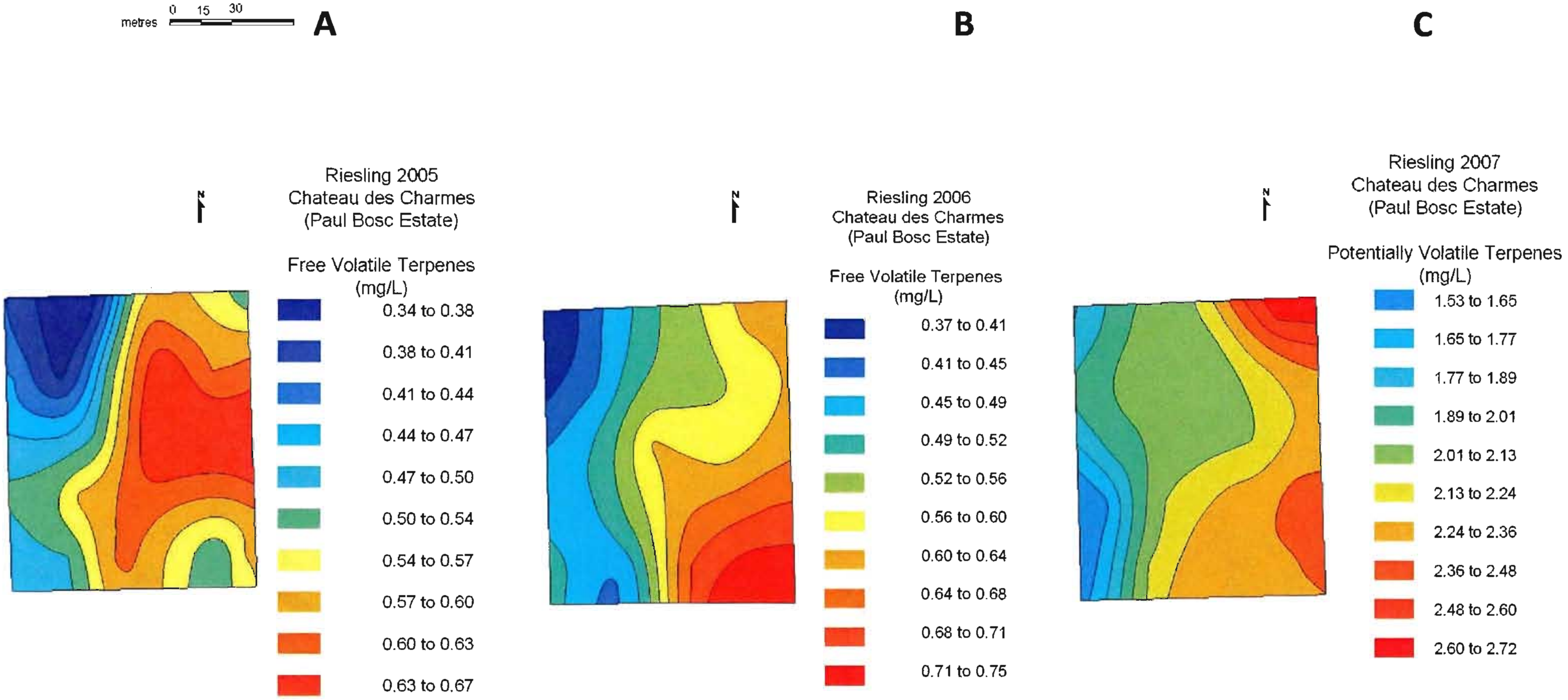

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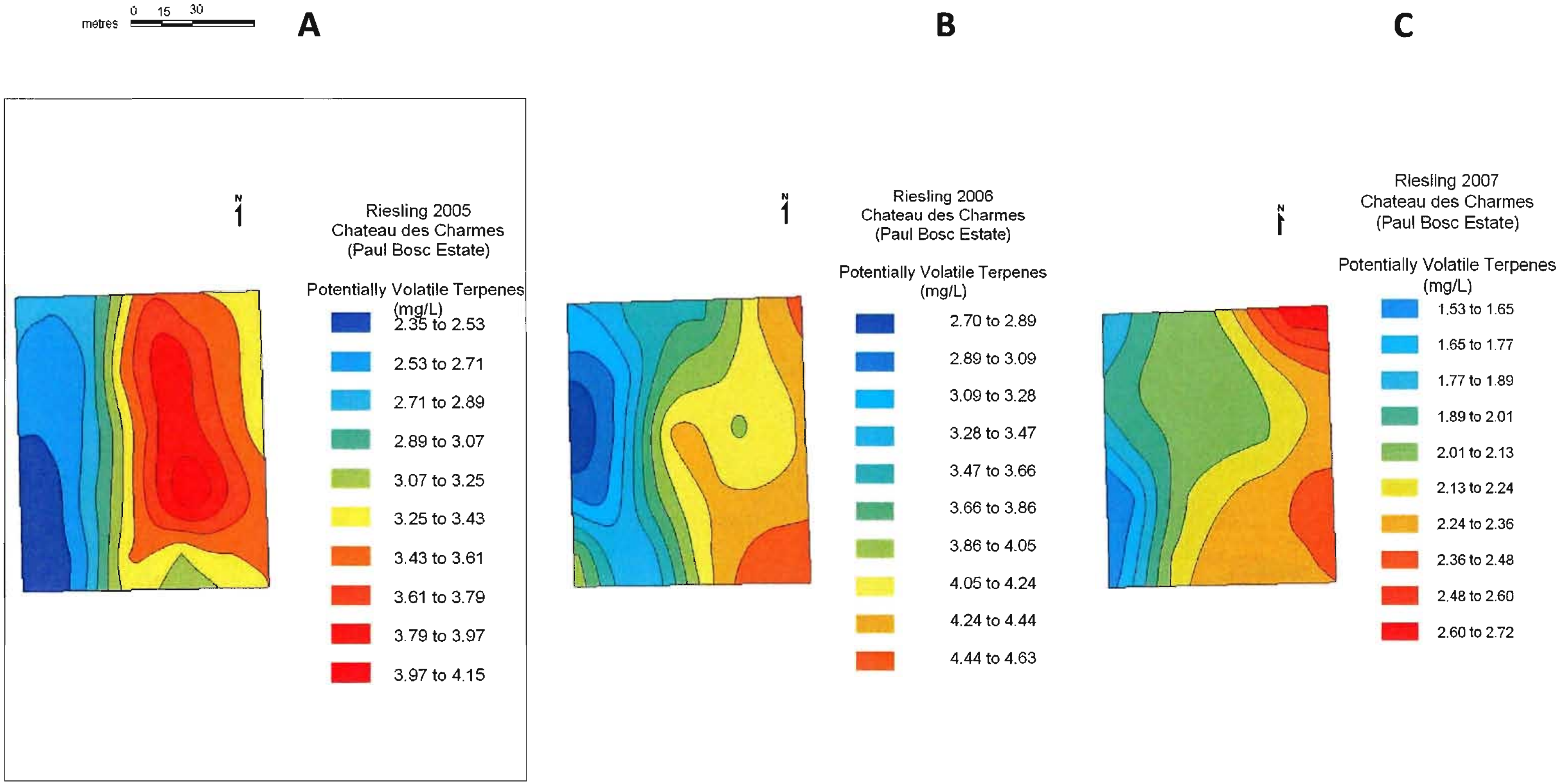
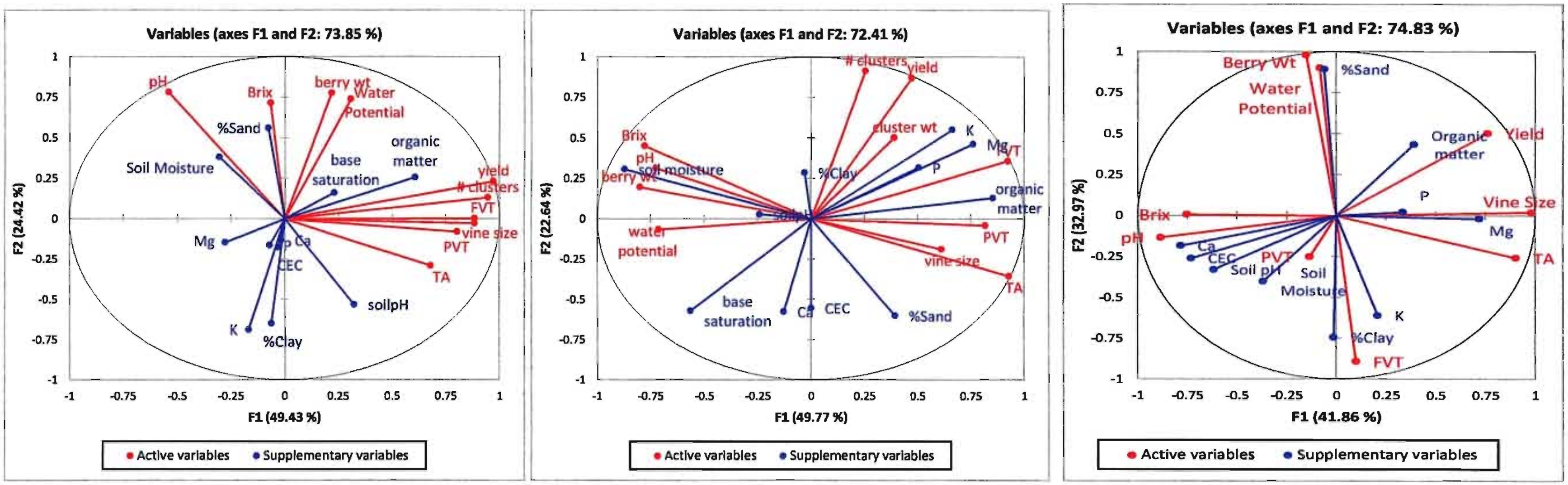
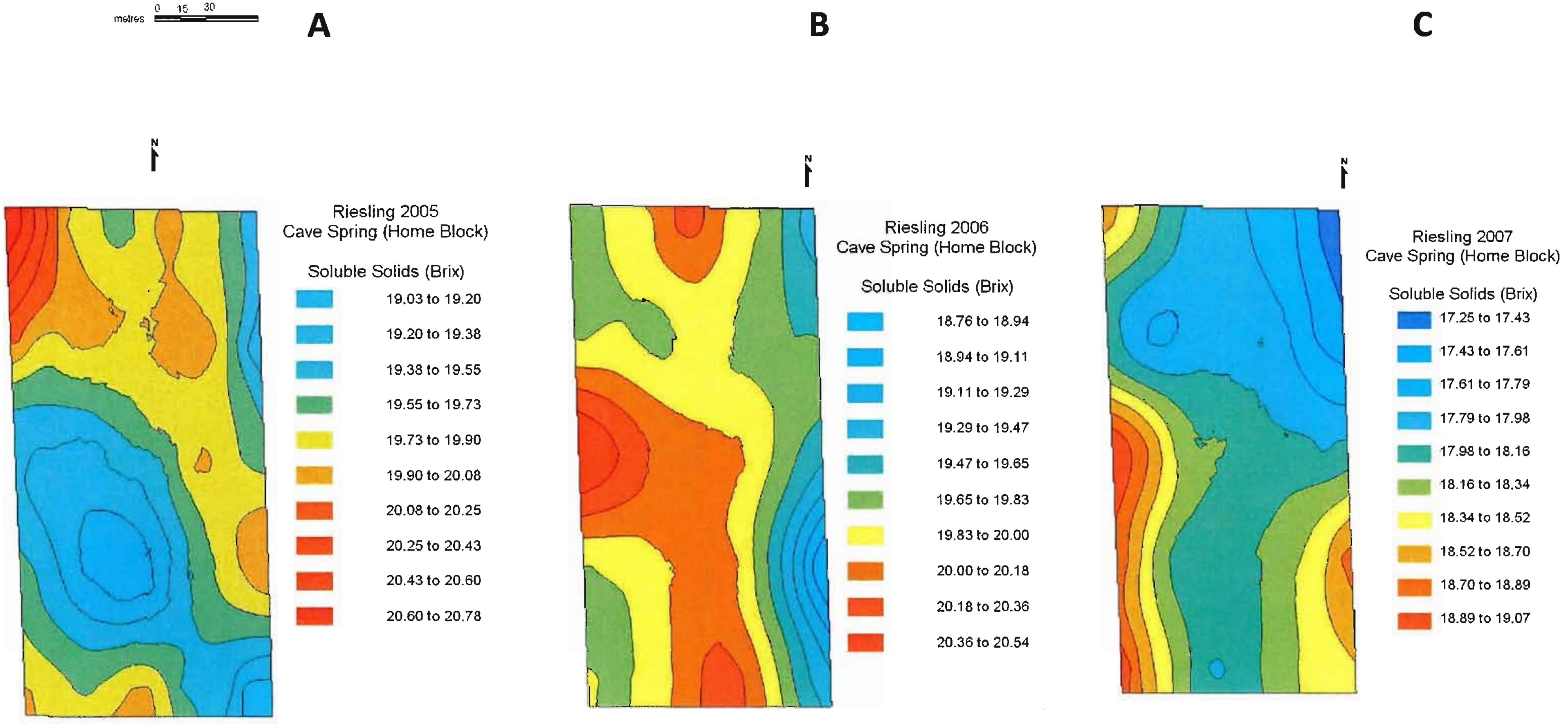


Supplemental Figure 4.4c. Spatial distribution of berry Potentially Volatile Terpenes (mg/L), Chateau des Charmes (Paul Bosc Estate), Niagara-on-the-Lake, ON; A: 2005; B: 2006; C: 2007.

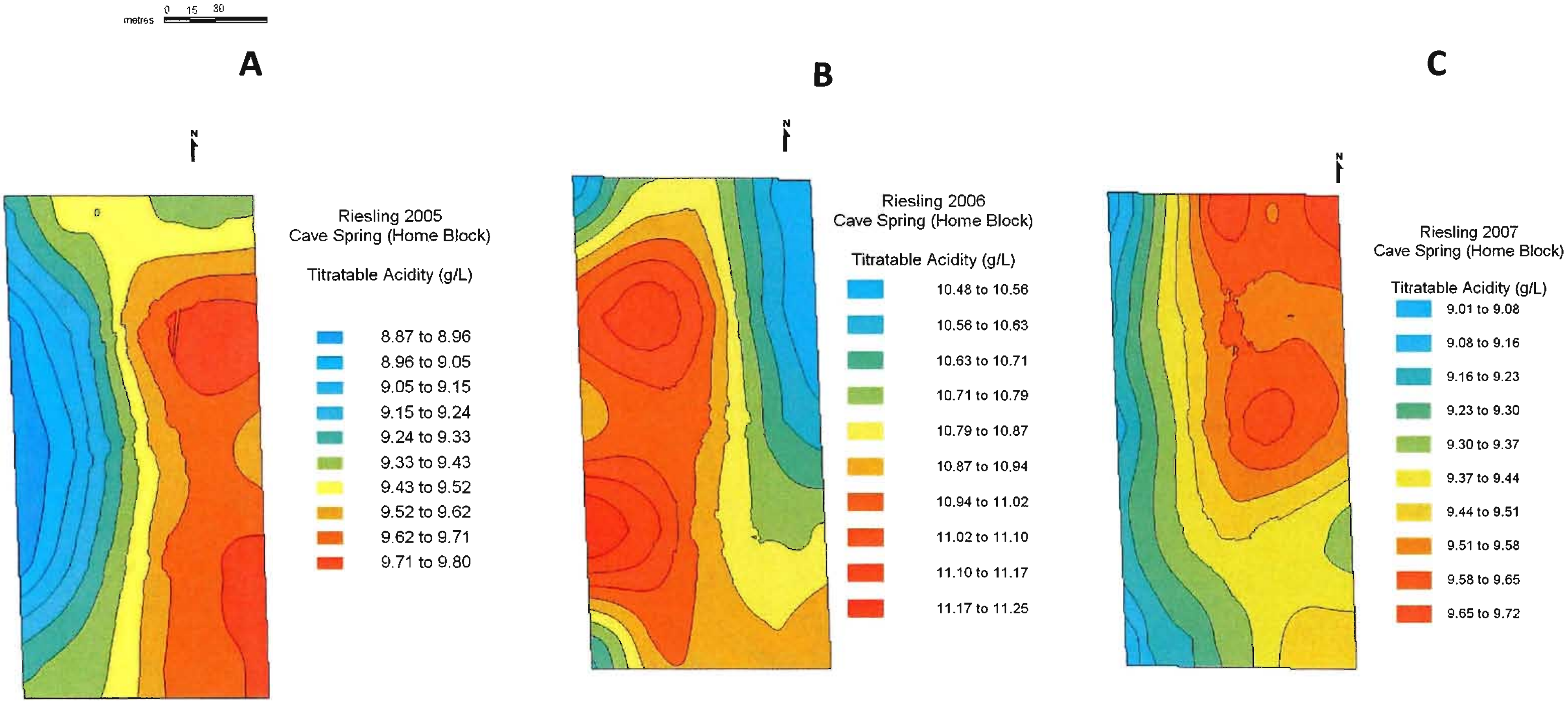


2005 2006 2007

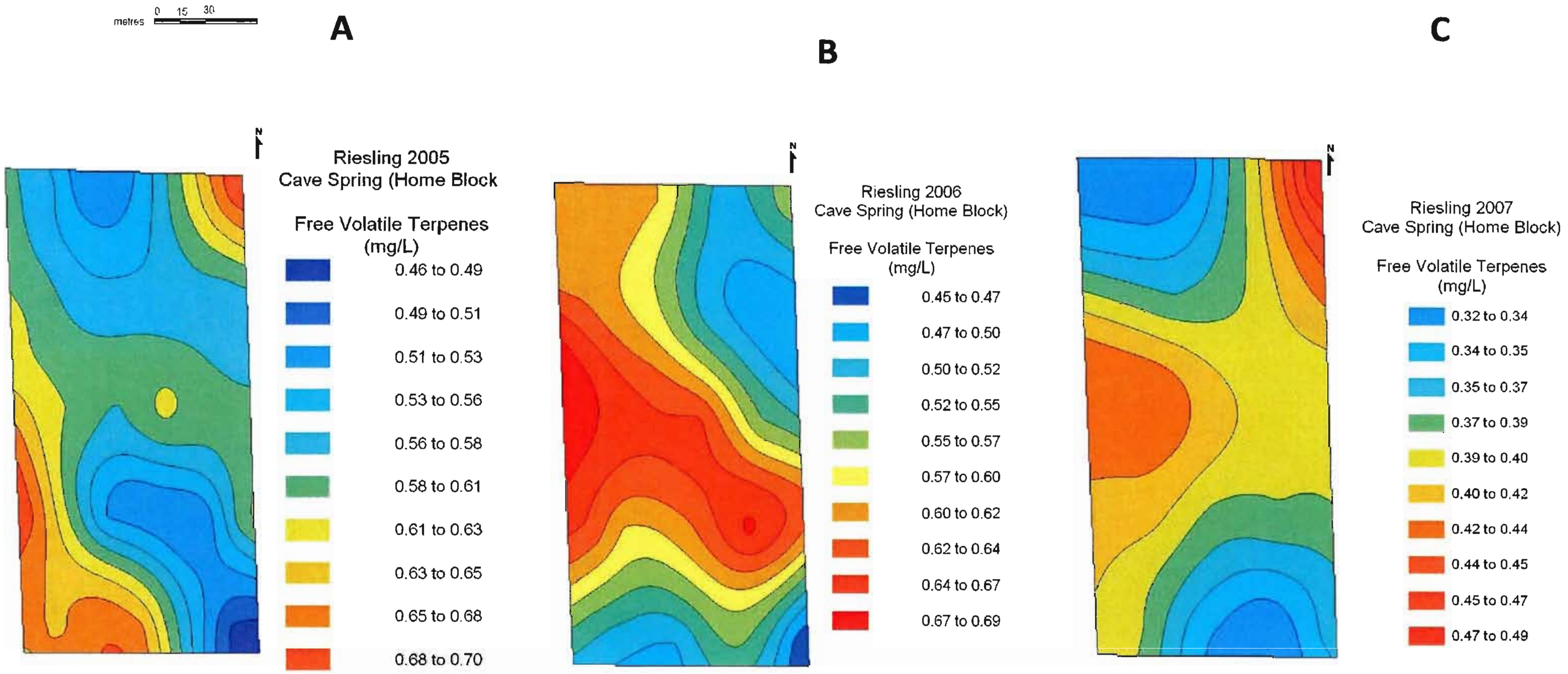
Supplemental Figure 4.5c. Principal component analysis of viticulture and soil variables for Chateau des Charmes (Paul Bosc Estate), 2005-2007. *Supplementary variables in blue are soil variables.*



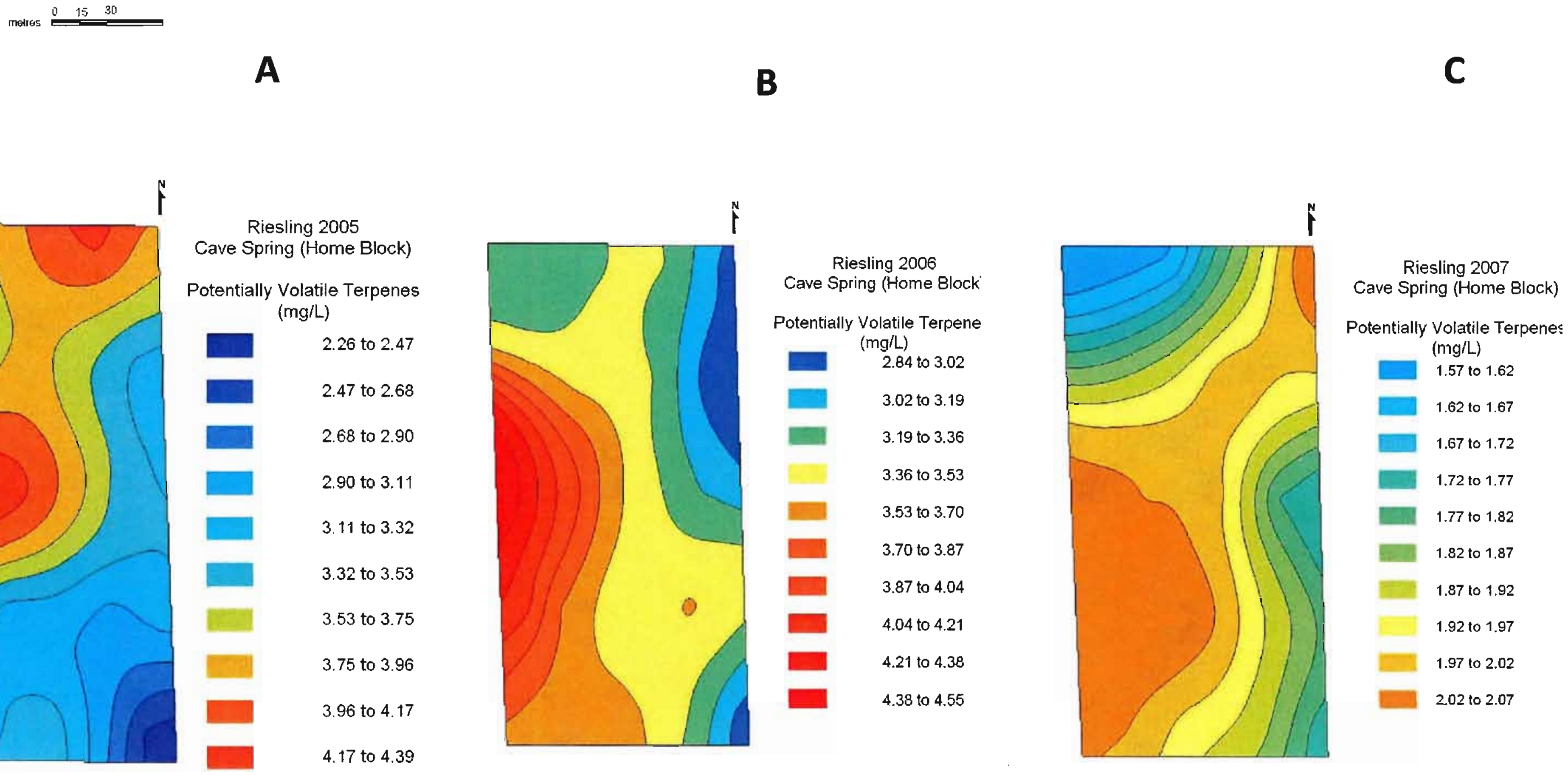
Supplemental Figure 4.1d. Spatial distribution of berry Brix, Cave Spring Cellars (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.



Supplemental Figure 4.2d. Spatial distribution of berry titratable acidity (g/L), Cave Spring Cellars (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.



Supplemental Figure 4.3d. Spatial distribution of berry Free Volatile Terpenes (mg/L), Cave Spring Cellars (Home Block), Beamsville, ON; A: 2005; B: 2006; C: 2007.



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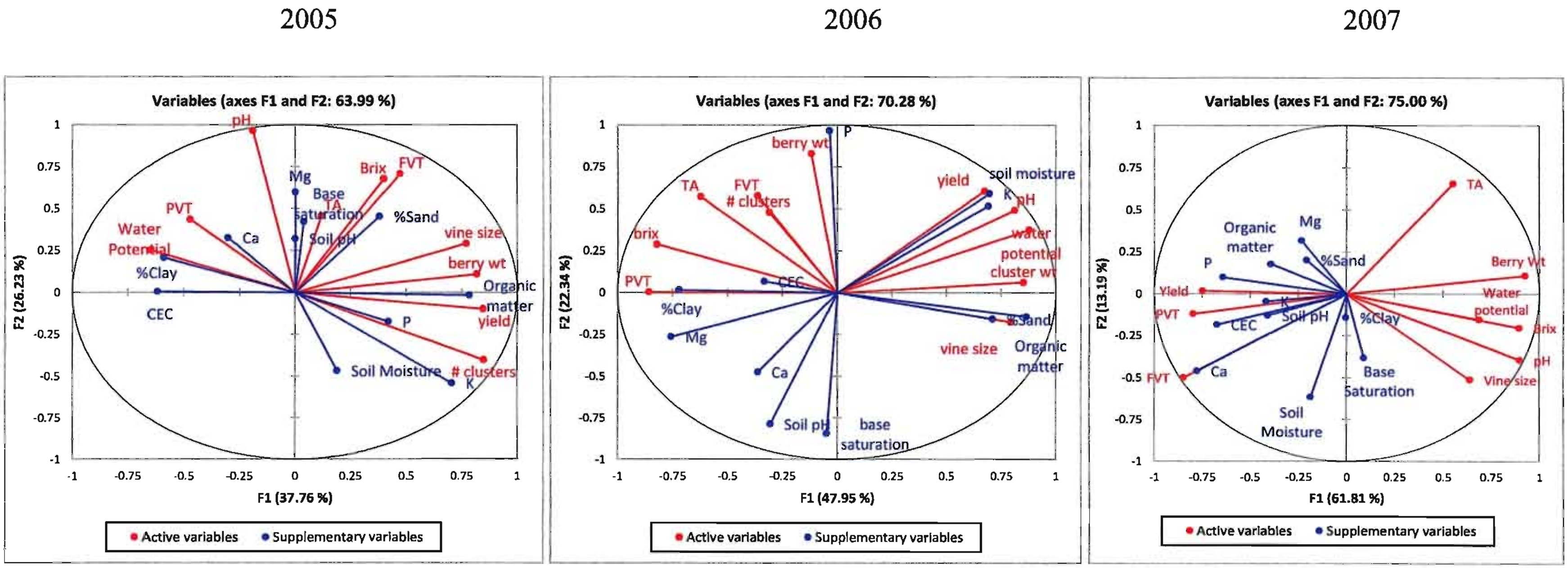
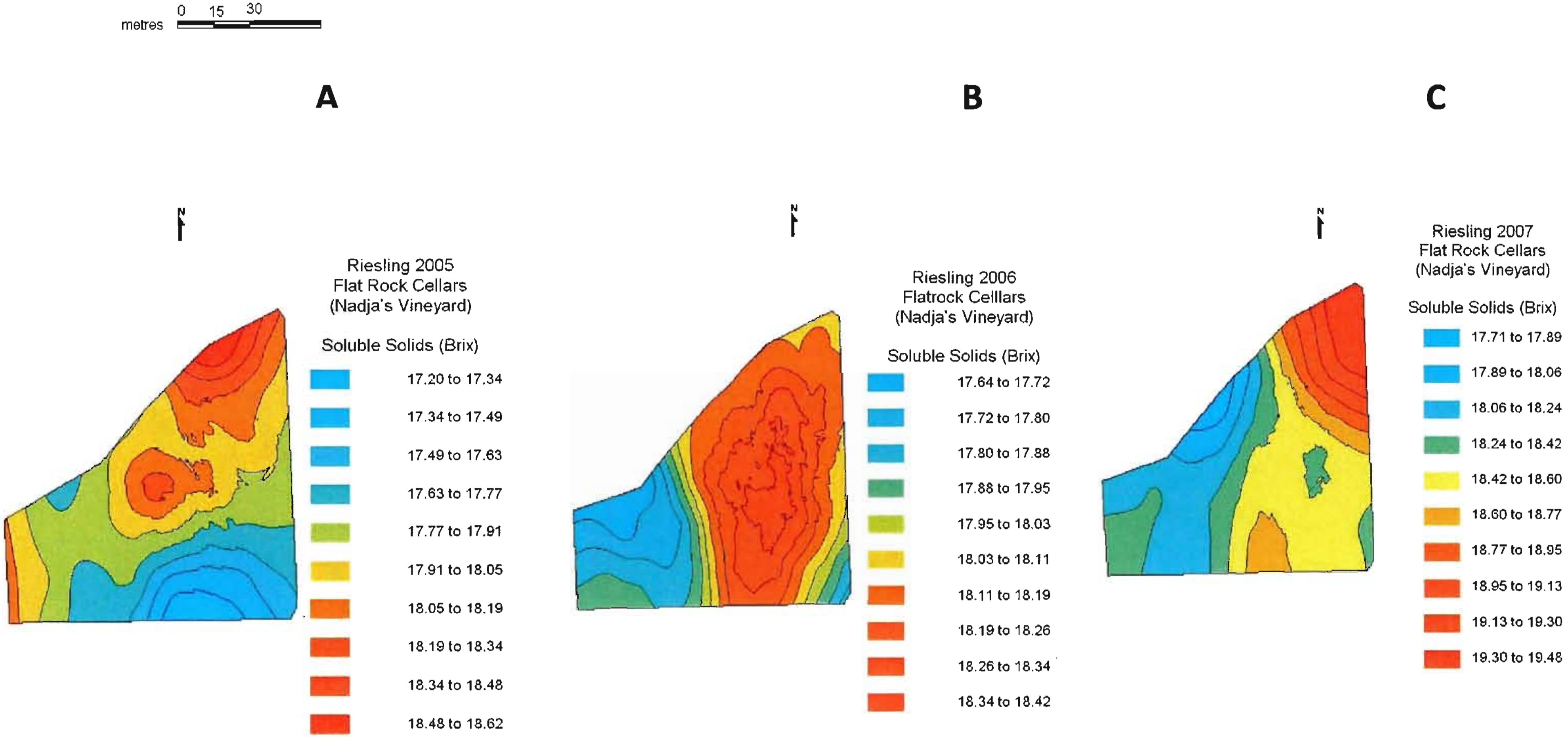
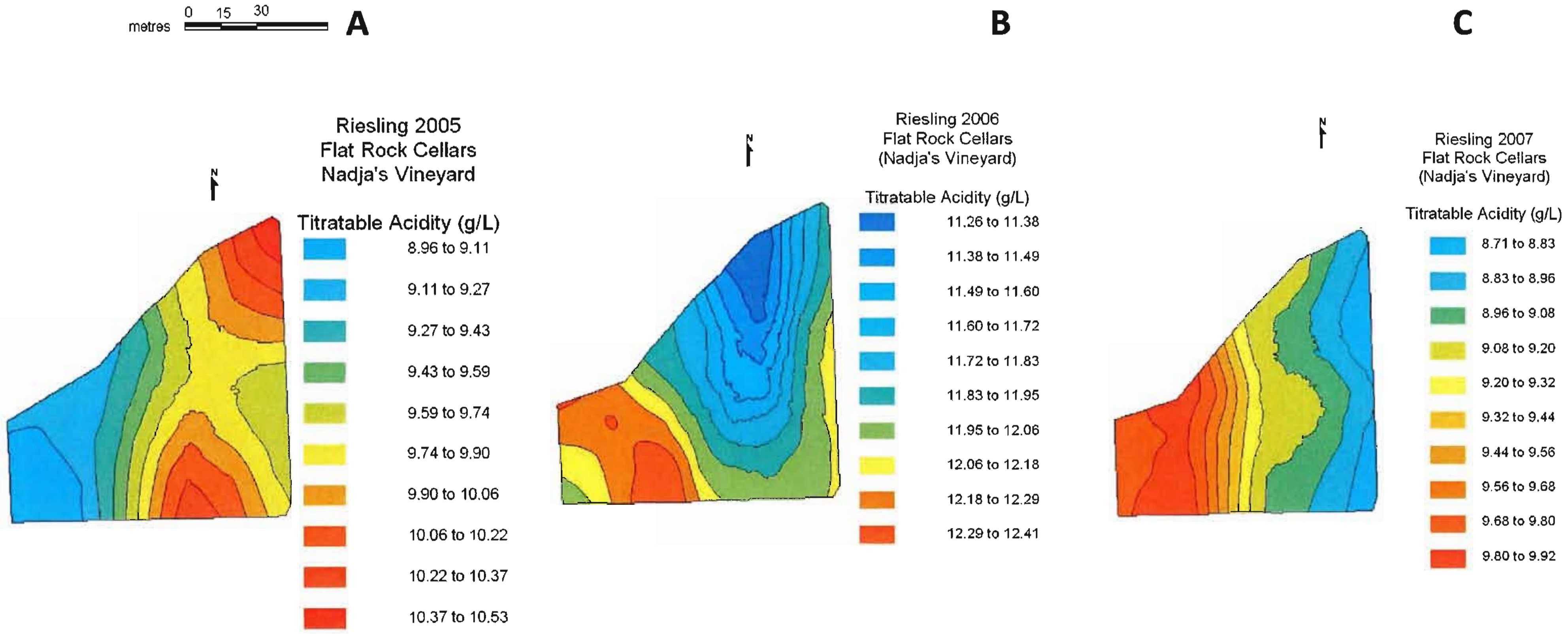


2005 2006 2007

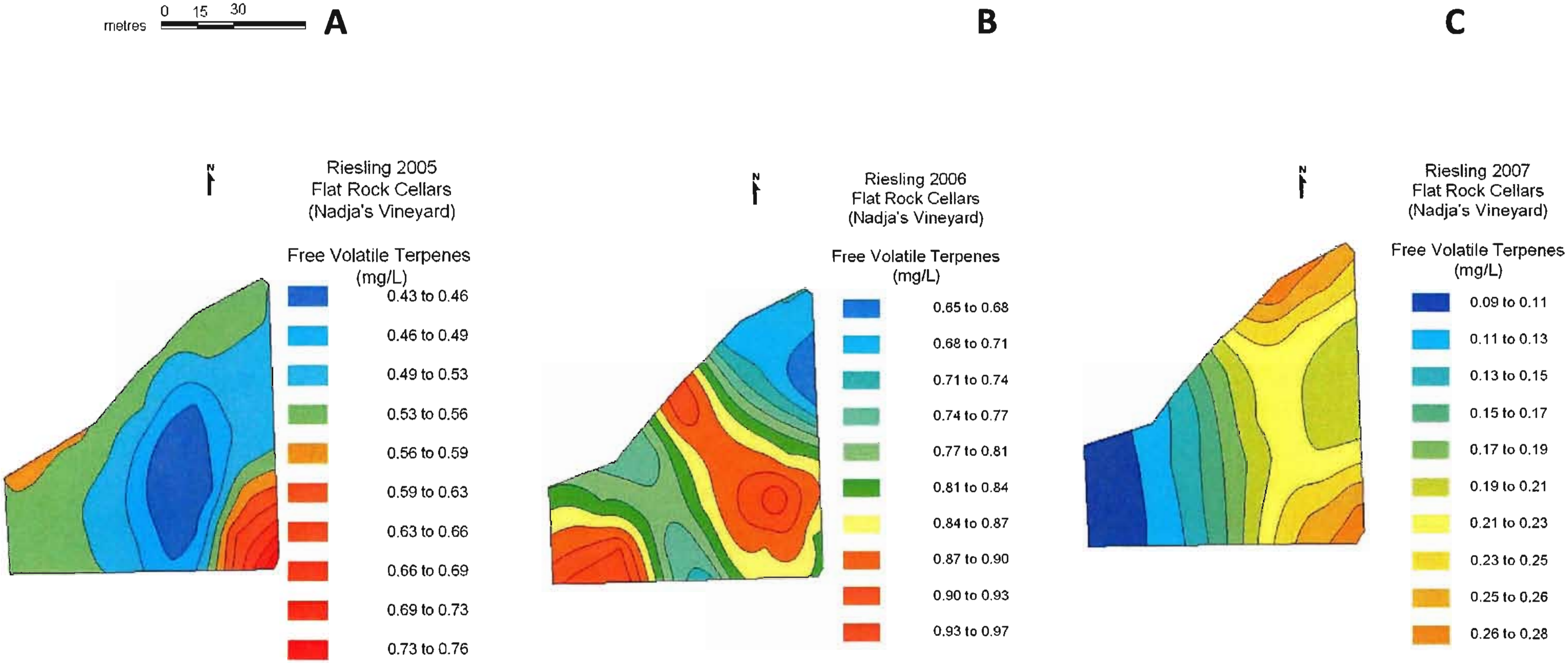
Supplemental Figure 4.5d. Principal component analysis of viticulture and soil variables for Cave Spring Cellars (Home Block), 2005-2007. *Supplementary variables in blue are soil variables.*



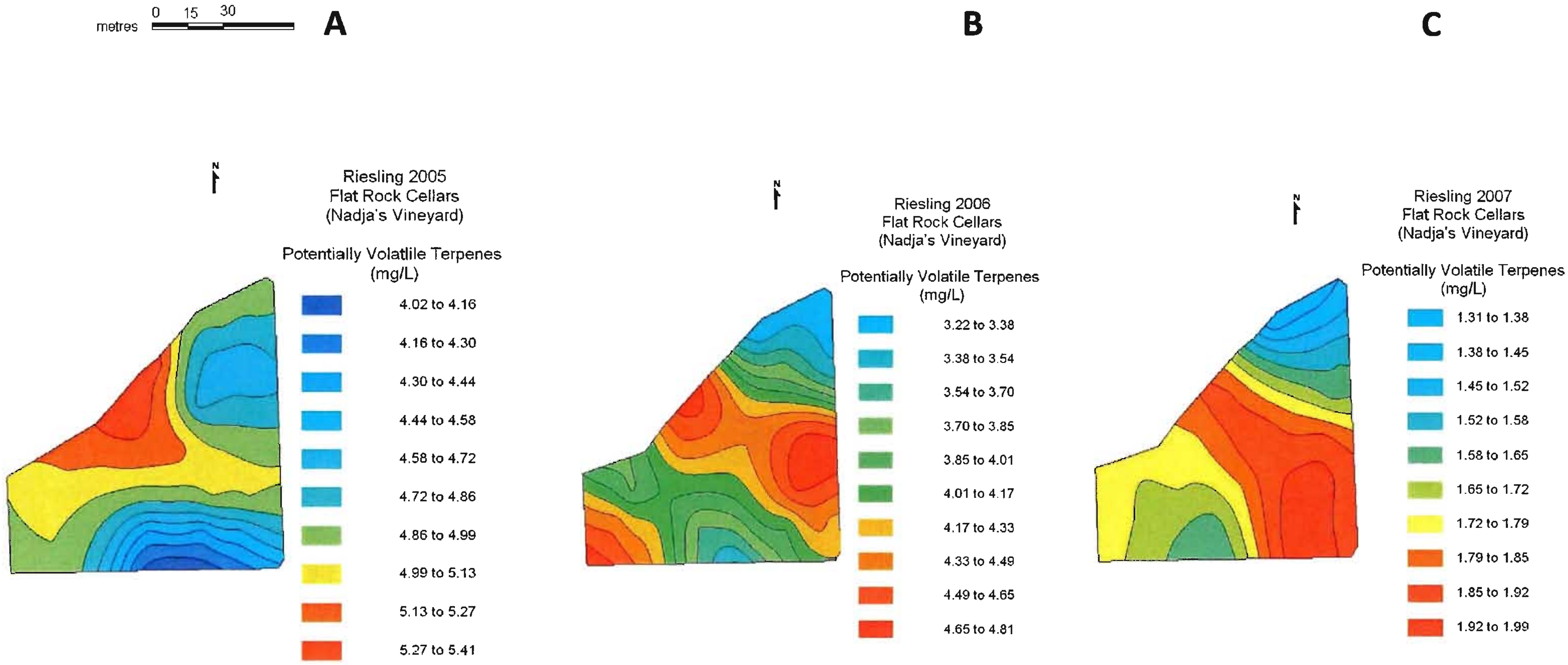
Supplemental Figure 4.1e. Spatial distribution of berry Brix Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.



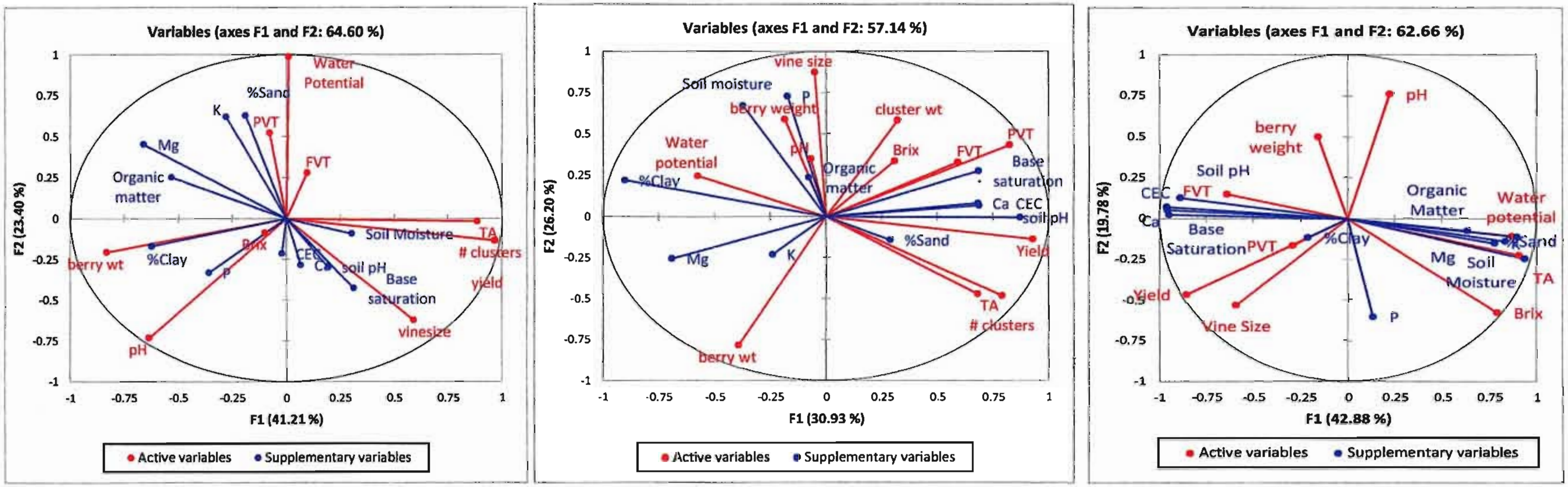
Supplemental Figure 4.2e. Spatial distribution of berry titratable acidity (g/L), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.



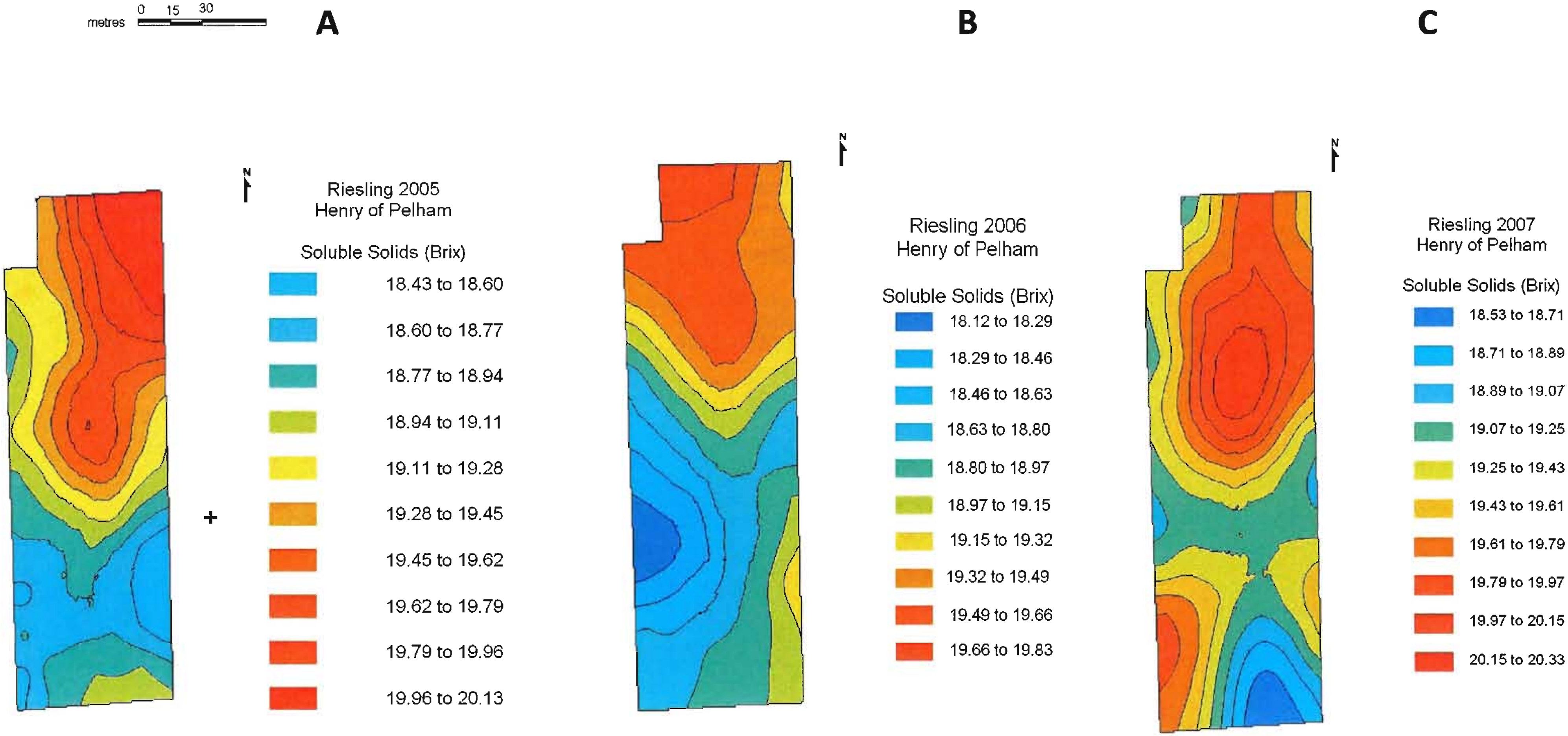
Supplemental Figure 4.3e. Spatial distribution of berry Free Volatile Terpenes (mg/L), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.



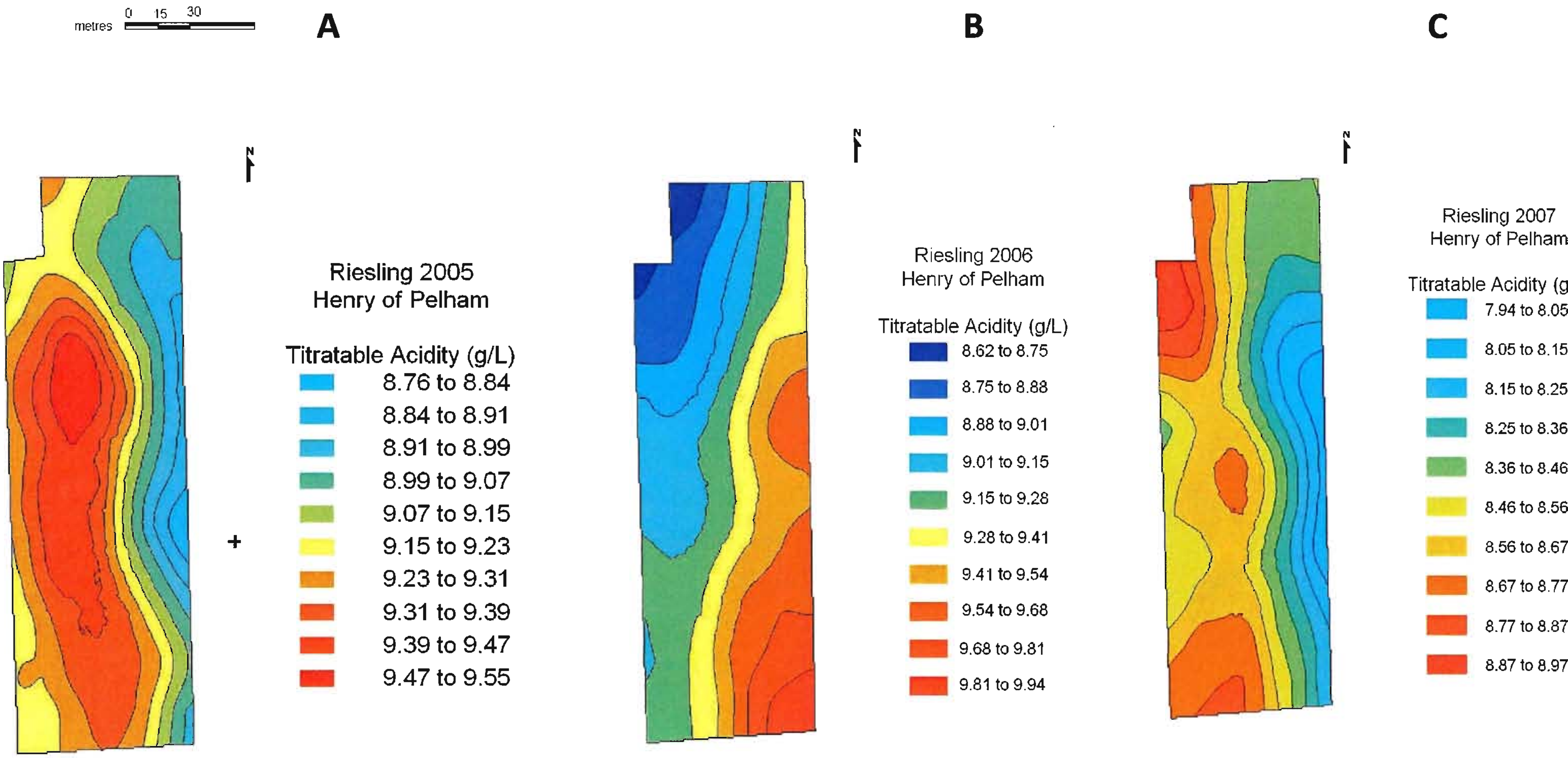
Supplemental Figure 4.4e. Spatial distribution of berry Potentially Volatile Terpenes (mg/L), Flat Rock Cellars (Nadja's Vineyard), Jordan, ON; A: 2005; B: 2006; C: 2007.


2005 2006 2007

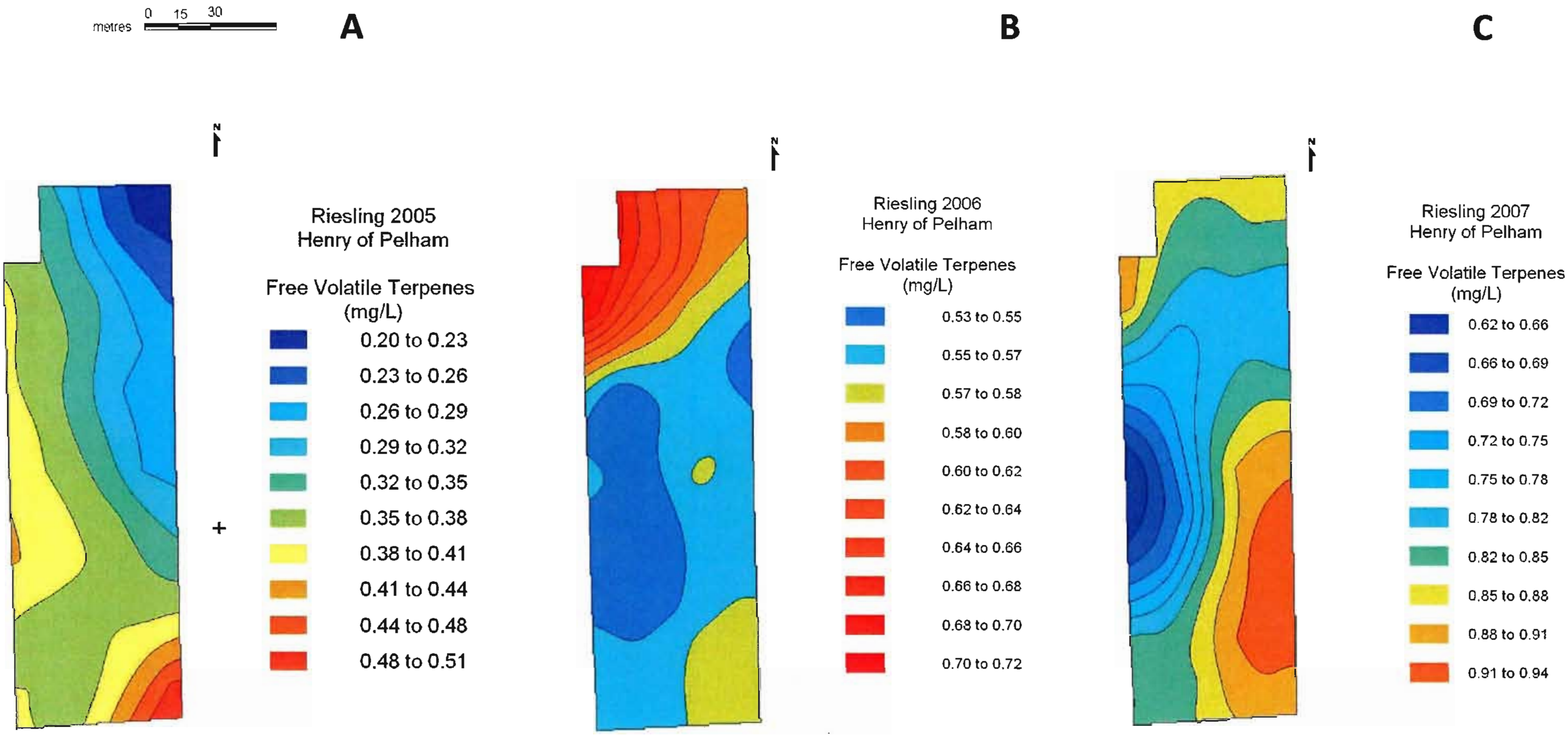
Supplemental Figure 4.5e. Principal component analysis of viticulture and soil variables for Flat Rock Cellars (Nadja's Vineyard), 2005-2007. *Supplementary variables in blue are soil variables.*



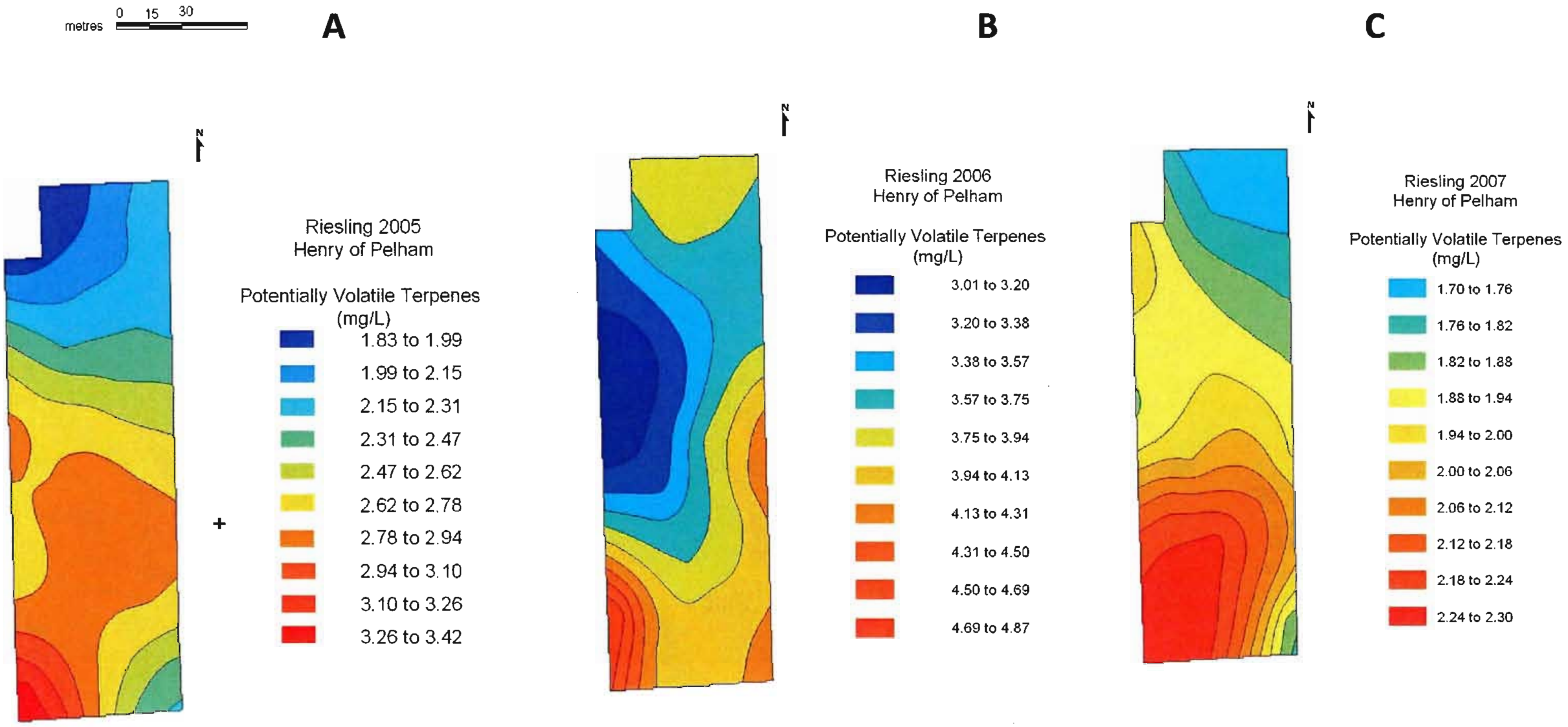
Supplemental Figure 4.1f. Spatial distribution of berry Brix, Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.



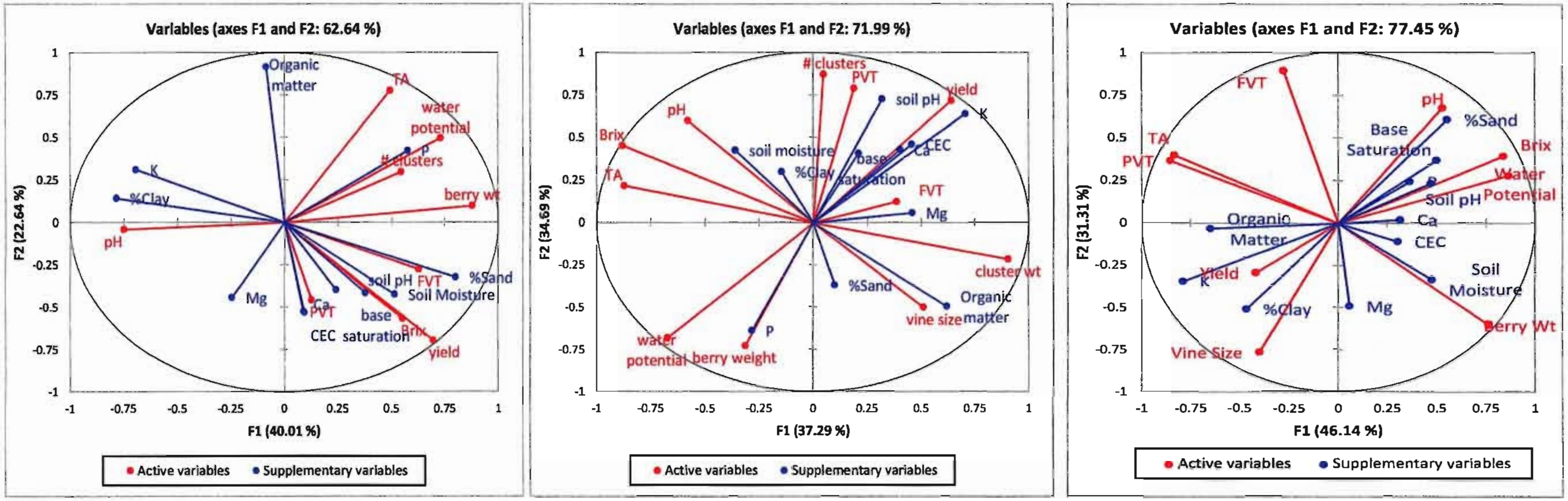
Supplemental Figure 4.2f. Spatial distribution of berry titratable acidity (g/L), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.



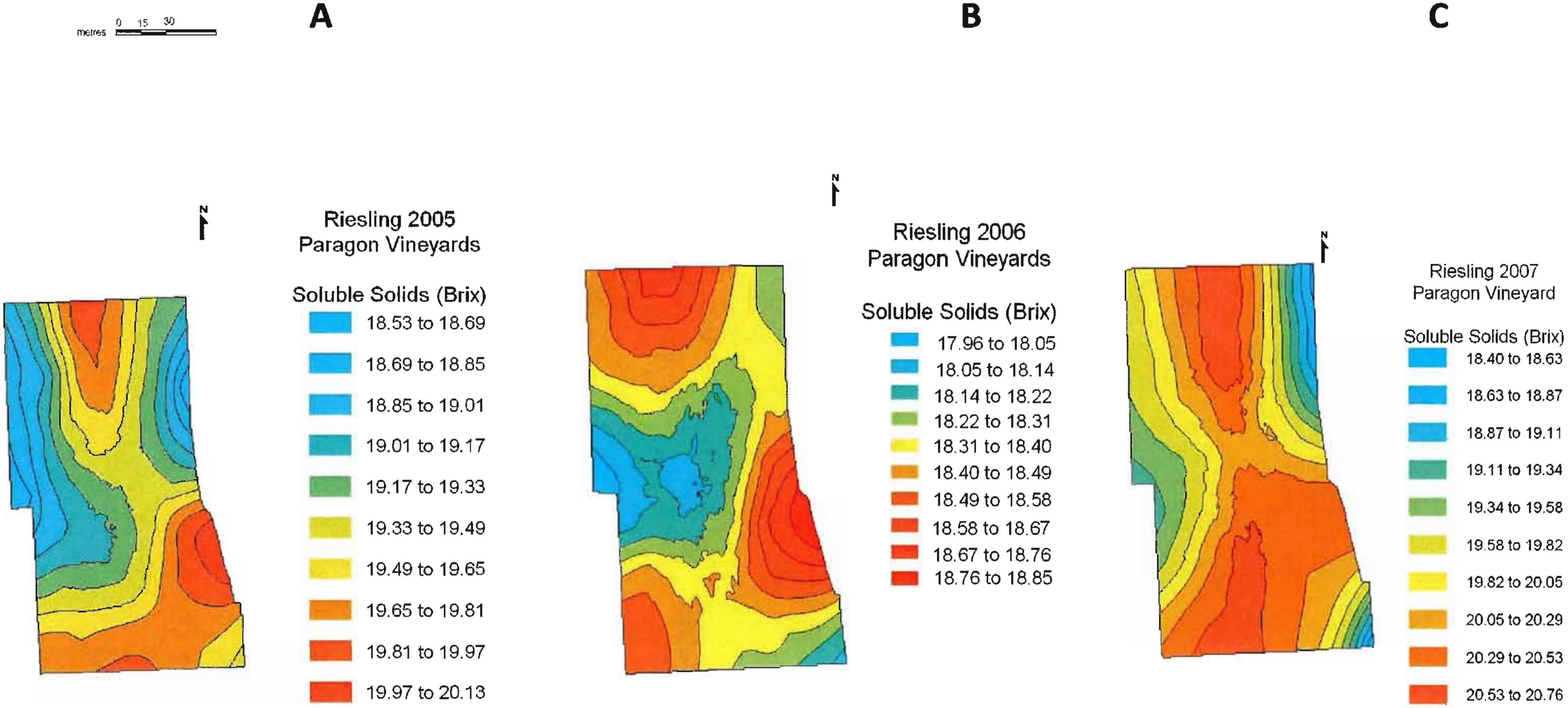
Supplemental Figure 4.3f. Spatial distribution of berry Free Volatile Terpenes (mg/L), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.



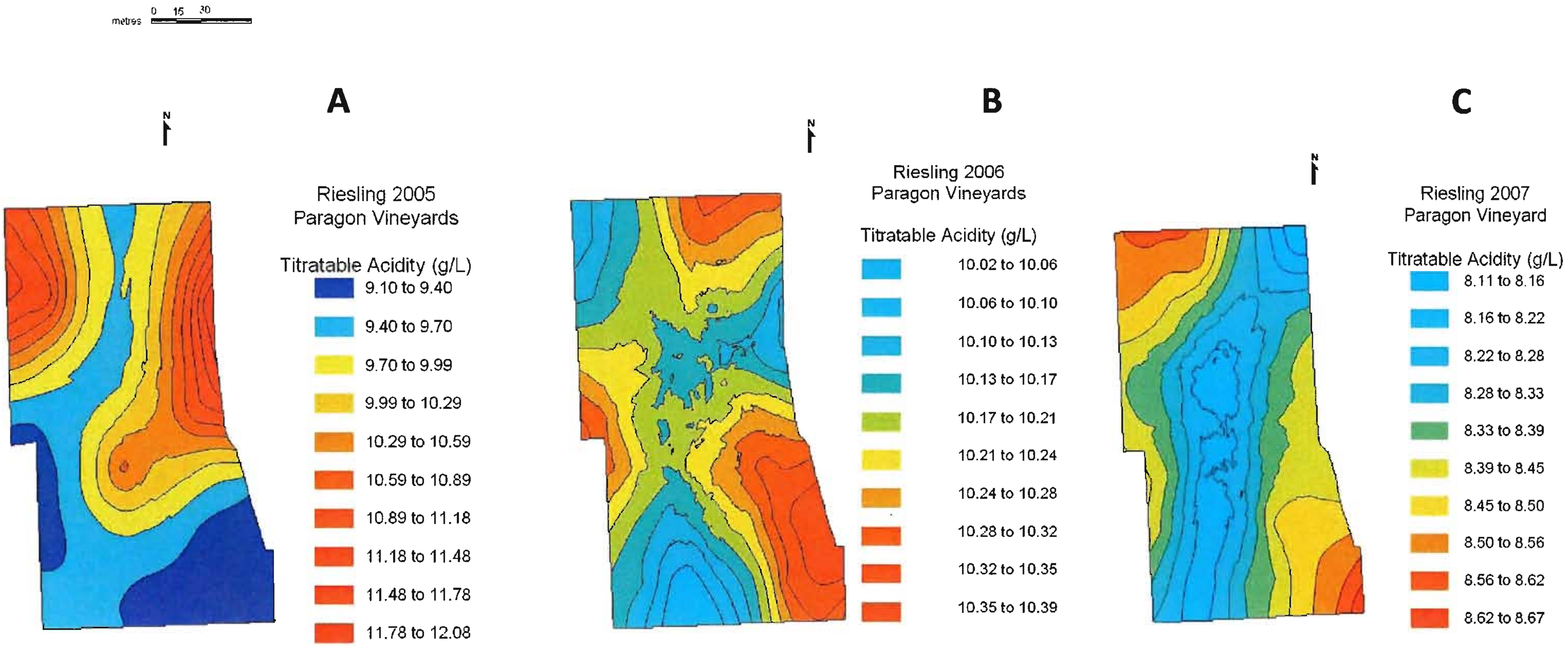
Supplemental Figure 4.4f. Spatial distribution of berry Potentially Volatile Terpenes (mg/L), Henry of Pelham, St. Catharines, ON; A: 2005; B: 2006; C: 2007.


2005 2006 2007

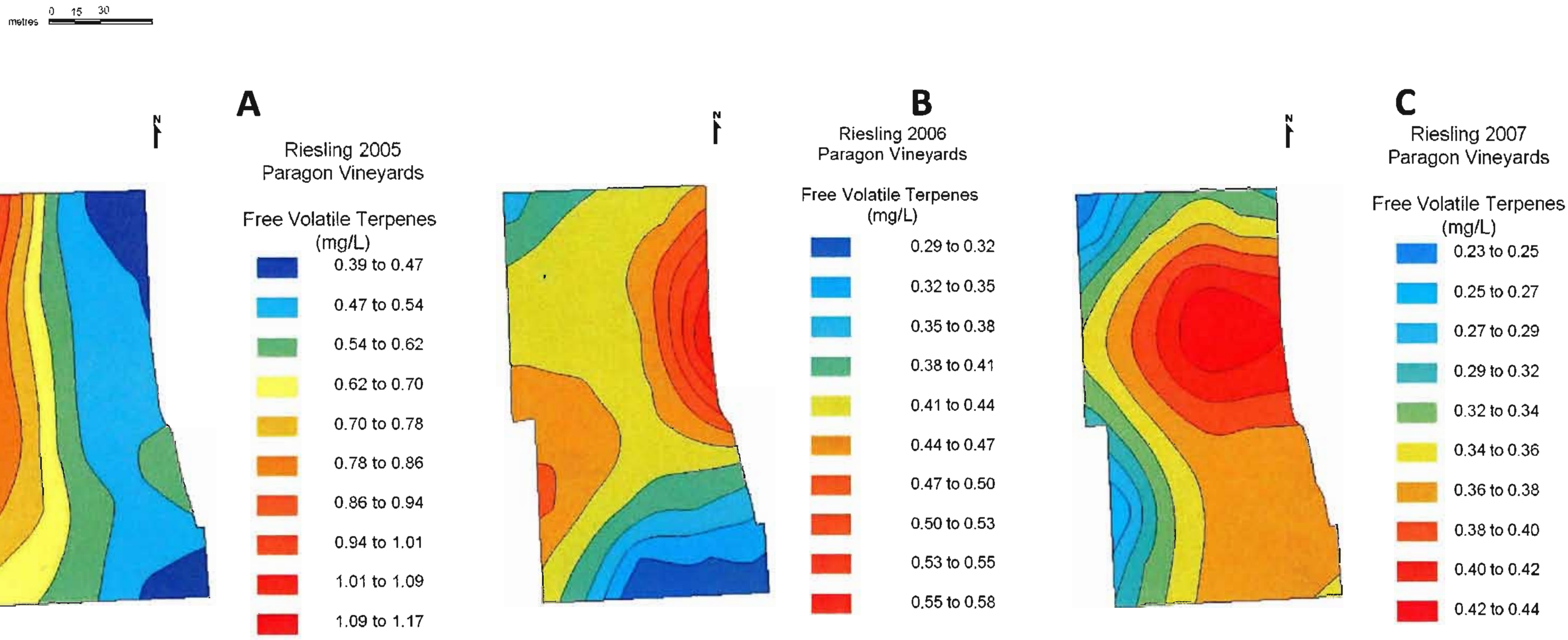
Supplemental Figure 4.5f. Principal component analysis of viticulture and soil variables for Henry of Pelham, 2005-2007. *Supplementary variables in blue are soil variables.*



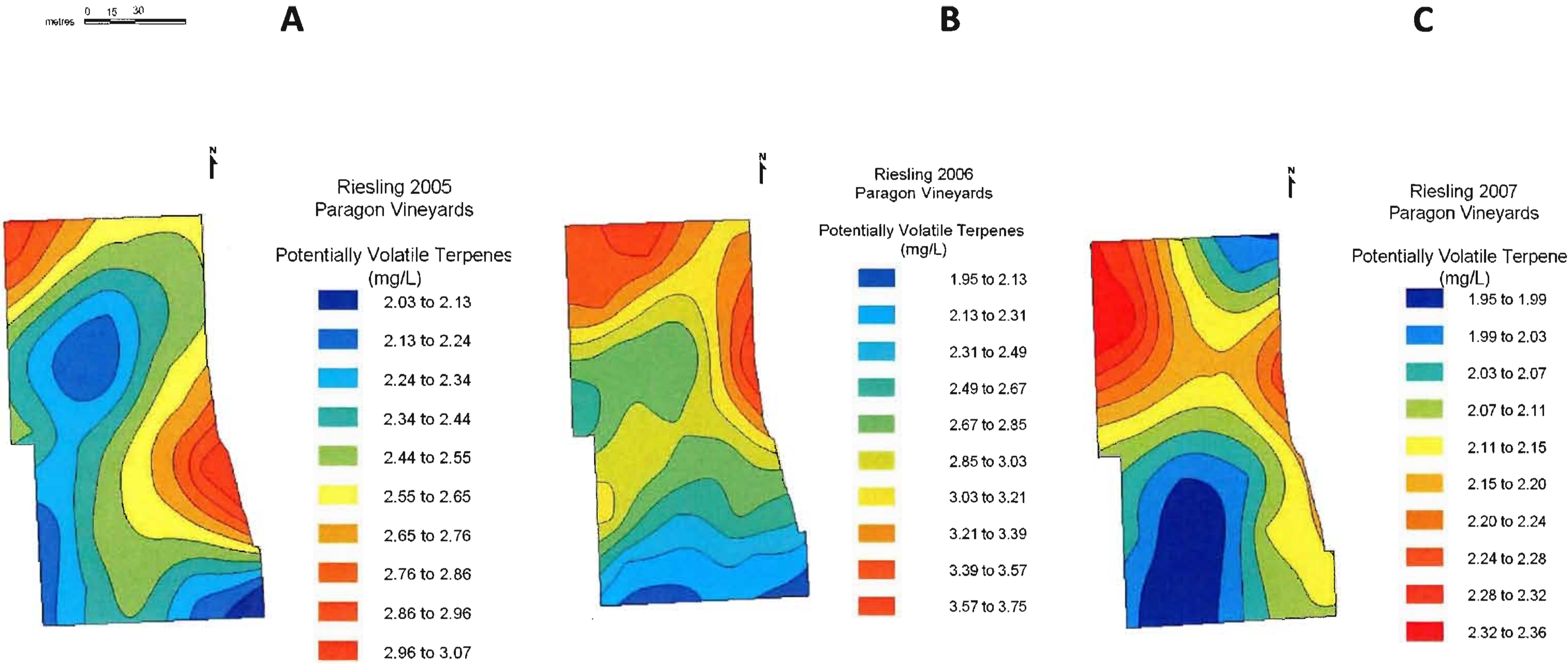
Supplemental Figure 4.1g. Spatial distribution of berry Brix, Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.



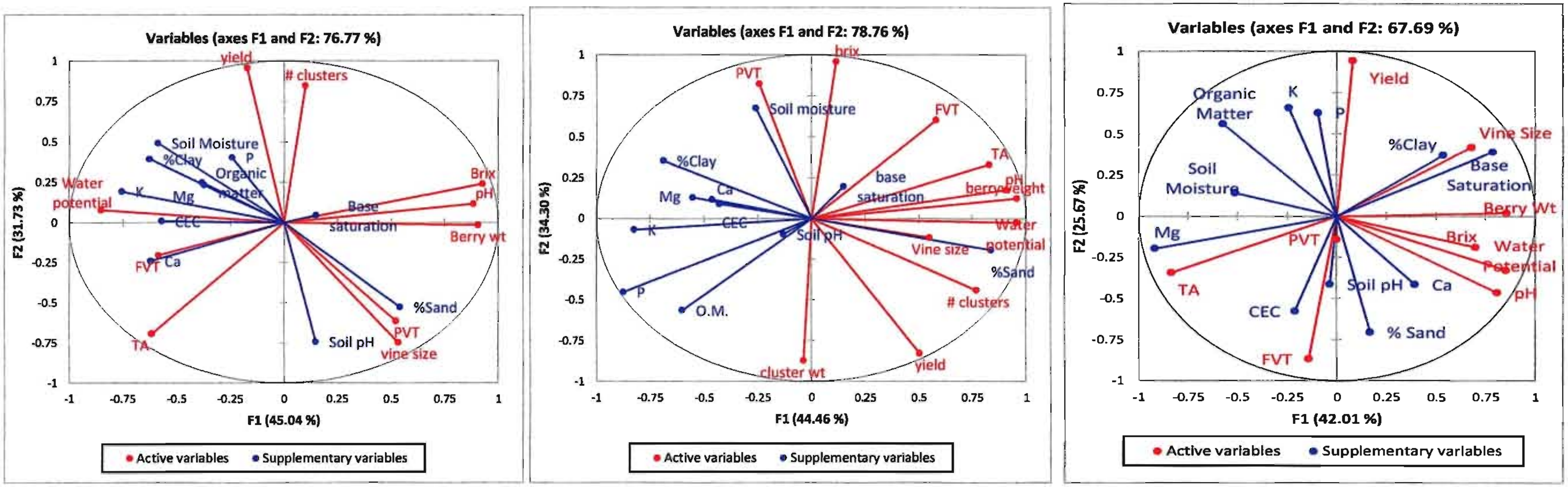
Supplemental Figure 4.2g. Spatial distribution of berry titratable acidity (g/L), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.



Supplemental Figure 4.3g. Spatial distribution of berry Free Volatile Terpenes (mg/L), Paragon Vineyards, Jordan, ON; A: 2005.



Supplemental Figure 4.4g. Spatial distribution of berry Potentially Volatile Terpenes (mg/L), Paragon Vineyards, Jordan, ON; A: 2005; B: 2006; C: 2007.



2005

2006

2007

Supplemental Figure 4.5g. Principal component analysis of viticulture and soil variables for Paragon Vineyards, 2005-2007. *Supplementary variables in blue are soil variables.*

Chapter 5: Sensory analysis of Riesling wines from different sub-appellations within the Niagara Peninsula

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Abstract

The major focus of our research is to explain potential terroir effects that impact wine varietal character. In recent years, the Vintners Quality Alliance of Ontario created sub-appellations within the Niagara Peninsula based on soil and climatic differences. Therefore, one of our research objectives was to determine differences that might validate the designation of these sub-appellations. Our hypothesis was that wines would differ in terms of fruit composition and wine sensory attributes among these sub-appellations. To test this hypothesis, ten commercial Riesling vineyards representative of each sub-appellation were selected from 2005-2006. Vineyards were delineated using global positioning systems (GPS) and 75-80 sentinel vines were georeferenced within a sampling grid. Since our primary research hypothesis is that vine water status plays a major role in the terroir effect, wines were made from vines of similar water status based upon leaf water potential. Standard winemaking protocol was used to minimize any enological effects. Descriptive analysis using a trained panel indicated that vineyard designation had an effect on wine sensory profiles for the 2005 and 2006 vintages. Using analysis of variance, 12 aroma and flavour attributes were found to be significantly different ($p<0.05$) in 2005 and 13 aroma and flavour attributes were found to be significantly different ($p<0.05$) in 2006. In both vintages, fruit and wines were also significantly different ($p<0.05$) in terms of chemical composition (titratable acidity, pH, free volatile terpenes, and potentially volatile terpenes). Through principal component analysis and partial least squares regression analysis, specific sensory and chemical attributes and vineyard variables were shown to be associated with wines from the different sub-appellations. However, wines were generally grouped in terms of their regional designation ('Lakeshore', 'Bench' and 'Plains') within the Niagara Peninsula.

Key words: Geographical origin, fruit composition, multivariate statistics, sensory analysis, terroir

Introduction

Appellations have been an integral part of 'Old World' wine grape growing regions for centuries. These geographical boundaries are mainly based on meteorological, pedological, and geological factors and they have governing bodies that regulate both viticulture and winemaking practices. Geographical origin has been widely used as an attribute that defines wine quality. Differences in sensory characteristics of wines between appellations can be related to the nature of the terroir. Terroir, which is loosely translated to "sense of place", can be defined as an integrative ecosystem, in a given place, including soil, climate, and the vine environment (van Leeuwen and Seguin 2006) that influences the character and quality of wine grapes. The importance of these combined pedoclimatic conditions, vine components and viticulture techniques has led researchers to try to categorize wines based on these parameters according to geographical origin. Studies have attempted to classify wines of origin by means of volatile composition (Arrhenius et al. 1996, Marais et al. 1981, Sabon et al. 2002), trace elements (Coetzee et al. 2005, Taylor et al. 2003), isotopes (Martin et al. 1999), phenolics (Rastija et al. 2009), organic and amino acids (Etievant et al. 1988, Seeber et al. 1991), proteins (González-Lara et al. 1989) and electronic nose (Berna et al. 2009). In the Rhone Valley, Sabon et al. (2002) found factors such as region and vintage influenced the level of varietal volatile compounds in Grenache wines. Kallithraka et al. (2001) found Greek red wines could be classified according to anthocyanins, whereas minerals and phenols did not result in any clustering of wines; however, white wines could not be classified by region using any criteria. In California Chardonnay wines, Arrhenius et al.

(1996) found that concentrations of volatiles were correlated with sensory data and that these were associated with regional distinctness. Reynolds et al. (1996) found some differences in monoterpene content and sensory properties in Gewürztraminer wines from different British Columbia vineyard sites that were attributable to climatic differences. Wines from the warmest site had the highest monoterpene concentrations, as well as, the most floral, fruity and cedar aromas and flavours. In Bordeaux, des Gachons et al. (2005) found that site did impact the aroma potential of Sauvignon blanc (due to the water holding capacities of the soils). However, the results were not consistent from year to year.

The evaluation of sensory characteristics and/or chemical components using multivariate analysis has been used to study regional or sub-regional differences among wines (Cliff et al. 2002, Sivertsen et al. 1999). Multivariate analysis of amino acid, volatile composition and mineral ions was used to discriminate vintages and vineyards with respect to Chardonnay grown in the Trentino region of Italy (Seeber et al. 1991). In Riesling wines from the Rheingau, Fischer et al. (1999) found variation of sensory characteristics within vineyard designations using principal component analysis (PCA), and that there was a stronger impact of individual wine estate and vintage than vineyard designation due to these variations. Lund et al. (2009) used PCA to differentiate chemical and sensory characteristics of Sauvignon blanc among regions and countries. Wines from Marlborough, New Zealand had more tropical, sweet, sweaty, passion fruit aromas as well as more methoxypyrazines and volatile thiols than those from France and South Africa. In California, Noble (1979) evaluated sensory differences of Chardonnay wines from various sites with different soil compositions. No consistent trends in wine from different soil textures were observed; however, soil, must, and wine compositions varied among locations.

The climate of the Niagara Peninsula is dominated by the moderating effect of its position between the Great Lakes (Lake Ontario & Lake Erie) and below the Niagara Escarpment. Soils are quite heterogeneous since they were derived mainly by direct organic and weathering breakdown of glacial, lacustrine, fluvial and alluvial sediments (Haynes 2000). Three appellations have been traditionally defined by mesoclimate differences influenced by the proximity to Lake Ontario and the Niagara Escarpment

(Wiebe and Anderson 1977) as well as soil and topography. These vineyard designations include 'Bench', 'Lake Plains' and 'Lakeshore' due to the vineyard proximity to the escarpment, lakeshore plain, and the shore of Lake Ontario, respectively. Studies have found sensory differences in Riesling (Douglas et al. 2001), Chardonnay (Schlosser et al. 2005) and Bordeaux-style (Kontkanen et al. 2005) wines originating from these appellations. Haynes (2000) first considered the creation of sub-appellations within the Niagara Peninsula based on climatic models being modified by geological differences in combination with anecdotal wine profiles based on winemaker notes. In 2005, the Vintners Quality Alliance of Ontario (VQAO) that regulates standards for Ontario wine, created sub-appellations within the Niagara Peninsula based on soil, climatic and topographical differences (Shaw 2004). However, the criteria used to create these sub-regions did not include any analytical or sensory analysis of fruit or wines. Assuming that wines from traditional sub-appellations across Europe have distinct chemical and sensory characteristics that distinguish them from one another, it is only logical to see if the grapes and wine from these various sub-appellations have unique qualities that can be measured. Therefore, this research study was conducted to validate these new sub-appellations in terms of chemical variables and sensory characteristics and to relate sensory profiles of the wines to the varying soil and vineyard features within the Niagara Peninsula and its sub-appellations.

Materials and Methods

Site selection. In April 2005, ten Riesling vineyard sites were selected throughout the Niagara Peninsula, Ontario, Canada. These sites were non-irrigated, commercial vineyards and the vineyard blocks had heterogeneous soil types. Each site was also representative of each VQAO sub-appellation. Details concerning soil and vineyard characteristics and vineyard management can be found in Tables 5.1a and 5.1b. In each vineyard block, a grid-style sampling pattern was established with a "sentinel vine" at each grid intersection point. These sentinel vines (72 to 80 per vineyard block) were flagged for identification to be used for data collection throughout the year. A global positioning system (Raven Industries, Sioux Falls, SD) was used in May 2005 to georeference each sentinel vine and to delineate the shape and size of each vineyard block.

Soil analysis. Once sites and vineyard blocks were chosen, detailed soil mapping was carried out on a site-by-site basis. Soil samples (ca. 200 g) were collected using a soil probe at depths of 0-60 cm at a subset of sentinel vines (every 4th vine in a serpentine pattern; ~ 20 vines/site) in June 2005. Soil analyses including pH, organic matter (OM) concentration, elemental concentration (P, K, Ca, Mg), cation exchange capacity (CEC), and base saturation (BS; as % Ca) were performed on each soil sample. Proportions of sand, silt, and clay were also determined. All soil analyses were carried out at Agri-Food Laboratories, Guelph, ON. Geospatial maps of each vineyard block were subsequently constructed from this information.

Soil water content and vine water status. At each vineyard, soil water content and leaf water potential were taken bi-weekly (every 10 to 14 days) from sentinel vines between the end of June and early September (beginning of fruit set to pre-harvest). Soil moisture was measured using a portable time domain reflectometer (TDR) (Spectrum Technologies, Plainfield, IL). Probe readings were taken in root zones of all sentinel vines at an approximate depth of 20 cm. On the same day, vine water status was determined on a subset of sentinel vines (≈18 vines) by midday leaf water potential (Ψ) using a Scholander-type pressure chamber (Soil Moisture, Santa Barbara, CA). Measurements were taken between 1100 and 1400 hours under full sun conditions. Water potential readings were taken from healthy, undamaged leaves that were sun-exposed. A recent fully expanded leaf was excised from the sentinel vine with a razor blade and immediately placed in a sealable plastic bag. The leaf was placed in the chamber and the pressure was increased slowly until air bubbles/sap exuded from the leaf petiole. At this point the pressure required to accomplish this was recorded.

Viticultural data collection. For each sentinel vine, data were collected annually at vine dormancy for weight of cane prunings as an estimate of vine vigour ("vine size"). Yield components (yield per vine; clusters per vine; cluster weight; berries per cluster; berry weight) were either measured directly or calculated from measured variables during harvest each season. Fruit was harvested as close to commercial harvest as possible and at a targeted sugar level of approximately 19-20 Brix. Fruit from each vine was harvested and weighed using an electronic scale (model SB32000; Mettler Toledo Canada, Mississauga, ON). Fruit was sorted based on vine water status and retained for winemaking. Clusters were counted from each sentinel vine and samples of 100 berries were taken for determination of berry weight and standard fruit composition indices (soluble solids; titratable acidity (TA); pH), samples of 250 berries were taken for monoterpene concentration analyses. All berry samples were stored in sealable plastic bags at -25 °C until analysis. Frozen berry samples were weighed using an electronic scale (model SB3200; Mettler Toledo Canada, Mississauga, ON)

Winemaking. Within each vineyard block, sentinel vines were sorted based upon water status and identified on GIS-generated maps. Vines from intermediate water status zones were used to represent the appropriate VQA sub-appellation for that particular vineyard. Winemaking practices were consistent for all treatments and replicates to minimize any enological effects.

The grapes were transported from the vineyard and immediately crushed and destemmed at the CCOVI winery using an electric crusher/destemmer (Criveller) and put into 20 L plastic buckets. 30 ppm of sulfur dioxide and 15 µL/L of Scottzyme Cinn-Free pectinase (Scott Laboratories, Pickering, ON) were added. The crushed grapes were given 2 hours of skin contact at 7 °C prior to pressing. The grapes were pressed to a maximum 200 kPA using a water bladder press. 250 mL must samples were taken from each pressing and frozen at -25°C for further analysis for soluble solids, TA, pH and monoterpenes. The pressed juice was cold settled at 7 °C for 24 hrs prior to being racked into 11-L glass carboys. 100 mg N/L was added using a diammonium phosphate (DAP) addition. The juice was brought to room temperature (20 °C), and inoculated with *Saccharomyces cerevisiae* strain W15 (Lallemand Inc.) at a dosage of 0.25 g/ L following the manufacturer's recommended rehydration procedure. After 12 hours, the carboys were transferred to a temperature controlled fermentation chamber set to 16 °C and remained there until the completion of fermentation (to dryness). The wines were then removed, racked into clean carboys and sulfited to 50 ppm and transferred to -2 °C to undergo cold stabilization and lees contact for ca. 2 months. Wines were then racked after warming to room temperature and 250 mL wine samples were taken and frozen at -

25 °C for further chemical analysis (TA, pH, monoterpenes and ethanol). The wines were analyzed for residual (reducing) sugar using the method described by Lane-Eynon (1923) and sucrose was added to the desired level of 15 g/L residual sugar. 150 mg/L of potassium sorbate and 30 ppm of sulfur dioxide were added just prior to filtering and bottling. Wines were filtered to 0.45 µm and bottled at 20 °C. Wines were stored at 15 °C and 70% relative humidity in a controlled cellar at CCOVI for 12 months prior to sensory analyses.

Berry, must, and wine composition. 100 g of frozen berries were retained for samples destined for monoterpene determination. For other analyses, the berry samples were thawed and heated to 80 °C in 100 mL beakers using a Fisher Isotemp 228 water bath (Fisher Scientific, Ottawa ON) to dissolve any precipitated tartaric acid. Samples were cooled to room temperature (20 °C) and then homogenized in a juicer (model 500; Omega Products, Harrisburg, PA) and then centrifuged at 4000 RPM for 10 minutes using an IEC Centra CL2 Centrifuge (International Equipment, Needham Heights, MA) to remove solids prior to analysis. Brix were measured using a temperature-compensated Abbé bench refractometer (American Optical Corp., Buffalo, NY, model 10450), while pH was measured using an Accumet pH/ion meter (Fisher Scientific, Ottawa, ON, model AR50). TA was measured on 5-mL clarified samples using a Man-Tech PC-Titrate autotitrator (Man-Tech Associates Inc., Guelph, ON, model PC-1300-475). Samples were titrated to a pH 8.2 endpoint with a 0.1 N NaOH solution. Results were expressed as tartaric acid equivalents (g/L).

Monoterpene analysis. *Berries and Must.* Monoterpene concentration in fruit, must, and wine was based on the method described by Dimitriadis and Williams (1984) as modified by Reynolds and Wardle (1989), and consisted of distillation of terpenes in free and bound forms, followed by colorimetric analysis using a spectrophotometer. Approximately 100 g of frozen berries or must samples were thawed at room temperature. For berry samples, partially frozen berries were homogenized in a Waring Pro commercial laboratory blender for 30 seconds prior to distillation. Sample pH was adjusted to between 6.6 and 6.7 through drop-wise additions of 20% NaOH. Distillation was performed using a 2-L steam generating flask, a distillation flask and a Friedrich condenser (Lurex, Vineland, NJ). A submersible heating coil connected to a variable transformer was used to generate steam. This enabled control of the temperature and thus the speed of the distillation. The condenser was cooled through the flow of cold water that circulated through a 5 mm copper coil submerged in an ice bath immediately before entering the condenser. The first fraction containing free volatile terpenes (FVT) was collected in a 25-mL volumetric flask held in an ice-water bath during the first 10-15 minutes. Precisely 10 mL of 50% phosphoric acid was added to the hot homogenate contained in the distillation flask to adjust to approximately a pH of 2.0. Within the next 15 minutes the potentially volatile terpene (PVT) fraction was collected in a 50-mL volumetric flask held in an ice-water bath. The sealed flasks containing the distillates were placed in a 4 C chamber until colorimetric analysis. The must and wine samples were treated in the same manner during the distillation process.

FVT analysis for wine. The PVT fractions of all samples required no additional procedure prior to the colorimetric analysis. However, compounds that could possibly interfere with the colorimetric analysis needed to be removed from the FVT wine fractions. Ethanol and other compounds have been found to interfere with colorimeteric analysis (Reynolds et al. 2007a). Sep-Pak C18 cartridges (Waters; Bedford, MA) were attached to Teflon tips in the top board of a vacuum chamber and a reservoir with a stopcock was attached above each cartridge. The columns were charged by running 5 mL of distilled water followed by successive 5-mL fractions of methanol and distilled water at < 34 KPa of vacuum pressure. With the stopcock closed, 25 mL of FVT distillate was added to the reservoir and diluted with 50 mL of distilled water. The stopcock was opened and the sample was passed through the column at < 34 KPa. The FVT adsorbed to the column were then washed into a 25-mL volumetric flask with 5 mL of methanol and made up to volume with distilled water. For colorimetric analysis, a separate set of standard linalool solutions were prepared in 20% methanol to account for the methanol contained in the FVT wine samples after following this procedure.

Colorimetric determination. A 100 mg/L linalool stock solution was prepared. Subsequent standard solutions of 0.5, 1, 2, 3, 5 and 10 mg/L linalool were prepared using the stock solution to create a standard curve. 20 mL glass test tubes were kept in an ice-water bath and duplicate 10 mL samples of standard solutions and distillates were added to the test tubes. 5.0 mL of 2% vanillin solution in concentrated sulfuric acid (w/v) was added to each. The tubes were capped, mixed and heated at 60 °C in a Fisher Isotemp 228 water bath (Fisher Scientific, Ottawa ON) for 20 minutes. Tubes were cooled at 25 °C for 5 minutes and the absorbance was read at 608 nm within 15 minutes using a Ultrospec 2100 Pro UV/Visible spectrophotometer (Biochrom Ltd., Cambridge, England). The FVT and PVT concentrations were expressed as mg/kg.

Ethanol. Ethanol was determined using gas chromatography-flame ionization detector (GC-FID) (Agilent 6890, CA, USA) equipped with a Carbowax (30m × 0.23mm × 0.25 µm*)* column. A sample of 0.5 µL wine was injected into the injection port heated to 250 °C. The carrier gas was helium (He) with a column head pressure of 137.9 kPA. The flow rate of He as carrier was 1.8 mL min^{-1}. The oven temperature was programmed to start at 60 °C, increased to 125 °C at 6°C min^{-1}, and then increased to 225 °C at 25 °C min^{-1} and held for 1 min. The detector temperature was 250 °C and 2% 1-butyl alcohol was used as an internal standard. A six-point calibration curve was used and these samples were diluted 1:10.

Sensory analysis. *Descriptive analysis.* The sensory panel ran from October 2007 until March 2008. Participants were members from the Cool Climate Oenology and Viticulture Institute (CCOVI). The assessors consisted of graduate students, undergraduate students, staff and faculty who were experienced with Riesling wines. Most of the judges had previously participated in descriptive analysis studies. In the first year the panel consisted of five males and six females between the ages of 23 and 65 years old (mean = 38). In the second year the panel consisted of seven males and three females between the ages of 23 and 54 years old, six of whom were on the previous year's panel. Training consisted of 24 hours conducted over 16 sessions in the first year and 18 hours in second year. In the first session, the panellists were screened for possible anosmias of typical wine aromas. Panellists were also assessed on odour and taste recognition and ranking ability thorough a series of identification and ranking exercises using model solutions. For the initial training sessions, judges generated descriptive terms using wines from the study. During the training period, aroma reference standards were given to define the aroma/flavour descriptors and were discussed and modified based on panel consensus. Standards for sweetness, sourness, bitterness, and astringency were also given during training. Panellists rated the intensities of each attribute for every wine and then, following discussion and panel consensus, the most appropriate descriptors to define and discriminate sensory differences in the wines were chosen. The seventeen aroma and flavour attributes that were selected can be found in Table 5.4a with the composition of the reference standard included. Subsequently, the four taste and tactile terms selected are listed in Table 5.4b with their reference standard compositions. These references were presented during all formal data collection sessions. No references were presented for flavour attributes. Sensory evaluations were conducted using Compusense Five® version 4.6 software (Guelph, ON, Canada) in individual booths at 18 °C in the sensory laboratory at CCOVI. Wines were served in a random order using a Williams Latin Square design (MacFie et al. 1989) and duplicated. Six wines were presented during each session as 30-mL samples contained in coded black glasses covered with plastic Petri dishes. There were forced 3-minute breaks between samples with a 30-minute break after the third sample. The judges were familiarized with the reference standards at the beginning of each session and the intensity of each aroma, flavour and mouthfeel attribute was scored on an unstructured 15-point intensity scale anchored with 'absent' and 'high'. Mineral water and filtered water were provided for rinsing between samples as well as unsalted crackers. All samples were expectorated following evaluation.

Data analysis. Analysis of variance (ANOVA) was performed with judges, wines, and replicates as fixed effects using SENPAQ v. 4.1 statistical packages (Qi Statistic Ltd.; Reading, UK). Least significant differences (LSD) between sample means were used. Principal components analysis (PCA) was performed for the means of all significant sensory attributes based on a covariance matrix using XLSTAT-pro 2008.5.1 (Addinsoft; Paris, France) with MX and PLS modules. Partial least squares (PLS) regression analyses were conducted to explain relationships between soil, vine and compositional data and to wine sensory attributes.

Results and Discussion

Chemical composition. ***Musts and wines:*** By analysis of variance (ANOVA) musts were significantly different ($p \leq 0.05$) among Niagara sub-appellations in terms of chemical composition including soluble solids, TA, pH, FVT, and PVT in the 2005 and 2006 vintages (Table 5.2). In both 2005 and 2006 wines were significantly different ($p \leq 0.05$) for TA, pH, FVT, PVT, and ethanol among sub-appellation wines (Table 5.3).

Sensory analysis. ***Analysis of variance.*** Results from analysis of variance (ANOVA) can be found in tables 5.5 and 5.6. Descriptive analysis revealed that wines from the different Niagara sub-appellations had distinctive sensory characteristics due to different intensity levels of aroma and flavour attributes. Through ANOVA, 12 aroma and flavour attributes were found to be significantly different ($p \leq 0.05$) in 2005 (15 at $p \leq 0.10$) and 13 aroma and flavour attributes were different ($p \leq 0.05$) in 2006 (14 at $p \leq 0.10$). Similar sensory attributes were different for both vintages including *baking spice*, *honey*, *mineral*, and *vegetal* aromas; *citrus*, *honey*, and *petrol* flavours; and *sweet*, *sour* and *astringent* taste/mouthfeel attributes. *Tropical fruit* and *apple/pear* characteristics were significantly different in the 2006 vintage only.

Multivariate analysis: Principal component analysis: *2005.* Principal component analysis (PCA) was used to evaluate differences in chemical composition and sensory characteristics of wines from the various sub-appellations. PCA is a multivariate statistical method used to extract the most important information by reducing the number of dimensions in the data set in order to interpret and visualize differences among groups of products. Therefore, PCA is a very useful way to show the relationship of the wines based on their chemical and sensory characteristics. Sensory attributes were used as the active variables whereas chemical attributes were supplementary variables in the PCA biplots. PCA explained 70.72% of the variation in the first two principal components with 45.77% on PC1 and 24.95% on PC2 (Fig. 5.2). The wines from the sub-appellations of Beamsville Bench, Twenty Mile Bench, and St. David's Bench were associated with higher intensities of *honey*, *baking spice*, and *apple/pear* aromas and *tropical fruit*, *honey*, *apple/pear* flavour, and *sweet* taste. These vineyard sites were separated from the others by PC2. Niagara and Lincoln Lakeshore sub-appellations as well as Short Hills Bench were found to be associated with higher intensities of *citrus*, *mineral/flint*, *vegetal* aromas and *petrol*, *vegetal*, and *mineral/flint* Flavours, whereas wines from the Vinemount Ridge sub-appellation were associated with higher intensities of *citrus* flavour, *sour* taste, and *astringency*. The two Lake Plain Appellations (Four Mile Creek, Creek shores) were not well described in two principal components.

Grape must from the Niagara Lakeshore, Lincoln Lakeshore, Niagara River and Creek Shores sub-appellations had higher TA and generally lower soluble solids with the exception of the Creek Shores vineyard. The highest soluble solids were found in musts from many of the 'Bench' vineyards including the St. David's Bench, Beamsville Bench, and Short Hills Bench as well as the Creek Shores sub-appellations. Lincoln Lakeshore and Twenty Mile Bench appellations had the highest FVT concentrations. The highest PVT concentrations were found in the Twenty Mile Bench and Niagara River vineyards.

2006. PCA explained 66.67% of the variation in the first two components (46.21% PC1; 20.46% PC2) with an additional 12.64% in PC3. Niagara Lakeshore, Niagara River and Lincoln Lakeshore appellations had several sensory characteristics in common. They were found to be associated with higher intensities of *mineral/flint* and *vegetal* aroma as well as *petrol* and *vegetal* flavours and *sour* taste. Short Hills Bench also had more intense *mineral/flint* aroma than the other vineyard wines. Four Mile Creek, Twenty Mile Bench and Beamsville Bench sub-appellations were found to be associated with higher intensities of *tropical fruit* and *baking spice* aromas and *honey* flavour as well as *sweet* taste. St. David's Bench and Four Mile Creek were associated with higher intensities of *honey* aroma and *apple/pear* flavour. The Lincoln Lakeshore vineyard was associated with the highest FVT, whereas the Niagara River was associated with the highest PVT as well as TA along with the Niagara Lakeshore Vineyard. The highest must Brix was associated with the Beamsville Bench and Creek Shores sub-appellation sites. As in 2005, the both Lakeshore sites had higher TA. Interestingly, the vineyards of Niagara-on-the-lake and those west of the city of St. Catharines, were separated essentially by PC1 in 2006. Also the more northern vineyards closest to Lake Ontario and those on the Escarpment were separated by PC2. In essence, the wines in the two dimensional space of the PCA plot can be pieced together to form a map of the Niagara Peninsula which is a very interesting finding. This demonstrates the usefulness of multivariate statistics when interpreting a large data set. This information would not be recognizable using univariate statistics alone (i.e., Tables 5.5 and 5.6).

The appellations closest to large bodies of water (Lake Ontario and Niagara River) had lower sugar and higher acid levels compared to the vineyards on the escarpment which are further away with no 'lake effect". St. David's Bench, Beamsville Bench and Creek shores had the highest soluble solids in both vintages. Some of these differences can be related to climate. The Lakeshore appellations have lower growing degree days (GDD) than most of the other sub-appellations (Shaw 2004) including those on the Niagara escarpment due to the mitigating effects of the cool bodies of water. During the growing season, cooler winds off the lake delay the warming in these vineyard locations. This results in a later budburst of up to a week and slows down the maturation process (Shaw 2005). The sites above the escarpment (i.e., Vinemount Ridge) also are slower to mature and have a later budburst than the inland vineyards below or on the escarpment. The cooler growing climates of these appellations and the lighter and more fertile soils produce larger vines that may have contributed to lower soluble solids and higher TA as discussed by Jackson and Lombard (1993).

Overall, FVT and PVT concentrations were site specific and there were not many consistent relationships that could be related to general groupings of sub-appellations using PCA. Ewart (1987) found that terpenes were higher in cooler vineyard locations. This supports our findings that some of the cooler sites had higher terpene concentrations. However, Reynolds et al. (1996) found some differences in monoterpene concentration and sensory properties in Gewürztraminer wines from different sites that were attributable to climatic differences. Wines from the warmest site had the highest monoterpene concentrations as well as the most floral, fruity and cedar aromas and flavours. This bodes well for our findings in some of the Bench vineyards which had high FVT and PVT concentrations. The warmer sites such as St. David's Bench, Beamsville Bench, Twenty Mile Bench, and Creek shores had more *baking spice*, *honey*, and *tropical fruit aromas* and *honey* and *tropical fruit* flavours. In both 2005 and 2006 the Lincoln and Niagara Lakeshore sites had more *citrus*, *vegetal* and *mineral/flint* character. The Short Hills Bench site was generally grouped with these two sites but was higher in *mineral/flint* and *petrol* intensities. The vineyards located equidistant between Lake Ontario and the Niagara Escarpment in the flatter and warm sites (Creek shores and

Four Mile Creek) weren't as well described in the PCAs for both vintages but had more *apple/pear* flavours.

For both vintages, many of the vineyards could be grouped to their regional classification. In general, wines were separated based on a north/south transect moving from Lake Ontario to the Niagara Escarpment. Wines from vineyards located close to the Lake Ontario were grouped together. Similarly, vineyards that were located on the Niagara Escarpment were also grouped together through PCA. This is an interesting finding considering the data was temporally stable for both vintages which varied in both temperature and precipitation events. These can probably be explained due to the fact that they were grown in similar mesoclimates and soil types with many viticulture trends (water status, vine size, yields etc.) being similar as further explained in the next section. Wines from vineyards designated in the Lake Plain region were not well described in PCA probably due to the fact that they had many common attributes with both the Lakeshore and Bench appellations.

Partial least squares. PLS is a widely used multivariate technique to investigate relationships between response variables (chemical, viticultural) and explanatory variables (sensory). PLS is a regression model that allows for the identification of underlying factors, which are a combination of the explanatory variables (Garthwaite 1994). It has fewer restrictions than other multivariate analyses such as PCA or discriminant analysis. Thus, it is a very powerful technique to relate soil and vineyard variables to sensory characteristics of the wines from the various sub-appellations. PLS was used to help interpret and explain the different chemical and sensory characteristics found from vineyards throughout the Niagara Peninsula. Through PLS we found that many vineyard characteristics could be related to sensory attributes of the Riesling wines (Figures 5.4 and 5.5).

2005. PLS explained 83.5% of the variability in Y and 64.5% in X from the 2005 data set (Figure 5.4). Vine water status, soil moisture, berry weight, vine size and yield were correlated with many of the aroma/flavour attributes. The remaining aroma and flavour attributes were more correlated with soil characteristics such as texture. An interesting finding was that wines made from vines with higher water status and soil moisture as well as larger berry weight, vine size and yields were associated with lower intensities of many of the desirable fruit-driven aroma/flavour attributes. These vineyard sites had more intense *petrol, citrus, mineral/flint, peach* aromas and flavours. The two Lakeshore appellations (Niagara and Lincoln) and Short Hills Bench were associated with these features and sensory attributes in 2005. Conversely vineyards with lower vine water status, smaller vines and berries were associated with more intense *baking spice*, *honey* aromas and *apple/pear* and *honey* flavours. Three vineyards located on the Escarpment (Beamsville Bench, Twenty Mile Bench and St. David's bench) as well as the Creek shores vineyard were associated with these characteristics. They also had higher levels of PVT. Berry FVT and PVT were correlated with more citrus and tropical fruit characteristics, respectively. Sefton et al. (1994) found that fruity and tropical aromas were related to monoterpenes. Furthermore, tropical/fruity style of Sauvignon blanc in South Africa was characteristic of warmer sites (Marais et al. 1999). The impact of soil and yields was found to be associated with the remaining sensory attributes. Vineyard sites with more sand content and higher yields had more *citrus* and *mineral* flavours and more *sour* and *astringent.* Conversely vineyard sites with more clay content had more *tropical fruit* and *honey* flavours and *sweet* taste.

2006. Similar findings were observed from PLS for the 2006 vintage of which 80.6% of the variability was accounted for in X and 48.5% in Y (Figure 5.5). Vineyards with more soil moisture, higher vine water status and larger vines had more intense *mineral/flint* aromas, *citrus* flavour and more *sour* and *astringent.* These vineyard sites also had lower Brix and lower intensities of *honey* and *baking spice* aromas as well as *honey* and *apple/pear* flavours and *sweet* taste. As in the 2005 vintage, Niagara Lakeshore and Lincoln Lakeshore were more associated with these characteristics. Many of the remaining sensory characteristics were correlated with soil parameters. Vineyards with larger yields and more sand content had more *vegetal* aroma and *petrol* and *vegetal* flavours and higher TA. Vineyards with higher vine water status, more water content in the soil, more vigorous vines and higher yields in the cooler and wetter 2006 vintage led to more vegetative wines and wines that were less fruit driven. These findings are similar to those of Penavayre (1991) who found that more vigorous vines on sandier soils with unlimited water supply throughout the growing season resulted in wines that had less intense varietal character. Clay soil content was found to be inversely correlated with vine size and vegetal flavour. This is consistent with other studies including Carey et al. (2008) who found that soils with high clay content were associated with reduced vegetative growth.

Through the use of multivariate statistics we were able to examine the relationships between 'water and growth' or production variables and wine elements. Some of the sensory characteristics can probably be directly related to general maturity and others appear to be quite independent suggesting specific effects on some particular elements. Higher Brix, which generally indicates a level of advanced maturity, was found to be associated with *honey* aroma, *tropical fruit* flavours, and *sweet* taste. Conversely, samples with lower Brix were associated with more *vegetal* character and *astringency*. Carbonneau (2007) distinguishes a general trend of berry maturation measured by berry sugar loading and corresponding to the general evolution of more fruity characteristics. In this study, some attributes related to general level of maturity but many other attributes were associated with lower vine water status, smaller vines and smaller berries. There were also some sensory attributes that were found to be associated more with soil variables such as *mineral/flint* aroma and *tropical fruit* and *mineral/flint* flavours. Therefore, multivariate analyses (i.e., principal component analysis and partial least squares) were useful to demonstrate that features associated with the sensory profiles of these wines were related to differences in soil type, vine water status, vine size, and yields but also possibly to a general level of maturity. Wines from sites with soils containing higher water content and vines with higher water status and larger vine size were associated with more *vegetal*, *petrol*, *citrus* and *mineral/flint* character and less *honey*, *apple/pear* and *baking spice*. Other studies have indicated that limiting water availability increased the aromatic potential of grapes and wines and that excess water leads to more vegetative characteristics (Chapman et al. 2005, Peyrot des Gachons et al. 2005). Large vine size due to high vegetative growth causes shading within the fruiting zone of the canopy and often results in more vegetal characteristics of wines due higher concentrations of methoxypyrazines and decreased photodecomposition as shown in Riesling (Hashizume and Samuta 1999). 'Bench' vineyards with heavier clay soils, higher calcium and magnesium, higher soil pH, lower yields, and lower number of clusters were more associated with *tropical*, *honey* and *baking spice* attributes while being less associated with *citrus*, *vegetal*, *petrol* as well as being less *sour* and *astringent* attributes which were found in mainly Lakeshore vineyards with sandier soils, larger vines and higher yields. This is similar to findings of Asselin et al. (1983) who found that calcareous soil and chalk content resulted in wines of different flavour intensity than other soils.

It is difficult to define the best soil in terms of texture, soil depth or mineral content, because high quality wines are grown on a diversity of soils worldwide. Soil type has been shown to indirectly impact varietal character and intensity through its association with varying vine vigour levels. For example, soils light in texture with constant water supply can lead to vigorous shaded canopies that can delay sugar accumulation and decrease fruit quality, as shown in this study. In California, Noble (1979) evaluated Chardonnay wines from various sites with different soil compositions and found that must and wine compositions varied among sites. In other studies (Chapman et al. 2005, Noble and Elliott-Fisk 1990), more fruit driven wines were found from soils with less water holding capacity and lower water status, which was also the case in our study. In Germany, different soil types were moved to the same vineyard site to study the impact of soil type on wine composition and sensory quality of Silvaner wines without any climatic interaction (Wahl 1988, Wahl and Patzwald 1997) and the authors found that soil type did not have any impact on wine flavour although yields varied between soils. This is consistent with what was found in the present study where sandier soils had larger yields than soils with higher clay content. This also is in agreement with the results of Reynolds et al. (2007b) who found that soils higher in sand content had larger yield components (clusters/vine, yields). Furthermore, we found that PVT was correlated with soil pH, cation exchange capacity and clay content which are also consistent with the study by Reynolds et al. (2007b).

The studies of Seguin (1970, 1975) in Bordeaux and its famous chateaux found that soil chemical composition did not have a specific influence on wine quality; instead it was the soil's physical properties to regulate water supply to the vine that did. Soil texture and rooting depth were noted as the most important soil factors, and the best soils were those that were free draining which avoided water logging in the rooting zone but did limit water availability later in the season. This was further supported by Asselin et al. (1983) where the authors were able to demonstrate some relationships between soil and wine sensory profiles using soil types from different sites within the Loire Valley. Many of effects of the soil on vine behaviour are mediated through varying water content levels and their effects on vine water status (Klepper 1968, Seguin 1983, 1986, van Leeuwen and Seguin 1994). This appeared to be the case in our study as many of the differences found to be associated with the sensory profiles of wines from the various sub-appellations were related to differences in vine water status, vine size, soil texture and yields. Therefore, it can be suggested that Niagara's sub-appellations can be generally described using these criteria because many of these variables are temporally stable from year to year. The vineyards studied within the Niagara Peninsula indicate that they are quite stable in terms of viticulture characteristics and sensory profiles regardless of vintage. This finding is consistent with studies previously performed in the Niagara Peninsula with Cabernet franc (Hakimi Rezaei and Reynolds 2010). Furthermore, wines from the Niagara Peninsula can generally be grouped into three distinct regional designations ('Lakeshore', 'Lake Plain' and 'Bench') which is in agreement with studies performed previously with examining sensory characterization of Riesling (Douglas et al. 2001). This is particularly important in a variety such as Riesling with minimal winemaking influence according to its traditional vinification process. Our study agrees with much of the anecdotal evidence from winemakers, wine estates and wine writers that Riesling produced from different vineyards within the Niagara Peninsula have different sensory expressions but consistent from vintage to vintage. However, it is not known to what extent this would be true if inconsistent winemaking regimes were used. Obviously mesoclimate differences cannot be ignored, however through multivariate statistics there are many variables that were found to be important criteria impacting the chemical composition and sensory profiles of the wines. Within site terroir related studies of these vineyard sites have also shown that these same variables such as vine water status, vine size and soil texture are important factors of the terroir effect.

Conclusions

There were differences found in both the chemical composition and sensory characteristics of wines produced from different sub-appellations of the Niagara Peninsula. Through PCA, specific sensory and chemical attributes were shown to be associated with clusters of different sub-appellations. Multivariate techniques such as PCA and PLS were useful to determine that many of the differences associated with the sensory profiles of the wines were related to soil texture, vine water status, vine size and yields. Finally, while each sub-appellation did have its unique sensory profile, wines were found to be generally grouped in terms of their regional designation ('Lakeshore', 'Bench' and 'Plain') within the Niagara Peninsula. Similar sensory profiles were found from these appellations, which indicate that wines classified from their place of origin in the Niagara Peninsula should exhibit certain varietal characters despite different growing seasons. These wine typicities are important for a small, young, quality driven wine region in Canada. It allows for easier marketing and expansion domestically and internationally, as the wines are distinct and recognizable. Further research can be done to explore other important cultivars as well as individual wine estates within the sub-appellations to further understand terroir within the Niagara Peninsula and its sub-appellations.

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List of Tables

Table 5.1a. General features of Niagara Peninsula Riesling vineyards used for elucidation of terroir studies, 2005-2006

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Table 5.2. Comparison of mean chemical attributes among Riesling musts from sub-appellations in the Niagara Peninsula, Ontario. 2005-2006.

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Table 5.1a. General features of Niagara Peninsula Riesling vineyards used for elucidation of terroir studies, 2005- 2006.

Variable	**Sites**				
	Chateau des Charmes	**Reif Estate Winery**	**Lambert Farms**	**Glenlake Vineyards (Lakelodge)**	**Henry of Pelham**
Location	St Davids	Virgil	Virgil	NOTL	West St Catharines
VQA Sub-appellation	St David's Bench	Niagara River	Four Mile Creek	Niagara Lakeshore	Short Hills Bench
Area of vineyard (ha)	1.68 ha	1.71 ha	0.81 ha	3.39 ha	1.57 ha
Number of sentinel vines	75	74	75	74	80
Soil series	TLD7; B>B	VLD 6; B=B	CGU19: B=B	TVK 15; c >B	BVY 8; c=B
Parent materials	Mainly lacustrine silty clay	Mainly reddish-hued lacustrine fine sandy loam & very fine sandy loam 40-100cm reddish-hued loamy textures over clay loam till	Mainly reddish-hued clay loam till	40-100cm reddish-hued loamy textures over clay loam till	Mainly lacustrine silty clay
Soil drainage	Imperfect to poor	Imperfect	Imperfect to poor	Imperfect	Imperfect to poor
Clone	R239	R239	R239	R239	R49 Colmar
Rootstock	SO4	SO4	SO4	SO4	C3309
Vine age at initiation of trial (yr planted)	22 yrs (1983)	22 yrs (1983)	5 yrs (2000)	9 yrs (1996)	7 yrs (1998)
Vine spacing (m; row X vine)	2.5 X 0.9	3.0 X 1.3	2.74 X 1.22	2.5 X 1.5	2.5 X 1.2
Number of rows; vines per row	47 rows; 7520 vines 160 vines/row	14 rows; 4104 vines 12 @ 298 v/r, 2@ 264 v/r	15 rows; 2400 vines 160 vines/row	58 rows; 10,940 vines 42 @ 198v/r, 16 @ 164v/r	27 rows; 5000 vines 21 @ 188v/r; 6 @ 165 v/r
Training system	Double Guyot	4-arm Kniffin	Scott Henry	Scott Henry	Pendelbogen
Floor management	Clean cultivation	Alternate Sod	Alternate Sod	Clean cultivation	Alternate Sod

Table 5.1b. General features of Niagara Peninsula Riesling vineyards used for elucidation of terroir studies, 2005-2006.

Variable	**Sites**				
	Paragon Estate Vineyards	**Flat Rock Cellars (Nadja's Vineyard)**	**Cave Spring (Home Block)**	**Myers Vineyard**	**Vailmont Vineyards (Vieni Estate)**
Location	West St Catharines	Jordan	Vineland	Vineland	Beamsville
VQA Sub-appellation	Creek Shore	Twenty Mile Bench	Beamsville Bench	Lincoln Lakeshore	Vinemount Ridge
Area of vineyard (ha)	1.55 ha	0.92 ha	2.22 ha	1.26 ha	1.26 ha
Number of sentinel vines	74	72	75	72	71
Soil series	MAT 1;B	CGU11;C>B	CGU14; c>B	JDD 1; B	JDD 1;B
Parent materials	40-100 cm lacustrine silty clay over clay till loam	No.1: Mainly clay loam till No.2: 40-100 cm lacustrine silty clay over clay loam till	No.1: 15-40 cm loamy textures over clay loam No.2: Mainly clay loam till	Mainly clay loam till	Mainly clay loam till
Soil drainage	Poor	Imperfect to Poor	Imperfect to Poor	Poor	Imperfect to Poor
Clone	R21B Weis	R21B Weis	R21B Weis	R21B Weis	R21B Weis
Rootstock	SO4	SO4	SO4	SO4	SO4
Vine age at initiation of trial (yr planted)	7 yrs (1998)	5 years (2000)	27 yrs (1978)	18 yrs (1987)	7 yrs (1998)
Vine spacing (m; row X vine)	2.3 X 1.2	2.3 X 1.2	2.5 X 1.5	3.0 X 1.5	2.5 X 1.2
Number of rows; vines per row	43 rows; 5800 vines 145 vines/row	46 rows; vines/row varies	45 rows; 6120 136 vines/row	17 rows; 2890 vines 170 vines/row	29 rows; 3828 vines 132 vines/row
Training system	Double Guyot	Double Guyot	Pendelbogen	Pendelbogen	Halbbogen
Floor management	Alternate Sod	Alternate Sod	Alternate Sod	Alternate Sod	Alternate Sod

Table 5.2. Comparison of mean chemical attributes among Riesling musts from sub-appellations in the Niagara Peninsula, Ontario. 2005-2006.

	Niagara Lakeshore	**Beamsville Bench**	**St. David's Bench**	**Twenty Mile Bench**	**Short Hills Bench**	**Four Mile Creek**	**Lincoln Lakeshore**	**Creek Shores**	**Niagara River**	**Vinemount Ridge**	**Pr > F**
2005											
Harvest Date	9/16/05	9/27/05	9/22/05	10/01/05	9/29/05	---[a]	9/19/05	9/18/05	9/21/05	9/30/05	
Brix	17.41f	19.17d	21.00a	19.11d	20.46b		19.93c	20.59ab	18.1e	18.16e	<0.001
TA (g/L)	14.45a	9.59de	8.98e	10.31bc	9.49de		10.34bc	10.89b	10.94b	9.87cd	<0.001
pH	3.01bc	2.91d	3.04bc	2.90d	2.80e		3.13a	2.91d	2.93cd	3.06b	<0.001
FVT (mg/L)	0.486c	0.270d	0.735b	0.549c	0.275d		1.10a	0.536c	0.899ab	0.455c	<0.001
PVT (mg/L)	1.47e	1.71de	1.97cd	3.89a	1.97cd		2.13c	2.19c	3.41b	2.12c	<0.001
2006											
Harvest Date	10/06/06	10/16/06	10/16/06	10/05/06	10/19/06	10/21/06	10/21/06	10/15/06	10/10/06	––[a]	
Brix	17.90cd	20.43a	19.57b	17.49d	19.67b	20.33a	17.90cd	19.30b	18.33c		<0.001
TA (g/L)	10.30a	10.53a	8.39c	10.9a	9.47b	9.48b	9.79b	9.71b	10.53a		<0.001
pH	3.15c	3.09d	3.17c	3.08d	3.22b	3.28a	3.04e	3.00f	3.14c		<0.001
FVT (mg/L)	1.17c	0.370f	0.577ef	2.12a	0.670ef	0.95cd	1.65b	0.860cd	0.991cd		<0.001
PVT (mg/L)	3.06bc	2.52de	3.22b	3.99a	2.76cd	2.39de	2.35de	2.10e	3.09bc		<0.001

Means within rows with different letters are significantly different. Duncan's multiple range test.

[a] No wines produced due to lack of fruit due to winter injury in 2005 and severe powdery mildew infection in 2006.

Table 5.3. Comparison of mean chemical attributes among Riesling wines produced from sub-appellations in the Niagara Peninsula, Ontario. 2005-2006.

	Niagara Lakeshore	**Beamsville Bench**	**St. David's Bench**	**Twenty Mile Bench**	**Short Hills Bench**	**Four Mile Creek**	**Lincoln Lakeshore**	**Creek Shores**	**Niagara River**	**Vinemount Ridge**	**Pr > F**
2005											
Harvest Date	9/16/05	9/27/05	9/22/05	10/01/05	9/29/05	----a	9/19/05	9/18/05	9/21/05	9/30/05	
TA (g/L)	12.44a	9.02e	8.92e	9.52d	9.62d		9.56d	11.08b	10.64bc	9.91cd	<0.001
pH	2.89e	3.00cd	3.05bc	3.08b	3.01cd		3.14a	2.97d	2.98de	3.01cd	<0.001
FVT (mg/L)	0.626abc	0.715ab	0.81ab	0.715ab	0.419c		0.509bc	0.636abc	1.034a	0.749ab	<0.001
PVT (mg/L)	0.736d	0.856cd	1.10bc	2.19a	1.05bc		1.19b	1.16bc	0.94bcd	1.11bc	<0.001
Ethanol (%v/v)	9.13d	10.2c	11.0a	10.1c	10.8ab		10.7b	10.9ab	9.9cd	9.78d	<0.001
2006											
Harvest Date	10/06/06	10/16/06	10/16/06	10/05/06	10/19/06	10/21/06	10/21/06	10/15/06	10/10/06	---a	
TA (g/L)	11.52a	11.28a	9.18e	11.48a	9.48de	9.75d	10.16c	10.62b	10.87b		<0.001
pH	2.98d	3.08c	3.14b	3.00d	3.21a	3.14b	3.13b	3.06c	3.08c		<0.001
FVT (mg/L)	0.369bc	0.445bc	0.467bc	0.429bc	0.561b	0.821a	0.284c	0.422bc	0.510b		<0.001
PVT (mg/L)	2.56bc	1.99d	3.69a	3.35a	2.42bc	1.41e	2.31cd	2.20cd	2.78b		<0.001
Ethanol (%v/v)	9.7c	10.9a	10.5b	9.3d	10.9a	10.4b	9.7c	10.4b	9.7c		<0.001

Means within rows with different letters are significantly different. Duncan's multiple range test.

[a] No wines produced due to lack of fruit due to winter injury in 2005 and severe powdery mildew infection in 2006

Table 5.4a. Aroma/flavour attributes used in sensory evaluation of Riesling wines, Niagara Peninsula, Ontario, 2005 to 2006.

Attribute	Reference (base wine was a neutral Riesling wine from CCOVI)
Apple/pear	5 g fresh Bartlett pear and 5 g Granny Smith and Red Delicious apples in 50 mL base wine
Baking spices (aroma only)	5 mL of stock solution*
Citrus	Fresh lime juice (20 mL), lemon juice (10 mL), and grapefruit juice (5 mL) in 100 mL base wine
Honey	*President's Choice* alfalfa honey (10 g in 50 mL base wine)
Mineral/flint	Ground slate (5 g) in 20 mL base wine
Peach	*Yoga* peach nectar (25 mL)in 100 mL base wine
Petrol	1 drop WD-40™ in 900 mL base wine
Tropical Fruit	*McCain* tropical fruit juice (10 mL), *Rubicon* passionfruit juice (5 mL), and *Rubicon* guava juice (5 mL) in 300 mL base wine
Vegetal	10 mL of vegetal stock solution** and canned bean brine (5 mL) in 100 mL base wine

*Cinnamon (0.1 g) and nutmeg (0.1 g) in 50 mL base wine
**1.1 g wheat grass blended in 100 mL water

Table 5.4b. Taste and mouthfeel attributes used in sensory evaluation of Riesling wines, Niagara Peninsula, Ontario, 2005 to 2006.

Attribute	Reference (in 1000 mL water)
Sweet	10 g sucrose
Sour	1.5 g citric acid
Bitter	0.01 g quinine
Astringent	0.05 g aluminum sulphate

Table 5.5. ANOVA with degrees of freedom, F-values and error mean square for sensory attributes of 2005 Riesling wines from different appellations within the Niagara Peninsula, ON. (n= 11 judges; 2 replicates)

	Treatment	Treatment x Judge	Error Mean Square
Degrees of Freedom	8	80	99
Aroma Attributes			
Apple/pear	0.53	1.12	5.3
Baking spice	2.40**	0.85	7.1
Citrus	1.73*	0.90	6.2
Honey	2.29**	0.77	10
Mineral/flint	2.06**	0.47	6.8
Peach	1.21	0.71	1.2
Petrol	0.75	1.42**	5.3
Tropical fruit	0.49	1.26	4.4
Vegetal	2.08**	1.00	3.4
Flavour Attributes			
Apple/Pear	1.84*	0.76	5.0
Citrus	2.18**	0.87	4.3
Honey	2.78***	0.70	7.6
Mineral/flint	2.76***	0.60	4.4
Peach	0.55	1.43**	0.5
Petrol	2.45**	1.04	2.6
Tropical fruit	2.01*	0.85	3.5
Vegetal	1.76*	0.85	1.3
Taste/Mouthfeel			
Sweet	3.41***	0.81	3.3
Sour	4.16****	1.72***	4.1
Bitter	0.41	1.89**	0.4
Astringent	2.11**	1.26	1.2

*,**,***, ****: Significant P values at p<0.10, 0.05, 0.01, 0.001, respectively.

Table 5.6. ANOVA with degrees of freedom, F-values and error mean square for sensory attributes of 2006 Riesling wines from different appellations within the Niagara Peninsula, ON. (n= 10 judges; 2 replicates)

	Treatment	Treatment x Judge	Error Mean Square
Degrees of Freedom	8	72	90
Aroma Attributes			
Apple/pear	0.38	1.97**	3.1
Baking spice	2.78***	1.07	4.6
Citrus	1.19	1.12	4.8
Honey	2.27**	2.27****	2.9
Mineral/flint	2.03**	1.18	6.1
Peach	0.63	0.83	1.5
Petrol	1.39	1.81***	2.7
Tropical fruit	2.46**	2.07***	3.0
Vegetal	2.27**	2.96****	1.6
Flavour Attributes			
Apple/pear	2.18**	1.25	3.2
Citrus	2.19**	1.65**	2.5
Honey	3.40***	1.41*	2.5
Mineral/flint	0.53	1.59**	1.9
Peach	1.02	0.41	1.8
Petrol	2.19**	2.06****	1.9
Tropical fruit	3.90****	1.32	3.2
Vegetal	2.03**	2.84****	1.2
Taste/Mouthfeel			
Sweet	4.86****	1.35*	3.1
Sour	5.73****	0.67	2.0
Bitter	1.38	1.82***	0.4
Astringent	1.85*	1.18	0.5

*,**,***, ****: Significant P values at $p<0.10$, 0.05, 0.01, 0.001, respectively.

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Figure 5.5. Partial least squares of sensory and vineyard data for Riesling wines from sub-appellations within the Niagara Peninsula, 2006 vintage. (variance explained in X 80.6%; in Y 48.5%).

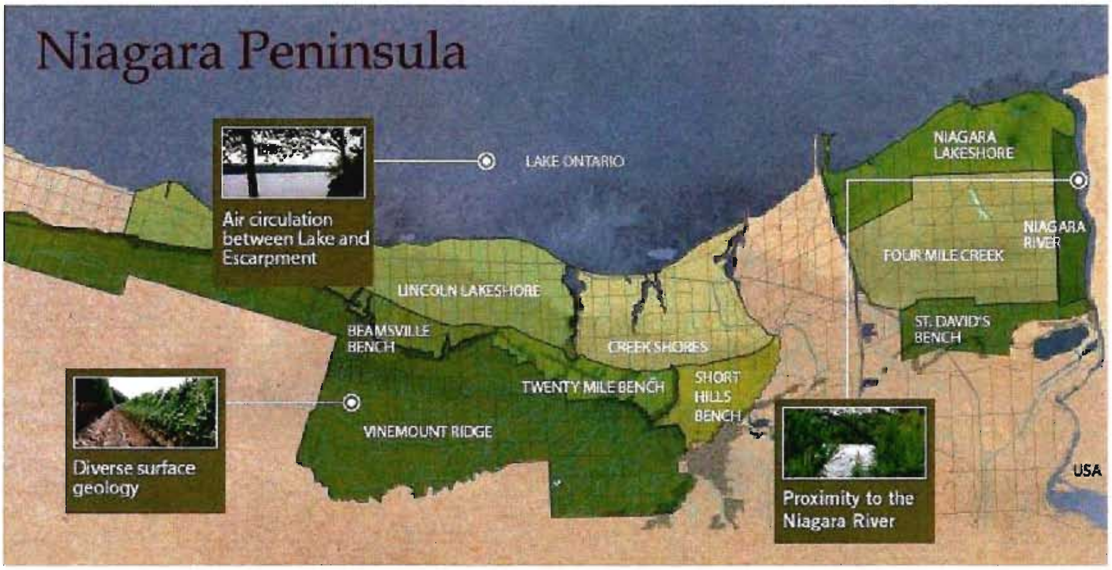

Figure 5.1. Map of the sub-appellations of the Niagara Peninsula (Courtesy of VQA Ontario)

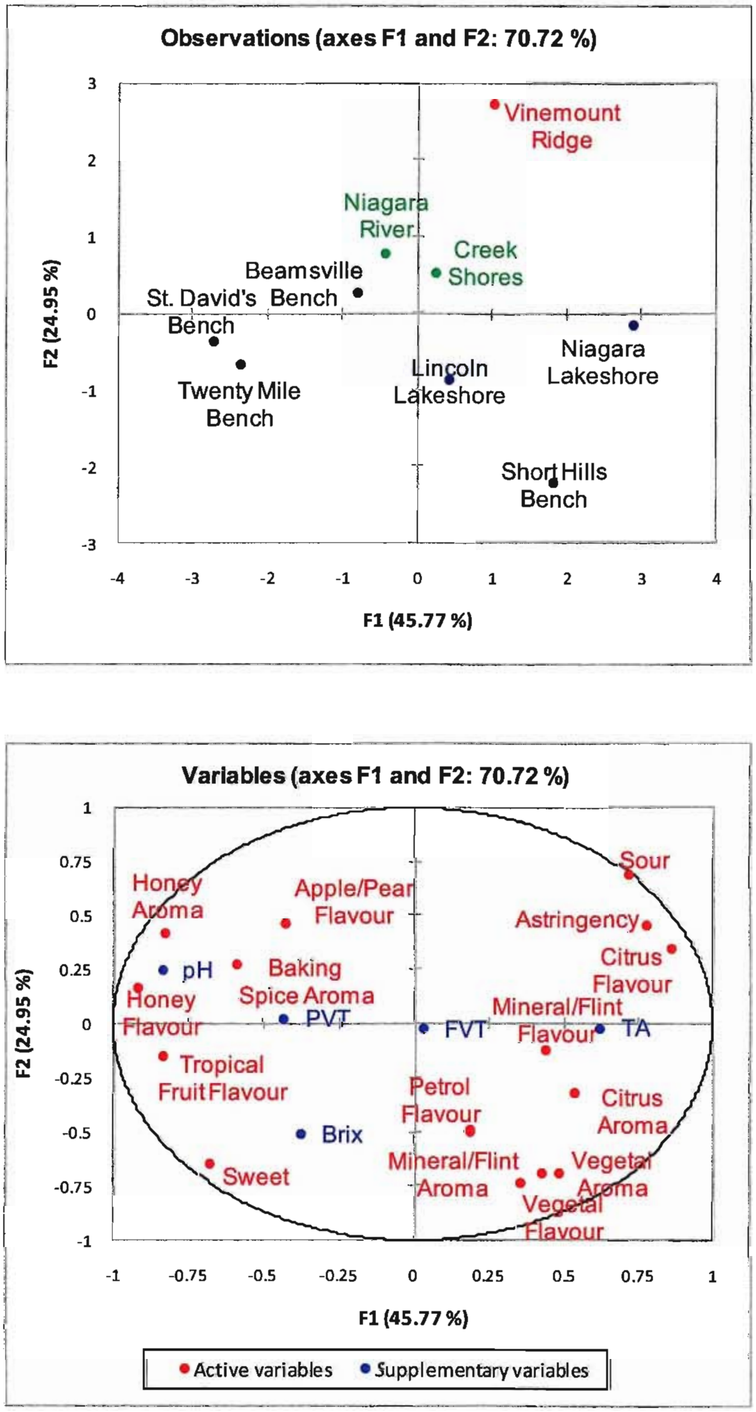

Figure 5.2. Principal component analysis of sensory and chemical data of Riesling wines from the sub-appellations within the Niagara Peninsula (PC1 vs. PC2), 2005 vintage. *Blue indicate 'Lakeshore' vineyards; green indicate 'Lake Plains' sites; black indicate 'Bench' sites.*

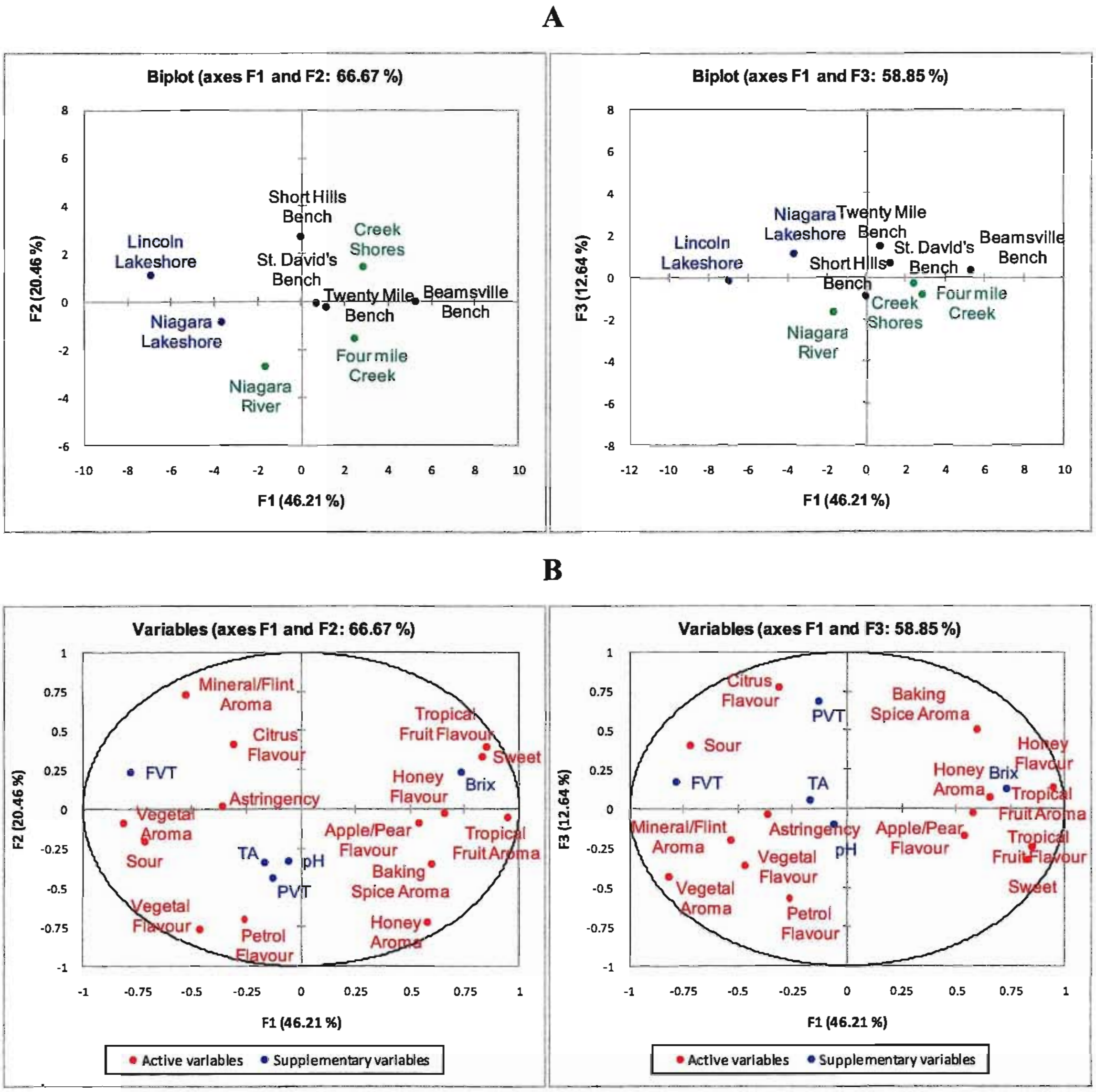

Figure 5.3(**A**). Principal component analysis of sensory and chemical data of Riesling wines from sub-appellations within the Niagara Peninsula (PC1 vs. PC2). (**B**) Principal component analysis of sensory and chemical data of Riesling wines from sub-appellations within the Niagara Peninsula (PC1 vs. PC3), 2006 vintage. *Blue indicate 'Lakeshore' vineyards; green indicate 'Lake Plains' sites; black indicate 'Bench' sites.*

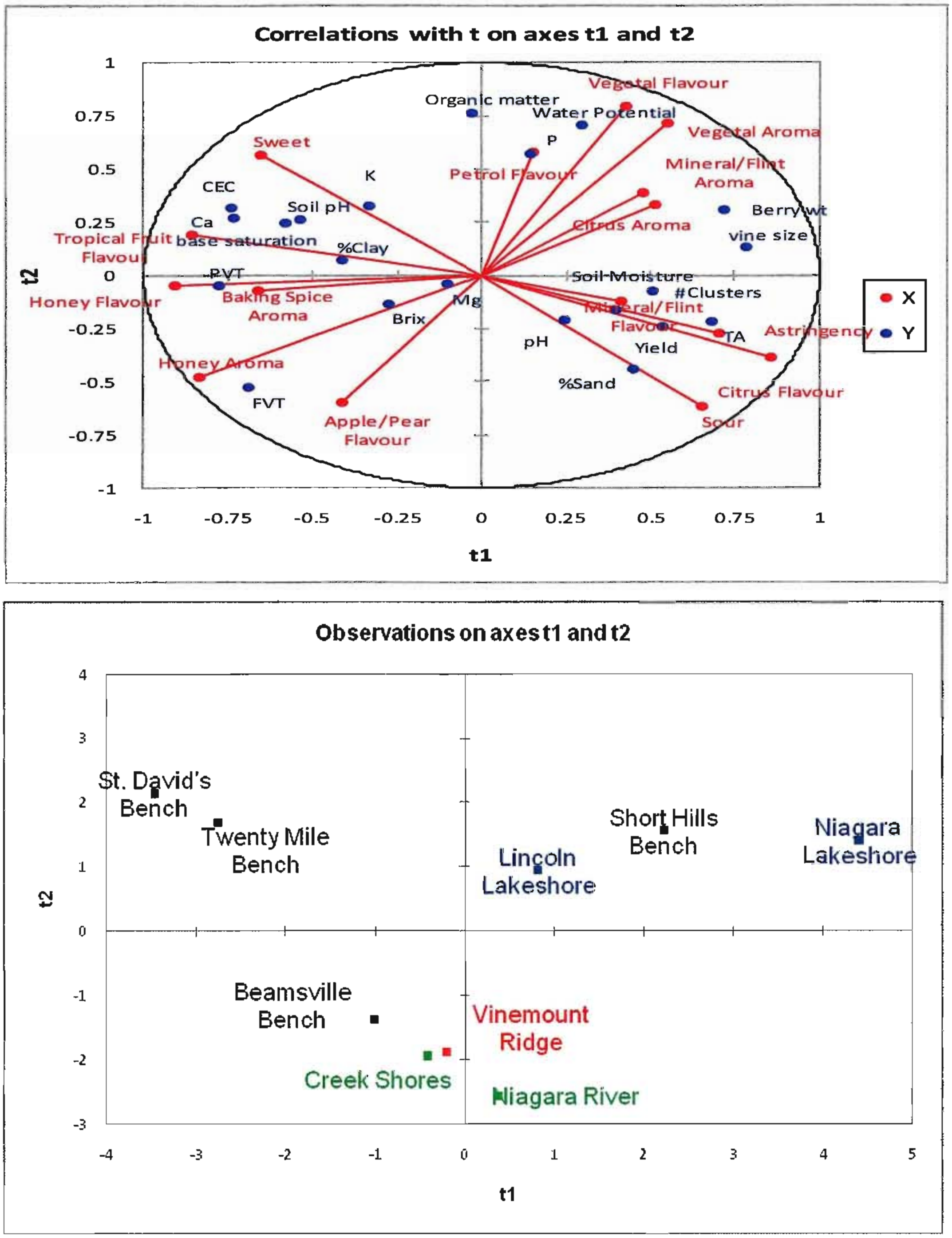

Figure 5.4. Partial least squares of sensory and viticulture data for Riesling wines from sub-appellations within the Niagara Peninsula, 2005 vintage. (variance explained in X 64.5%; in Y 89.5%). *Blue indicate 'Lakeshore' vineyards; green indicate 'Lake Plains' sites; black indicate 'Bench' sites.*

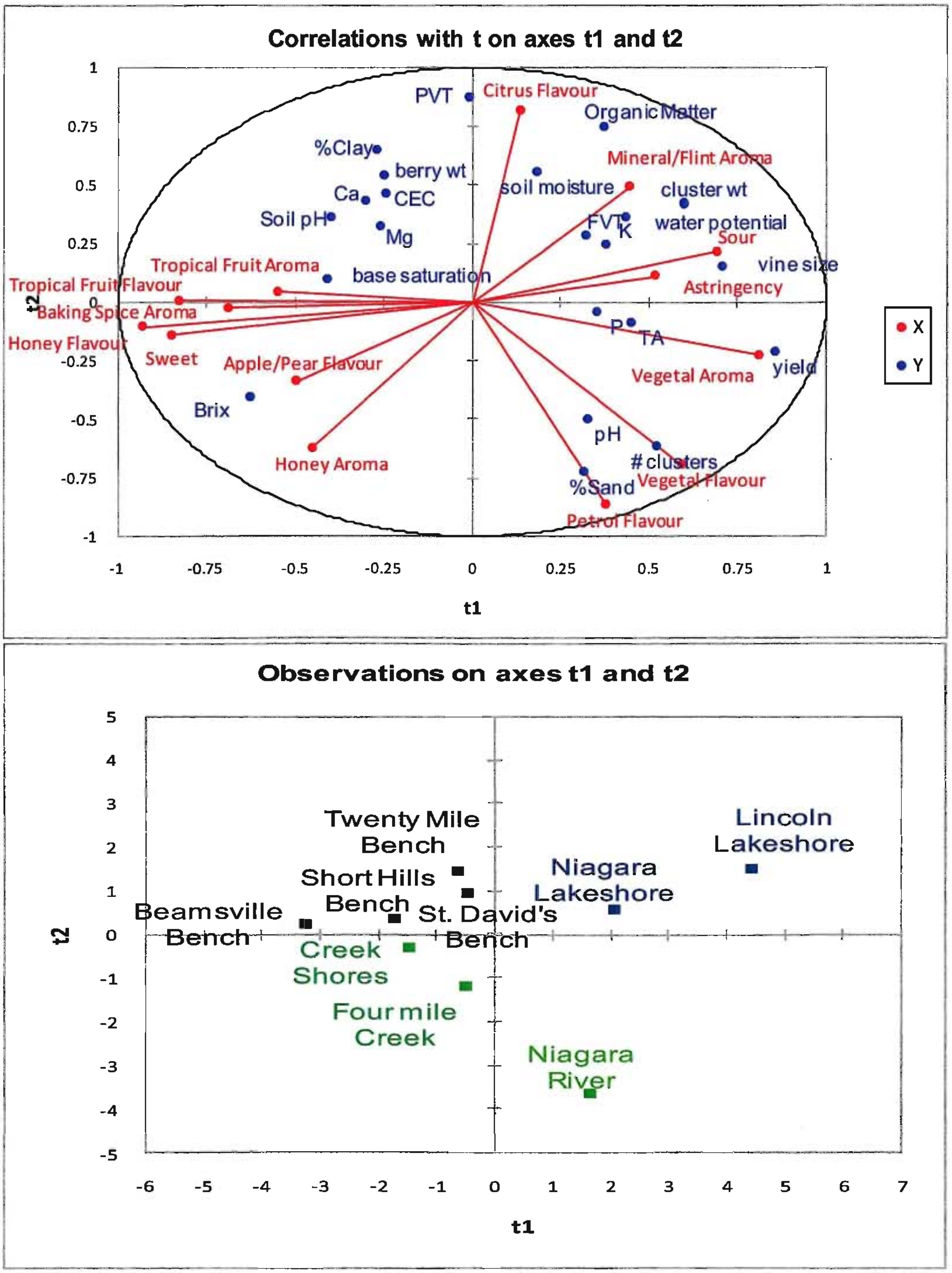

Figure 5.5. Partial least squares of sensory and vineyard data for Riesling wines from sub-appellations within the Niagara Peninsula, 2006 vintage. (variance explained in X 80.6%; in Y 48.5%). *Blue indicate 'Lakeshore' vineyard; green indicate 'Lake Plains' sites; black indicate 'Bench' sites.*

Chapter 6: Sensory analysis of Riesling wines from various water status zones.

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Abstract

We sought to elucidate potential determinants of terroir by choosing vine water status as a major factor of the terroir effect. One of our hypotheses was that consistent water status zones could be identified within vineyard sites and that differences in wine sensory attributes could be related to vine water status. To test this hypothesis, 10 commercial Riesling vineyards representative of each sub-appellation created by the Vintners Quality Alliance of Ontario were selected within the Niagara Peninsula. These vineyards were delineated using global positioning systems and 75 to 80 sentinel vines were geo-referenced within a sampling grid for data collection. During the 2005 and 2006 growing seasons, vine water status measurements [midday leaf water potential [(Ψ)] were collected bi-weekly from a subset of these sentinel vines. Vines were categorized into "low" and "high" water status regions within each vineyard block through the use of these geospatial maps and replicate wines were made from each region. Wines of similar water status were shown to have similar sensory properties through sorting tasks and multidimensional scaling in both the 2005 and 2006 vintages despite different growing conditions experienced during each season. Descriptive analysis using a trained panel further indicated that water status had an effect on wine sensory profiles. Similar attributes were significantly different for wines from different water status zones ($p<0.05$). Through multivariate analyses, specific sensory attributes were shown to be associated with wines of different water status. Several common attributes were found to differ in treatments within multiple vineyard sites despite different growing seasons. Wines produced from vines with leaf $\Psi > -10$ bars had the highest *apple/pear*, *tropical*, *vegetal* aromas and *citrus* flavour whereas those with leaf $\Psi < -13$ bars were highest in *honey, petrol* and *tropical fruit* flavours. Vines under mild water deficit had the highest *honey*, *mineral*, and *petrol* aromas and lowest *vegetal* aromas. These results indicate that water status has a profound impact on the sensory characteristics of Riesling wines and that there may be a quality threshold for optimum water status.

Key words: Vine water status, multivariate statistics, sensory analysis, terroir, precision viticulture

Introduction

Terroir related studies have been performed on many single variables such as soil (Seguin 1975) and climate (Winkler et al. 1962). Climate has been shown to be a very important criterion of the terroir effect as it has been shown to impact wine character in numerous studies (Jackson and Lombard 1993, Jones and Davis 2000, Tonietto and Carbonneau 2004). Soil, however, has traditionally been associated as the main constituent of terroir. While studies have explored many characteristics of soils, including chemical constituents, several studies have indicated that the soil's physical properties to regulate water supply to the vine is the most critical role that soil has on the terroir effect. In Bordeaux, Seguin (1970) found that soil texture and rooting depth were the most important soil factors and that the best soils were those that were free draining, which avoided water logging in the rooting zone but also limited water availability later in the season. Many of the effects of the soil on vine behaviour are due to varying water content levels throughout the growing season and their effects on vine water status. Studies have suggested that vine water status is the means by which 'terroir' affects a wine's quality and style (Choné et al. 2001, Koundouras et al., 1999, Willwerth et al. 2010). Vine water supply has been identified as a major factor in the terroir effect due to its impact on early budburst potential and potential vine vigour (Morlat et al. 2001). Grapes cultivated under mild water stress can improve berry composition (Matthews and

Anderson 1988, Smart 1985) and mild water deficits have been shown to be a major factor in the terroir effect (Seguin 1983, van Leeuwen et al. 2009).

Water potential has been widely accepted as a fundamental measure of plant water status in grapevines. Water potential represents a simple and reliable method for evaluating the physiological condition of a plant, since cell growth, photosynthesis and crop productivity are strongly influenced by water potential and its components (Repellin et al. 1997). The influence of water supply on grapevine development and physiology has been widely addressed in the literature (Grimes and Williams 1990, Hardie and Considine 1976, Matthews and Anderson 1988). Grapes are commonly grown in areas with low water supply and are subjected to some form of water stress during the summer months. Generally, the water obtained by grapevines depends on the water table and rainfall as well as irrigation in some regions. The availability of water to grapevines is one of the most important factors of terroir, and in determining wine quality (Deloire et al. 2005, Seguin, 1986, van Leeuwen and Seguin 1994). Water deficits in vines have been shown to reduce shoot growth (Kliewer et al. 1983, Reynolds and Naylor 1994) and canopy density (Smart et al. 1990). Fruit quality may be directly affected by vine water status via changes in turgor or indirectly via the effects of canopy sink competition (Smart et al. 1990) and light penetration in the cluster zone (Smart 1985). A vine suffering from some water stress may have less shoot growth and therefore have better leaf and fruit exposure to sunlight than a vine growing with abundant water supply that tends to have over vigorous canopies and poor fruit exposure.

Most of the research related to water relations has involved studies with red wine cultivars. This is probably due to the fact that drought stress regularly occurs in the regions of hotter and drier climates where red grapes thrive and are widely planted. In many of these cases, mild water deficits have been shown to be beneficial to red grape and wine quality, mainly due to reduced berry size and increased anthocyanin and tannin content (Kennedy et al. 2002, Roby et al. 2004). Studies have suggested the impact of vine water status on vegetative performance (Smart 1974), fruit composition (Reynolds et al. 2007), and aroma compounds in white wine cultivars (Peyrot des Gachons et al. 2005; Reynolds et al. 2006). In terms of white grape quality, studies are more limited but as in the case of red grapes mild deficits also seem to improve grape quality (Peyrot des

Gachons et al. 2005, van Leeuwen et al. 2009). Most studies investigating white wine quality have focused on aroma compounds or their precursors. Peyrot des Gachons et al. (2005) found that vine water status had an impact on volatile thiol precursors in Sauvignon blanc grapes and that mild water deficits resulted in higher grape quality whereas severe water deficit limited aroma potential.

While quality has been analysed through measuring chemical variables in fruit, there has not been a focus on wine produced from fruit harvested from vines of different water status. To this end, very few studies have examined sensory differences in wines made solely of fruit from vines of different water status. In terms of white wine production, the authors could not find any studies performed to date that used descriptive analysis. Through difference testing, Matthews et al. (1990) found that red wines of different water status had different sensory characteristics. Significant differences were found in terms of appearance, aroma, taste and flavour among different irrigation treatments. Through descriptive analysis, Chapman et al. (2005) found that Cabernet Sauvignon wines produced from vines of higher water status had more vegetal and less fruity aromas and flavours than vines with lower water status.

The intent of our research was to study the impact of vine water status within vineyard sites to minimize any climatic effects. Vine water status measurements taken throughout the growing season were used in combination with GIS software to designate specific vines into different water status categories. Wines were then made with fruit harvested from these wines, and chemical and sensory analyses were then conducted in order to determine differences of these resultant wines.

Materials and Methods

Site selection. Ten Riesling vineyard sites were selected throughout the Niagara Peninsula, Ontario, Canada. These sites were non-irrigated, commercial vineyards and the vineyard blocks had heterogeneous soil textures. Each site was also representative of each VQA sub-appellation. In each vineyard block, a grid-style sampling pattern was established with a "sentinel vine" at each grid intersection point. These sentinel vines (72 to 80 per vineyard block) were flagged for identification to be used for data collection throughout the year. A global positioning system (Raven Industries, Sioux Falls, SD) was used to georeference each sentinel vine and to delineate the shape and size of each vineyard block.

Geographic information systems (GIS). The delineated vineyards and data layers were incorporated into a MapInfo Professional 8.0 GIS database with Vertical Mapper 3.1 (Northwood GeoScience, Ottawa, ON). Inverse distance weighting (IDW) was used to construct grid files. This interpolation method was chosen due to uneven nature of vineyards. In this method, closer known points have more influence on the estimation of unknown points that are further away. Spatial maps were generated for leaf water potential to depict the spatial distribution within each vineyard and used to categorize vines based on vine water status.

Soil water content and vine water status. At each vineyard, soil water content and leaf water potential were taken bi-weekly (every 10 to 14 days) from sentinel vines between the end of June and early September (beginning of fruit set to pre-harvest). Soil moisture was measured using a portable time domain reflectometer (TDR) (Spectrum Technologies, Plainfield, IL). Probe readings were taken in root zones of all sentinel vines at an approximate depth of 20 cm. On the same day, vine water status was determined on a subset of sentinel vines (every 4th vine in a serpentine pattern;≈18 vines) by midday leaf water potential (Ψ_{leaf}) using a Scholander-type pressure chamber (Soil Moisture, Santa Barbara, CA). Measurements were taken between 1100 and 1400 hours under full sun conditions. Water potential readings were taken from healthy, undamaged leaves that were sun-exposed. A recent fully expanded leaf was excised from the sentinel vine with a razor blade and immediately placed in a sealable plastic bag. The leaf was placed in the chamber and the pressure was increased slowly until air bubbles/sap exuded from the leaf petiole. At this point the pressure required to accomplish this was recorded.

Viticultural data collection. For each sentinel vine, data were collected annually at vine dormancy for weight of cane prunings as an estimate of vine vigour ("vine size"). Yield components (yield per vine; clusters per vine; cluster weight; berries per cluster; berry weight) were either measured directly or calculated from measured variables during harvest each season. Fruit was sorted based on treatments and retained for winemaking. Clusters were counted from each sentinel vine and samples of 100 berries were taken for determination of berry weight and standard fruit composition indices (soluble solids; titratable acidity; pH), whereas a sample of 250 berries were taken for monoterpene concentration analyses.

Must composition. Each 100-berry and 250-berry sample was weighed to determine the mean berry weight. The frozen berry samples were then heated in 250-mL beakers to an internal temperature of 80°C in a Fisher Scientific Isotemp 228 water bath (Fisher Scientific, Ottawa, ON) to dissolve any precipitated tartaric acid. The heated berry samples were then cooled, juiced in a laboratory juicer (Omega Products Inc., Harrisburg, PA, model 500), and an approximately 35-mL portion was clarified using a IEC Centra CL2 Centrifuge (International Equipment Co., Needham Heights, MA) to remove large particles that might cause problems with the autotitrator sampling mechanism. Soluble solids (expressed as °Brix) were measured on the unclarified berry juice samples using a temperature-compensated Abbé bench refractometer (American Optical Corp., Buffalo, NY, model 10450). The pH was measured using an Accumet pH/ion meter Model AR50 (Fisher Scientific, Ottawa, ON). Titratable acidity (TA) was measured on 5-mL clarified samples using a Man-Tech PC-Titrate autotitrator (Man-Tech Associates Inc., Guelph, ON, model PC-1300-475). Samples were titrated to a pH 8.2 endpoint with a 0.1 N NaOH solution. Results were expressed as tartaric acid equivalents (g/L). Monoterpenes were analysed for the 250-berry samples using the method developed by Dimitriadis & Williams (1984) as modified by Reynolds & Wardle (1989). The free volatile terpene (FVT) and potentially-volatile terpene (PVT) concentrations were expressed as mg/kg.

Ethanol. Ethanol was determined using gas chromatography-flame ionization detector (GC-FID) (Agilent 6890, CA, USA) equipped with a Carbowax *(*30m × 0.23mm × 0.25 μm*)* column. A sample of 0.5 μl wine was injected into the injection port heated to 250 °C. The carrier gas was helium (He) with a column head pressure of 137.9 kPA. The flow rate of He as carrier was 1.8 mL min^{-1}. The oven temperature was programmed to start at 60 °C, increased to 125 °C at 6°C min^{-1}, and then increased to 225 °C at 25 °C min^{-1} and held for 1 min. The detector temperature was 250 °C and 2% 1-butyl alcohol was used as an internal standard. A six-point calibration curve was used and these samples were diluted 1:10.

Winemaking. Within each vineyard block, sentinel vines were sorted based upon water status and identified on GIS-generated maps. Two water status categories were established as "high" and "low" and wines were made with the fruit from vines with the lowest and highest leaf water potential. There were three replicates of both categories (two water status categories treatments x three replicates). Vines from intermediate ("medium") water status zones were placed into a separate treatment to represent the appropriate VQA sub-appellation for that particular vineyard and not included in this study. Winemaking practices were consistent for all treatments and replicates to minimize any oenological effects.

The grapes from each treatment replicate were transported from the vineyard and immediately crushed and destemmed at the CCOVI winery using an electric crusher/destemmer (Criveller) and put into 20 L plastic buckets. Sulfur dioxide (30 ppm) and Scottzyme Cinn-Free pectinase (Scott Laboratories; Pickering, ON) at a dose of 15 µL/L were added. The crushed grapes were given 2 hours of skin contact at 7 °C prior to pressing. The grapes were pressed to a maximum 200 kPA using a water bladder press. Must samples (≈250 mL) were taken from each pressing and frozen at -25°C for further analysis for soluble solids, TA, pH and monoterpenes. The pressed juice was cold settled at 7 °C for 24 hrs prior to being racked into 11-L glass carboys. 100 mg N/L was added using a diammonium phosphate (DAP) addition. The juice was brought to room temperature (20 °C), and inoculated with *Saccharomyces cerevisiae* strain W15 (Lallemand Inc.) at a dosage of 0.25 g/ L following the manufacturer's recommended rehydration procedure. After 12 hours, the carboys were transferred to a temperature controlled fermentation chamber set to 16 °C and remained there until the completion of fermentation (to dryness). The wines were then removed, racked into clean carboys and sulfited to 50 ppm and transferred to -2 °C to undergo cold stabilization and lees contact for ≈ 2 months. Wines were then racked after warming to room temperature and 250-mL wine samples were taken and frozen at -25 °C for further chemical analysis (TA, pH, monoterpenes and ethanol). The wines were analyzed for residual (reducing) sugar using the method described by Lane-Eynon (1923) and sucrose was added to the desired level of 15 g/L residual sugar. Potassium sorbate (150 mg/L) and 30 ppm of sulfur dioxide were added just prior to filtering and bottling. Wines were filtered to 0.45 µm and bottled at 20 °C. Wines were stored in at 15 °C and 70% relative humidity in a controlled cellar at CCOVI for 12 months prior to sensory analyses.

Sensory analysis. *Sorting tasks:* A group of untrained participants consisting of 16 wine professionals from the Niagara wine industry were selected on the basis of having extensive experience with Riesling wines. Each person sorted the wines into groups based on retro-nasal perceptions. Evaluations were conducted in a controlled environment. Sorting was performed on a per vineyard basis where panellists received the entire set of wines for each vineyard. The presentation of samples was presented according to a Latin Square. Each participant was asked to sort wines into groups based on similar taste characteristics. No criterion was provided to perform this task and the panellists were free to make as many groups of wines as they wanted but could only group a wine once (i.e., a wine could not appear in more than one group). After performing their sorting task, they were asked to provide descriptors on the basis of their decision to designate the wines into their respective grouping(s).

Data from the sorting tasks were put into a distance matrix by the frequency that the wines were grouped together. For each assessor, a value of 1 indicated that the wines were grouped together and conversely a value of 0 meant the wines were not grouped together. For each vineyard, these matrices were then converted into similarity/dissimilarity matrices and were analyzed with multi-dimensional scaling (MDS) through XLSTAT-pro v. 2008.5.1 (Addinsoft; Paris, France). MDS was conducted for each task using Euclidean distance and was depicted in 3-dimensional space using XLSTAT-3D plot. In these maps, the proximity between the wines reflects their similarity.

Descriptive analysis. The sensory panel ran from October 2007 until March 2008. Participants were members of the Cool Climate Oenology and Viticulture Institute (CCOVI). The assessors consisted of graduate students, undergraduate students, staff and faculty who were experienced with Riesling wines and sensory methodology. Most of the judges had previously participated in descriptive analysis studies. In the first year the panel consisted of five males and six females between the ages of 23 and 65 years old (mean = 38). In the second year the panel consisted of seven males and three females between the ages of 23 and 54 years old, six of whom were on the previous year's panel. Training consisted of 24 hours conducted over 16 sessions in the first year and 18 hours in the second year. In the first session, the panellists were screened for possible anosmias of typical wine aromas. Panellists were also assessed on odour and taste recognition and ranking ability thorough a series of identification and ranking exercises using model solutions. For the initial training sessions, judges generated descriptive terms describing differences perceived between the wines from the study. During the training period, aroma reference standards were given to define the aroma/flavour descriptors and were discussed and modified based on panel consensus. Standards for sweetness, sourness, bitterness, and astringency were also given during training. Panellists rated the intensities of each attribute for every wine and then following discussion and panel consensus the most appropriate descriptors to define and discriminate sensory differences in the wines were chosen. The 17 aroma and flavour attributes that were selected can be found in Table 6.1a with the composition of the reference standard included. Subsequently, the four taste and tactile terms selected are listed in Table 6.1b with their reference standard compositions. These references were presented during all formal data collection sessions. No references were presented for flavour attributes. Sensory evaluations were conducted using Compusense Five ® version 4.6 software (Guelph, ON, Canada) in individual booths at 18 °C in the sensory laboratory at CCOVI. Wines were served in a random order using a Williams Latin Square design (MacFie et al., 1989) and duplicated. Six wines were presented during each session as 30 mL samples contained in coded black glasses covered with plastic Petri dishes. There were forced 3-minute breaks between samples with a 30-minute break after the third sample. The judges were familiarized with the reference standards at the beginning of each session and the intensity of each aroma, flavour and mouthfeel attribute was scored on an unstructured 15-point intensity scale anchored with 'absent' and 'high'. Mineral water and filtered water were provided for rinsing between samples as well as unsalted crackers. All samples were expectorated following evaluation.

Data analysis. Analysis of variance (ANOVA) was performed with judges, wines, and replicates as fixed effects using SENPAQ v. 4.1 statistical packages (Qi Statistic Ltd.; Reading, UK). Least significant differences (LSD) between sample means were used. Principal components analysis (PCA) was performed for the means of all significant sensory attributes based on a covariance matrix using XLSTAT-pro 2008.5.1 (Addinsoft; Paris, France) with MX and PLS modules.

Results and Discussion

General comments. The 2005 and 2006 growing seasons were ideal for studying the impact of vine water status. Climate data for the two growing seasons are shown in Figure 6.1. The 2005 vintage was a hot and dry growing season with abundant sunshine allowing for an earlier harvest. There were many days throughout June, July and August which exceeded 30 °C. From the beginning of May until the middle of August there were few rain events over 10 mm of precipitation. Autumn rainfall events were quite sporadic however, Riesling harvests occurred prior to many of the heavier rains caused by Hurricane Katrina. The 2006 growing season was cooler and wetter than the previous vintage. In general, the growing season was warm but there were more rainfall events particularly during the harvest period. There were however, periods lacking rain. From the beginning of June until the beginning of August there was an extensive period of drought with only one rainfall event over 15 mm. June and July was characterized by many days between 25-30 °C.

Through the use of GPS and GIS technologies, vine water status data collected from each vintage were depicted spatially (Figure 6.2). Consistent water status zones could be delineated and spatial patterns of vine water status were found to be temporally stable within all vineyards in the study despite different weather conditions during each growing season. In every vineyard studied, distinct regions were delineated that could be categorized as "high" and "low" water status as shown in Figure 6.2. This is in agreement with the findings of Acevedo-Opazo et al. (2008) who found that it was possible to assess spatial variability of vine water status within vineyards, even those small in size (<1 ha). In many cases, particularly in the hot and dry 2005 vintage, the "low" water status regions consisted of vines suffering moderate to high water stress (Figure 6.2). In general, there were more sites with higher within-site variability in terms of water status in 2005.

Sensory analysis. ***Sorting tasks.*** The use of sorting tasks is a simple but very reliable method to collect similarity data and has been used in numerous studies involving wine (Ballester et al., 2005; Parr et al., 2007). One of its main advantages is that sorting tasks are less tedious and time consuming than other methods so information can be obtained about sensory differences among products in an efficient manner (Abdi et al., 2007). Sorting tasks are particularly suitable when there are a large number of samples as was the case in this study. Most importantly results obtained are comparable with those obtained from other sensory descriptive methods such as free profiling (Tang and Heymann, 2007).

Sorting tasks performed on wines from the 2005 and 2006 vintages indicated that wines from similar water status vines were shown to have similar sensory properties through sorting tasks and multidimensional scaling. Three dimensions were used as opposed to two dimensional space to reduce stress values to acceptable levels under 0.1. Then, 3-D plots were created to ease interpretation rather than using biplots which wouldn't have captured the necessary space of the data set (Figures 6.3 and 6.4; Supplemental Figures 6.1a to 6.1e). For many of the vineyards, the wines treatments were visibly separated into two groups based on vine water status (Figure 6.3 and 6.4). In some cases one of the treatment replicates was separate from the other treatments such as in Figure 6.4. These findings are explainable by the fact that there weren't large enough differences in water status between treatments. For example, the third replicate of one treatment in some cases was similar to the third replicate of the other treatment just due to less variability within the vineyard. The separation of "low" and "high" water status wines was greater in the warmer and drier 2005 vintage than the cooler, wetter 2006 vintage. The longer period of drought in 2005 resulted in a greater range of leaf ψ values within many of the vineyard blocks as opposed to the 2006 growing season where wetter conditions resulted in less variability within sites but still some interesting findings nonetheless.

Descriptive analysis. ***Analysis of variance.*** Descriptive analysis using a trained panel further indicated that water status had an effect on wine sensory profiles and also described these differences in terms of aroma and flavour attributes. Results from analysis of variance (ANOVA) are found in Tables 6.2 and 6.3. Descriptive analysis revealed that wines of different water status had some distinctive sensory profiles due to differences in the levels of the intensity of aromas and flavours.

2005. Results from ANOVA can be found in Table 6.2. Within-site sensory differences of wines ranged from four aroma and flavour attributes to nine attributes with a median of seven. The most common aroma attributes to differ were *honey*, *tropical fruit* and *mineral/flint* aromas followed by *petrol*, *tropical fruit* and *baking spice*. *Honey*, *apple/pear*, *citrus*, and *petrol* flavours were the most common flavour attribute differences followed by *tropical fruit*. *Sour* and *sweet* tastes were different in seven and four vineyards, respectively. *Peach* aroma and *bitter* taste were non-factors in 2005 whereas *apple/pear* aroma, *citrus* aroma, *mineral/flint* flavour, *peach* flavour and *astringency* were different in one vineyard site only.

2006. Results from ANOVA are found in Table 6.3. Differences of sensory attributes within vineyards ranged from two to eight aroma and flavour attributes with a median of four. The most common aroma attribute difference within vineyards was *vegetal* aroma followed by *apple/pear*, *baking spice*, *mineral/flint* and *petrol* aromas. In terms of flavour attributes, *tropical fruit* and *vegetal* flavours were the most common differences within vineyards followed by *apple/pear*, *honey*, and *peach* flavours. *Sweet* taste was different within six vineyards while *bitter* and *sour* tastes were different in two vineyards. *Citrus*, *honey*, *peach* and *tropical* aromas were different within one vineyard only. *Petrol* flavour was a non-factor whereas *citrus*, *mineral/flint* flavours and *astringency* were site specific and only differed within one site.

Most of the sensory descriptors were found to be appropriate for this study. In terms of aroma attributes, c*itrus* and *peach* aromas were found to be site specific and not very important descriptors to discriminate Riesling wines of different water status. *Mineral/flint* flavours and *astringency* were also found to not be of much importance in terms of their discriminatory characteristics of the wines. White wines are not normally described as being astringent, however, in cooler climates Riesling wines can have quite high acidity (i.e., some wines in the study had TA > 13g/L and pH < 2.9). Acids have been shown to elicit tactile sensations such as astringency (Thomas et al., 1995); therefore it was a valid descriptor but was not very important in this study.

Principal component analysis. PCA was used to help interpret the results of the significant sensory attributes within each vineyard site. Chemical variables of the must were used as supplementary variables to determine their relationship although most did not differ substantially between vine water status treatments (data not shown). Examples of some of the PCA biplots are shown in Figures 6.5 through to 6.7 (others can be seen under Supplemental Figures 6.2a to e). In both vintages wines of similar water status were clustered together with similar sensory characteristics. Comparing results from the sorting tasks and descriptive analysis lead to some interesting conclusions. In this study, similar findings were obtained with descriptive and sorting tasks which is consistent with other research experiments (Preston et al., 2008).

2005. PCA performed using significant sensory attributes of water status treatments within Myers vineyard explained 71.32% of the variance (46.34% PC1; 24.98% PC2) in the 2005 data set (Figure 6.5). Wines of high water status had higher intensity ratings for *apple/pear* and *vegetal* aromas and *apple/pear* and *sour* flavour whereas wines of low water status had higher in *honey* aroma and *petrol*, *honey* and *peach* flavour. High water status replicate 3 was associated with soluble solids and PVT. Low water status replicate 1 was most associated with TA and low water status replicate 2 with FVT and pH. The association with terpenes may relate to some of the more fruit driven aromas of the wines. The PCA for the Chateau des Charmes vineyard (Figure 6.6) accounted for 83.16 % of the variance in the first two PCs (61.82% PC1; 21.34% PC2). Low water status replicates 1 and 3 were associated with *petrol* and *mineral/flint* aroma whereas replicate 2 was associated with higher intensity of *tropical fruit* flavour and *sweet* taste. High water status replicates 1 and 3 were associated with higher intensity ratings for *apple/pear* flavour whereas replicate 2 had higher intensity of *vegetal* and *mineral/flint* flavours and *sour* taste. Low water status replicate 3 was associated most with soluble solids, FVT, and pH. High water status replicates 1 and 3 were related to PVT whereas low water status replicate 2 was mostly associated with TA.

2006. The PCA biplot accounted for 72.71% (48.98% PC1; 23.73% PC2) of the variation of the 2006 data set (Figure 6.5). Wines of low water status had higher mean intensity ratings for *mineral/flint* aroma and *petrol*, *tropical fruit*, *mineral/flint* and *sweet* flavour. They were also associated more with FVT (replicate 3), pH and soluble solids which may relate to more tropical fruit and sweeter sensory profiles. High water status wines were associated with higher *citrus* aroma and flavour as well as *astringency* intensity ratings. In terms of chemical variables, high water status wines had higher TA and PVT. These may relate to the higher intensities of *citrus* aromas and flavours. For the Chateau des Charmes vineyard (Fig. 6.6), the PCA performed on the sensory data accounted for 88.21% of the variation with the first two PCs (64.66% PC1; 23.55% PC2) (Figure 6.8). From the PCA, low water status wines were associated with *peach* and *honey* flavour as well as *sweet* taste. They were also associated with higher soluble solids again possibly accounting for the more sweet taste and riper flavours due to a slightly higher level of maturity. High water status wines were associated with *apple/pear* aroma and flavour (replicate 1) and *sour* and *bitter* taste (replicate 2). In terms of chemical variables, high water status replicate 2 was most associated with FVT, PVT, and TA. It is logical to assume that the higher TA and sour taste are related. This is a noteworthy finding as it shows that the panel training was adequate.

Integration of sensory data across vintages and vineyard sites. Interestingly, there were common attributes that were found to be similar in both vintages for wines of similar water status despite variations in the growing seasons. Yearly variations in some of the sensory attributes between high and low water status wines within a vineyard may be related to differences in the absolute ψ values of the given year. For example, vines designated as "low water status" had lower ψ values in 2005 than those from the 2006 vintage. Since the fruit was harvested systematically through the use of data imported into GIS software it was possible to assign an actual range of ψ values to each wine as all the grapes used in production of the wine treatment would fall into that particular criteria. Furthermore, the wines were both viticulture and oenological replicates and there was no amalgamation so the fruit/wine's geographical location could be accounted for within the vineyard site.

Through examination of leaf ψ values for both vintages of the wines depicted in PCA biplots (Figures 6.5-6.6, Suppl. Figures 6.2e to 6.2e) it was found that wines of values <-12 bars had more *honey*, *tropical* and *petrol,* and *sweet* intensity ratings, wines >-10 bars had more *vegetal*, *citrus, apple*, *sour* and *astringent* intensity ratings, whereas the wines between these two categories had more *peach*, *petrol* and *mineral* aroma/flavour characteristics. Therefore, the entire data set was used for the sensory attributes that were significantly different within sites. Only sensory attributes that were different in at least two vineyard sites for that particular vintage were used to reduce the effect of site specific sensory attributes. Categories were assigned to different leaf ψ values. These included no water deficit (>-10 bars), mild water deficit (-10 to -13 bars), and water deficit (<-13 bars). Means were then calculated for intensity ratings of relevant sensory attributes for each category based on the vineyard treatment replicates and their leaf ψ range. The integrated results are depicted using PCA biplots in Figure 6.7.

2005. Results of PCA for the 2005 vintage are depicted in Figure 6.7. Wines made from vines with the highest water status (>-10 bars) had lowest intensity ratings for *petrol aromas* and *apple/pear, peach, honey* flavours and *sweet* taste but had the highest *baking spice* aroma as well as *vegetal and tropical fruit* flavour. Conversely, wines produced from vines of the lowest water status category (<-13 bars) were found to be highest in *tropical fruit* and *petrol* flavours and lowest in *citrus* flavour. Wines made from fruit that was produced under mild water deficit (-10 to -12 bars) had sensory profiles highest in *mineral/flint*, *petrol*, and *honey* aromas and *apple/pear* flavour. There were little differences in terms of *baking spice* aroma, *apple/pear* and *honey* flavour as well as *sweet* and *sour* tastes.

2006. The results of the sensory profiles of wines of different water status categories are shown in Figure 6.7. The vintage effect is particularly noteworthy in this radar plot. Since the 2006 vintage was cooler and wetter than 2005, there were fewer vineyards with vines experiencing moderate to high water deficits. Therefore, there are only two main categories for this vintage except that *petrol, peach* and *honey* flavours were highest in the case of some vines which had leaf ψ <-13 bars in vineyards in two of the warmest sub-appellations, Beamsville Bench and Four Mile Creek. Wines produced from vines > -10 bars were found have sensory profiles with the highest *apple/pear, baking spice,* and *vegetal* aromas as well as *tropical fruit* flavour and *sour* taste. The wines made from vines that experienced some mild deficit (-10 to -12 bars) had the highest *mineral/flint* aroma. There were no large differences in terms of many of the flavour attributes in 2006. *Vegetal* and *tropical fruit* flavours as well as *sweet* taste did not discriminate the wine treatments very well. Some of these results can be explained with the rainfall events late in the growing season during the harvest period. The significant rain events possibly mitigated a lot of the water status differences that were observed during the growing season hence influencing the final quality of the wines. Still, some consistent trends were found in that wines made from vines of lower water status resulting in mild water deficit had more *mineral/flint* and *petrol* aromas as well as *honey* character. Wines produced with vines with no water deficit had more *vegetal* aroma, *citrus* flavour and *sour* taste.

Summary of 2005-2006 vintages. The results of the sensory profile of wines from combined vintages of different water status categories can be found in Figure 6.7. Categorizing the wines based on absolute water status as opposed to the lowest and highest water status category allows for interpretation of the results of within site-differences across all vineyards and vintages. Wines produced from vines with leaf ψ > -10 bars had sensory profiles with the highest intensity ratings of *tropical fruit and vegetal characteristics*, *citrus* flavours, and sour taste. These wines also had the lowest *honey* and *petrol* aromas. On the contrary, wines that were made from vines <-13 bars were highest in *honey*, *petrol* and *peach* flavours and lowest in *baking spice*, *tropical fruit*, *vegetal*, *mineral/flint* aromas and *citrus* flavours. The sensory profiles of wines where the vines had some mild water deficit were highest in *honey*, *mineral/flint*, and *petrol* aromas and lowest in *vegetal aroma.*

Partial least squares. 2005. PLS was used to investigate relationships between vine water status and viticulture variables and sensory characteristics and help interpret and explain the different sensory characteristics found due to water status differences within vineyards throughout the Niagara Peninsula, ON. PLS explained 45.8% of the variability in X and 22.6% in Y from the 2005 data set (Figure 6.8). Leaf water potential (ψ) was shown to be correlated with vine size, berry weight, yield and percent sand and was associated with higher intensities of *vegetal* character, *citrus* and *apple/pear* flavour. Lower water status was found to be associated with more *honey* character.

2006. PLS explained 46.1% of the variability in X and 26.9% in Y from the 2006 data set (Figure 6.9). As in 2005, leaf water potential (ψ) was shown to be correlated with vine size and yield. Leaf ψ was associated with higher intensities of *vegetal* character, *mineral/flint* aroma and *petrol* flavour. Lower water status was associated with *honey* and *tropical fruit* character. From these data, as in the case of the 2005 vintage, vine water status had a significant impact on vine performance and the sensory characteristics of Riesling wines.

The findings of this study support our hypothesis that vine water status has a substantial impact on the sensory properties of Riesling wines. It was demonstrated that variability of leaf ψ within vineyard sites (regardless of size) can lead to wines that differ in their sensory profiles. These findings were also consistent among vineyards across the Niagara Peninsula. Many sensory differences were consistent across many vineyards while some other attributes were site specific or insignificant. The results support other studies that show the dependence on wine sensory attributes on vine water status such as those of Matthews et al. (1990) and Chapman et al. (2005). In those studies irrigation treatments were performed on the vines. Since no treatment manipulations were imposed on the vines, our study indicates that vine water status is in fact a major determinant of the terroir effect. This supports other terroir-related studies which indicate that water availability and vine water status are the means by which the terroir affects wine style and quality (Koundouras et al., 1999; Penavayre et al., 1991; Peyrot des Gachons et al., 2005; Seguin, 1983; van Leeuwen et al., 2009).

This is the first study in a New World wine region that supports this notion which is very significant. Wines with higher water status had more *vegetal*, *citrus* and *apple/pear* character. Bearing in mind that no consumer preference data were collected, these wines did not appear to have many of the complexities or characteristics desirable in Riesling wines, especially the vegetative character. These findings are similar to those of Penavayre et al. (1991) who found that vines with unlimited water supply throughout the growing season resulted in wines that had less intense varietal character. High water status due to an abundant water supply has been shown to be detrimental to grape and wine quality in research for many years. Grapevines with an abundant water supply produce a dense, shaded canopy that reduces wine grape quality (Reynolds and Naylor, 1994; Smart, 1974; Smart et al., 1974). Shading retards fruit maturation and can lead to unripe flavours due to methoxypyrazine formation as well as slower methoxypyrazine degradation (Hashizume and Samuta, 1999). On the contrary, mild water deficits have been shown to be beneficial to grape and wine quality. The more fruit forward wines were found to be those of lower water status (<-10 bars or less). This agrees with the findings of irrigation studies involving red wine cultivars (Chapman et al., 2005) and the work of Noble et al. (1995) who found more fruit driven wines from soils with less water holding capacity and lower water status. Treatments resulting in higher vine water status and soils with more available water produced more vegetative wines. Vines that exhibited some water deficit had the highest intensities of many of the desirable attributes in Riesling wines including *honey*, *mineral/flint*, *tropical fruit*, and *petrol* and lowest in *vegetal* aromas which wouldn't be considered an ideal sensory characteristic in Riesling.

Mild water deficits have been shown to be most beneficial to grape and wine quality. Peyrot des Gachons et al. (2005) found that mild water deficits improved grape quality through higher volatile thiol content in Sauvignon blanc grapes. Therefore, this research further supports the importance of vine water status and its impact on aroma potential and sensory qualities of white wine cultivars. Water deficits have been shown to reduce berry size and increase the skin to juice ratio (Becker and Zimmermann, 1984; Ojeda et al., 2001; Poni et al., 1994). This is important in an aromatic white cultivar such as Riesling where much of their aroma potential is found in the skins. The increase in fruit driven aromas may be related to smaller berry weights (data shown in Chapter 4) and more aroma compounds in the wines since most of them and their precursors reside in the skin (Park et al., 1991). However, once vine water status was below -13 bars (showing more water deficit) some of these characters were decreased including *mineral/flint*, *tropical fruit*, and *baking spice* and in the 2005 vintage some vegetative character were found to be the highest in some wines. Lack of the fruit character and increased vegetative characteristics could possibly be related to delayed maturity due to an excessively small canopy and poor vine balance as well as delayed maturity. This would have been even more exaggerated due to some winter injury which occurred during the cold 2004/05 winter. Vines may have been struggling as a result of cold related injury and the hot and dry season may have delayed maturity as one of the negative consequences of drought stress demonstrated in the study by Hardie and Considine (1976). Petrol flavours were also highest in these wines which can result in an overpowering bouquet in the wine particularly after some bottle age. The aroma compound responsible for the petrol or kerosene aroma particularly in Riesling is 1,1,6-Trimethyl-1,2-dihydronaphthalene

(TDN) and is known for its potency with a threshold of 20 ppb (Simpson, 1978). TDN normally is absent in young grapes and wine but develops as a wine matures (Winterhalter, 1991). Many of the vines that had very low water status were very low in vigour and had a lot of fruit exposure. Grapes exposed to direct sunlight were found to contain more TDN and other norisoprenoids than those shaded (Marais et al., 1992). Therefore, these wines may not age well as they possess some "aged" character already. Therefore, it appears that water stress can be both a positive or negative determinant of *terroir* depending on its severity and timing of onset.

It should be noted that no off-flavour comments or descriptors were generated by the sensory panel. Specifically, none of the wines, particularly the low water stress ones had any untypical 'aging off-flavour' (UTA) or 'atypical aging' (ATA) attributes. This off-flavour is characterized by odours of naphthalene, floor polish, wet wool, fusel alcohol or acacia blossom and has been found in Riesling wines from grapes which were grown under water or nitrogen stress (Hoenicke et al., 2002; Rapp et al., 1993).

It does appear that there may be a quality threshold for optimum water status that could be potentially elucidated with consumer preference studies. Most importantly, our findings indicate that wines of similar water status had similar sensory characteristics despite vintage to vintage variations and that within a given year wines made from low and high water status regions within a specific vineyard were distinct from each other. Similar to the findings of Matthews et al. (1990), we found that wines of different water status were determined to have different sensory profiles without there being many differences in terms of basic fruit composition. This also supports the results/opinions of other authors (Chapman et al., 2005) that soluble solids, TA and pH are generally arbitrary and not useful predictors to the sensory properties of a wine. Soluble solids are useful to predict potential ethanol in the final wine where TA and pH can be useful for winemaking considerations. However, aroma and flavours are not directly related to these variables. Our findings indicate that vine water status is having a strong influence on synthesis or degradation of aroma compounds or their precursors in Riesling which is consequently impacting their sensory characteristics.

Conclusions

To our knowledge this is the most extensive study pertaining to the impact of vine water status on white wine sensory attributes and quality. Through sorting tasks and descriptive analysis vine water status was shown to have a profound impact on the sensory characteristics of Riesling wines. Consistent water status zones were found within vineyard blocks and these zones produced wines with different sensory profiles of which several attributes were similar across multiple vineyards throughout the Niagara Peninsula, Ontario. These differences were found without any vineyard manipulation or cultural practice imposed onto the vines meaning that vine water status is a major factor of the terroir effect. Vines of different water status produced wines with distinct sensory profiles within vineyard sites but some attributes were found to be site or vintage specific. Since many attributes were similar across vineyards and vintages, examination of leaf water potential ranges of the wines gave a clearer explanation of the impact of water status on their sensory characteristics. Sensory profile differences were found with wines produced from vines that had no water deficit, mild water deficit and more severe water deficit. It does appear that there may be a quality threshold for optimum water status that could be potentially elucidated with consumer preference studies. Sensory attributes differed without there being differences in terms of basic fruit composition. Therefore, basic fruit composition does not appear to be a useful predictor for Riesling wine quality in the Niagara Peninsula. This is an important finding as many winemakers and growers rely on soluble solids as an indicator of quality and are paid higher prices according to sugar levels. Vine water status could be potentially a positive or negative determinant of terroir and is more than likely one of the largest factors impacting wine quality worldwide, especially with climate change affecting many of the important wine regions. Ultimately, it can be concluded that neither severe water deficit nor lack of water stress or will result in ultra-premium Riesling wine production.

Acknowledgments

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Table 6.1. (a) Aroma/flavour attributes used in sensory evaluation of Riesling wines, Niagara Peninsula, Ontario, 2005 to 2006. (b) Taste and mouthfeel attributes used in sensory evaluation of Riesling wines, Niagara Peninsula, Ontario, 2005 to 2006.

Table 6.2. ANOVA p-values (<0.10) for wines from vines of different water status within vineyard sites across the Niagara Peninsula, Ontario. 2005 vintage.

Table 6.3. ANOVA p-values (<0.10) for wines from vines of different water status within vineyard sites across the Niagara Peninsula, Ontario. 2006 vintage.

Table 6.1a. Aroma/flavour attributes used in sensory evaluation of Riesling wines, Niagara Peninsula, Ontario, 2005 to 2006.

Attribute	Reference (base wine was a neutral Riesling wine from CCOVI)
Apple/pear	5 g fresh Bartlett pear and 5 g Granny Smith and Red Delicious apples in 50 mL base wine
Baking spices (aroma only)	5 mL of stock solution*
Citrus	Fresh lime juice (20 mL), lemon juice (10 mL), and grapefruit juice (5 mL) in 100 mL base wine
Honey	*President's Choice* alfalfa honey (10 g in 50 mL base wine)
Mineral/flint	Ground slate (5 g) in 20 mL base wine
Peach	*Yoga* peach nectar (25 mL)in 100 mL base wine
Petrol	1 drop WD-40™ in 900 mL base wine
Tropical fruit	*McCain* tropical fruit juice (10 mL), *Rubicon* passionfruit juice (5 mL), and *Rubicon* guava juice (5 mL) in 300 mL base wine
Vegetal	10 mL of vegetal stock solution** and canned bean brine (5 mL) in 100 mL base wine

*Cinnamon (0.1 g) and nutmeg (0.1 g) in 50 mL base wine

**1.1 g wheat grass blended in 100 mL water

Table 6.1b. Taste and mouthfeel attributes used in sensory evaluation of Riesling wines, Niagara Peninsula, Ontario, 2005 to 2006.

Attribute	Reference (in 1000 mL water)
Sweet	10 g sucrose
Sour	1.5 g citric acid
Bitter	0.01 g quinine
Astringent	0.05 g aluminum sulphate

Table 6.2. ANOVA p-values (<0.10) for wines from vines of different water status within vineyard sites across the Niagara Peninsula, Ontario. 2005 vintage.

	Niagara Lakeshore	**Beamsville Bench**	**St. David's Bench**	**Twenty Mile Bench**	**Short Hills Bench**	**Four Mile Creek**	**Lincoln Lakeshore**	**Creek Shores**	**Niagara River**	**Vinemount Ridge**
Aroma										
Apple/Pear	NS	NS	NS	NS	NS	---[a]	**0.009**	NS	---[a]	NS
Baking Spice	NS	NS	NS	**0.006**	NS		NS	NS		**0.049**
Citrus	NS	NS	NS	**0.022**	NS		NS	NS		NS
Honey	**0.011**	**0.018**	**0.005**	NS	NS		**0.039**	NS		NS
Mineral/Flint	**0.100**	NS	**0.079**	NS	**0.052**		NS	NS		NS
Peach	NS	NS	NS	NS	NS		NS	NS		NS
Petrol	NS	NS	**0.032**	NS	NS		NS	**0.052**		NS
Tropical Fruit	NS	**0.085**	NS	NS	NS		NS	NS		**0.059**
Vegetal	NS	**0.059**	NS	NS	**0.054**		**0.092**	NS		NS
Flavour										
Apple/Pear	NS	NS	**0.043**	**0.042**	NS		**0.049**	**0.007**		**0.030**
Citrus	**0.095**	**0.037**	NS	**0.01**	**0.029**		NS	NS		NS
Honey	**0.030**	**0.087**	NS	**0.043**	**0.024**		**0.088**	NS		**0.030**
Mineral/Flint	NS	NS	**0.046**	NS	NS		NS	NS		NS
Peach	NS	**0.036**	NS	NS	NS		NS	NS		NS
Petrol	**0.076**	NS	NS	NS	NS		**0.029**	NS		**0.050**
Tropical Fruit	NS	NS	**0.045**	NS	**0.034**		NS	NS		NS
Vegetal	NS	NS	**0.053**	NS	NS		NS	NS		NS
Taste/ Mouthfeel										
Sweet	NS	NS	**0.046**	**0.044**	**<0.001**		NS	**0.020**		NS
Sour	NS	**0.01**	**0.049**	**0.077**	**<0.001**		**0.042**	**0.030**		**0.006**
Bitter	NS	NS	NS	NS	NS		NS	NS		NS
Astringency	**0.040**	NS	NS	NS	NS		NS	NS		NS

[a] No wines produced due to lack of fruit due to winter injury

Table 6.3. ANOVA p-values (<0.10) for wines from vines of different water status within vineyard sites across the Niagara Peninsula, Ontario. 2006 vintage.

	Niagara Lakeshore	Beamsville Bench	St. David's Bench	Twenty Mile Bench	Short Hills Bench	Four Mile Creek	Lincoln Lakeshore	Creek Shores	Niagara River	Vinemount Ridge
Aroma										
Apple/Pear	NS	NS	**0.001**	NS	NS	NS	NS	NS	**0.08**	—[a]
Baking Spice	NS	**0.049**	NS	**0.01**	NS	NS	NS	NS	NS	
Citrus	NS	NS	NS	NS	**0.022**	NS	NS	NS	NS	
Honey	NS	NS	NS	NS	NS	NS	**0.049**	NS	NS	
Mineral/Flint	NS	NS	NS	NS	NS	NS	**0.091**	NS	**0.008**	
Peach	NS	NS	NS	NS	NS	NS	**0.059**	NS	NS	
Petrol	NS	**0.087**	NS	NS	NS	**0.032**	NS	NS	NS	
Tropical Fruit	NS	**0.084**	NS	NS	NS	NS	NS	NS	NS	
Vegetal	**0.074**	**0.073**	NS	**0.024**	NS	NS	**0.041**	NS	NS	
Flavour										
Apple/Pear	NS	NS	**0.048**	NS	**0.027**	NS	NS	**0.09**	NS	
Citrus	NS	NS	NS	NS	NS	NS	**<0.001**	NS	NS	
Honey	**0.029**	NS	**0.067**	NS	NS	NS	NS	NS	**0.054**	
Mineral/Flint	NS	NS	NS	NS	NS	NS	NS	**0.01**	NS	
Peach	NS	**0.029**	**0.019**	NS	NS	NS	NS	NS	NS	
Petrol	NS	NS	NS	NS	NS	NS	NS	NS	NS	
Tropical Fruit	NS	**0.004**	**0.045**	NS	NS	NS	NS	**0.093**	**0.072**	
Vegetal	**0.071**	**0.1**	NS	NS	**0.037**	NS	NS	NS	**0.07**	
Taste/Mouthfeel										
Sweet	NS	**<0.001**	**0.017**	NS	**0.009**	**0.032**	**0.031**	**0.005**	NS	
Sour	NS	NS	**0.009**	NS	NS	NS	NS	NS	**0.048**	
Bitter	NS	NS	**0.059**	NS	NS	NS	NS	NS	**0.054**	
Astringency	NS	NS	NS	NS	NS	NS	**0.056**	NS	NS	

[a] No wines produced due to fruit being infected with severe powdery mildew

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Figure 6.1. Climate data for the 2005 and 2006 growing seasons. Vineland Station, Ontario.

Figure 6.2. Identification and sorting of sentinel vines based on vine water status zones on GIS-generated maps. Vines in blue zones placed in high water status treatments; vines in orange zones placed in low water status treatments.

Figure 6.3. Three-dimensional MDS of sorted wines from areas of different water status Legend: H, L = High water stress (low water status); Low water stress (high water status). Myers Vineyard. A:2005, B:2006. Kruskal's stress 0.050 in 2005; 0.062 in 2006.

Figure 6.4. Three-dimensional MDS of sorted wines from areas of different water status Legend: H, L = High water stress (low water status); Low water stress (high water status). Chateau des Charmes Vineyard. A:2005, B:2006. Kruskal's stress 0.100 in 2005; 0.083 in 2006.

Figure 6.5. Principal component analysis for Myers Vineyard depicting intensity ratings of significant sensory attributes on principal components (PC1 and PC2). 2005-2006.

Figure 6.6. Principal component analysis for Chateau des Charmes vineyard depicting intensity ratings of significant attributes on principal components (PC1 and PC2). 2005.

Figure 6.7. **(A)** Principal component analysis depicting intensity ratings of Riesling wines of different water status categories from within vineyards across the Niagara Peninsula. (PC1 vs. PC2). **(B)** Principal component analysis depicting intensity ratings of Riesling wines of different water status categories from within vineyards across the Niagara Peninsula (PC1 vs. PC3). 2005-2006. Legend: ● 2005; ▲2006.

Figure 6.8. Partial least squares of sensory and vineyard data for Riesling wines of different water status within vineyards across the Niagara Peninsula, 2005 vintage. (variance explained in X 45.8%; in Y 22.6%).

Figure 6.9. Partial least squares of sensory and vineyard data for Riesling wines of different water status within vineyards across the Niagara Peninsula, 2006 vintage. (variance explained in X 46.1%; in Y 26.9%).

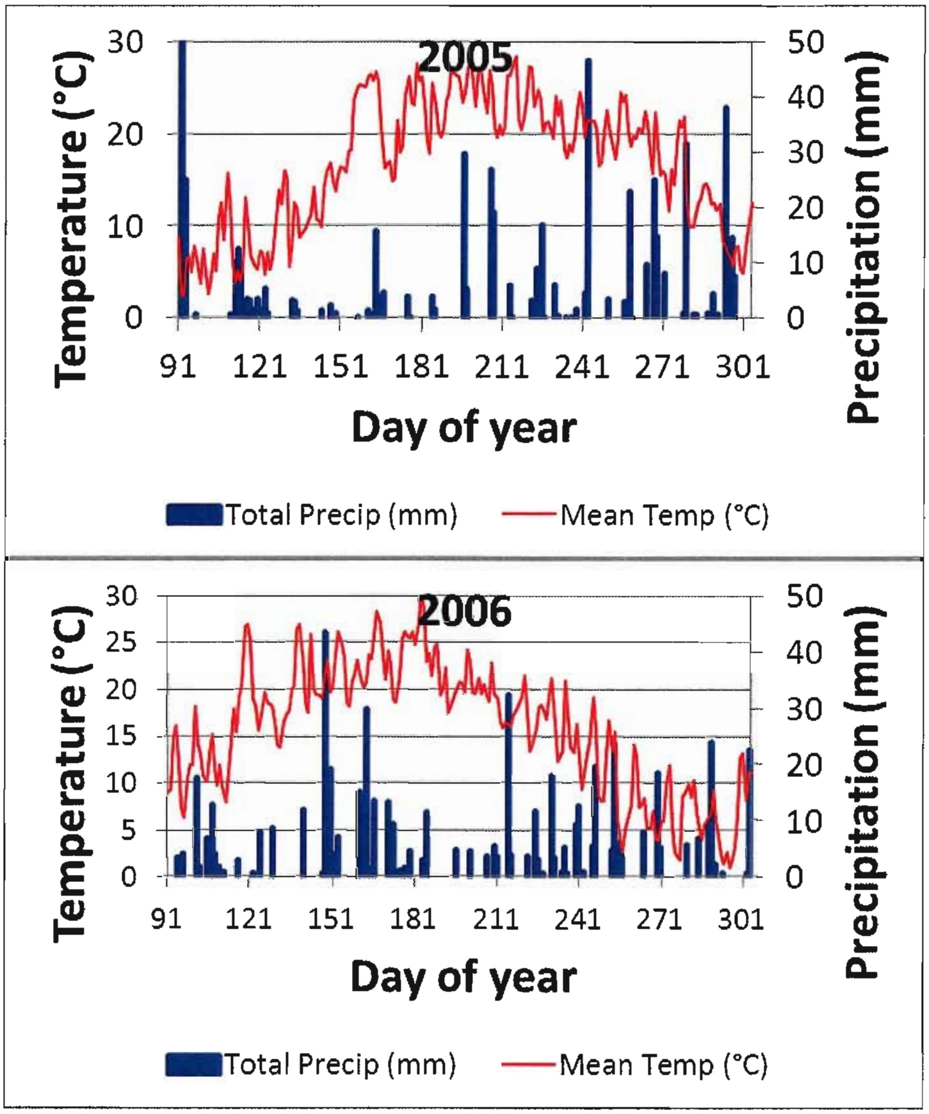
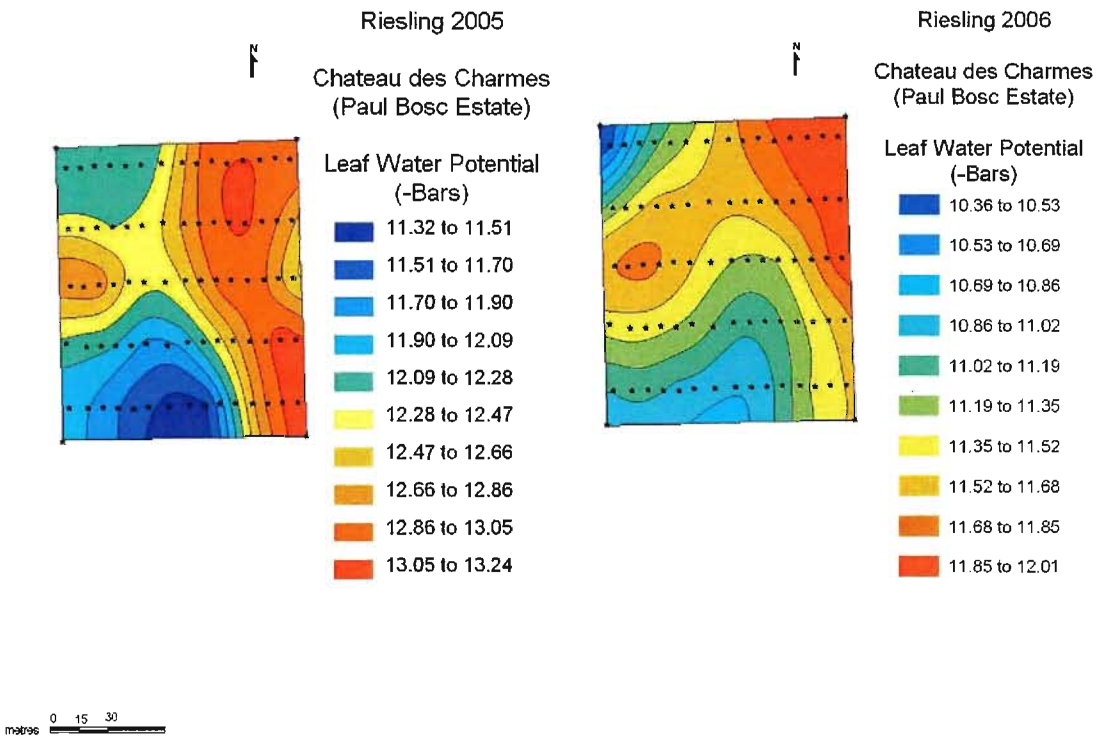


Figure 6.1. Climate data for the 2005 and 2006 growing seasons. Vineland Station, ON.



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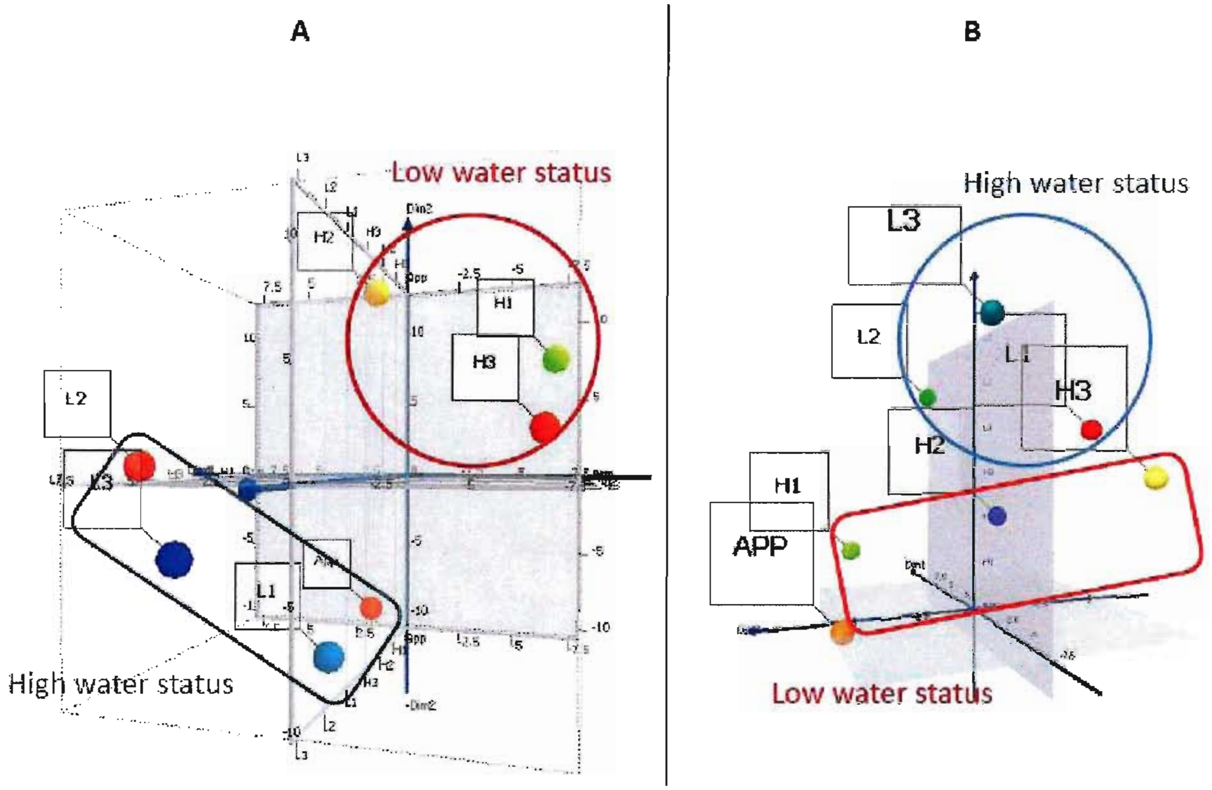

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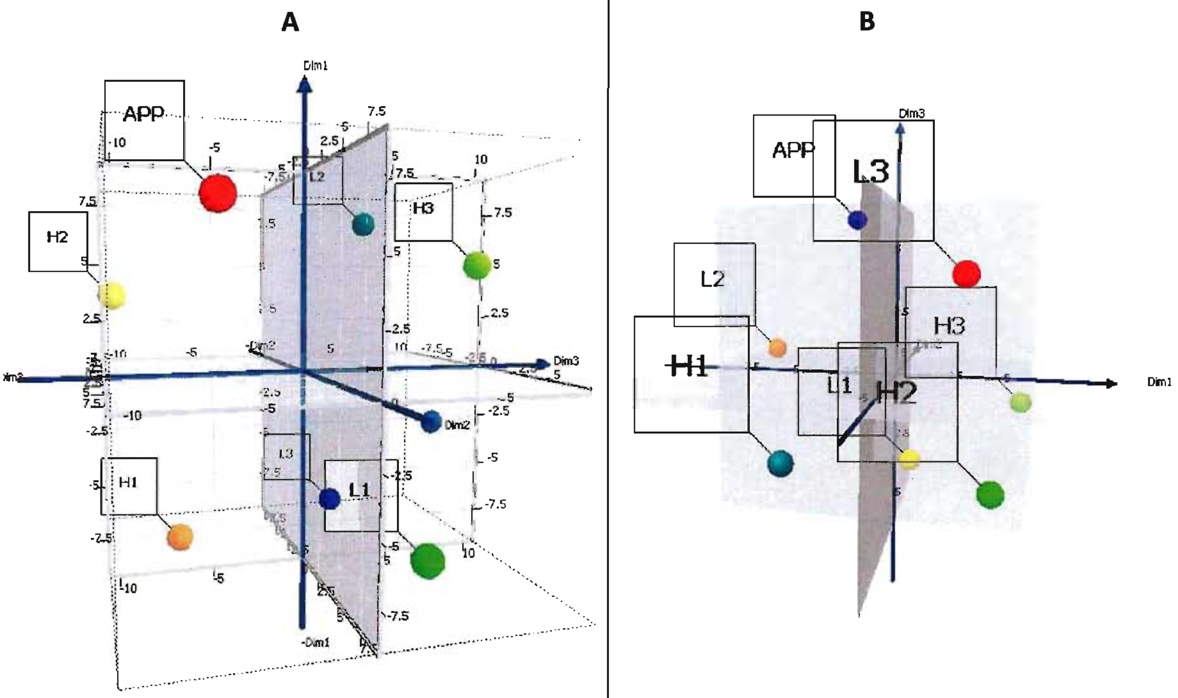

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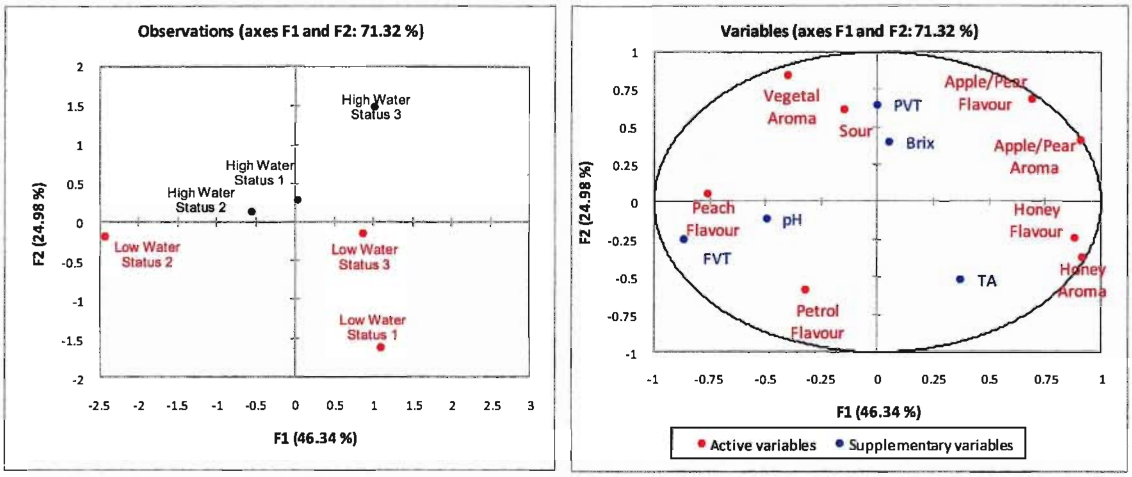
2005



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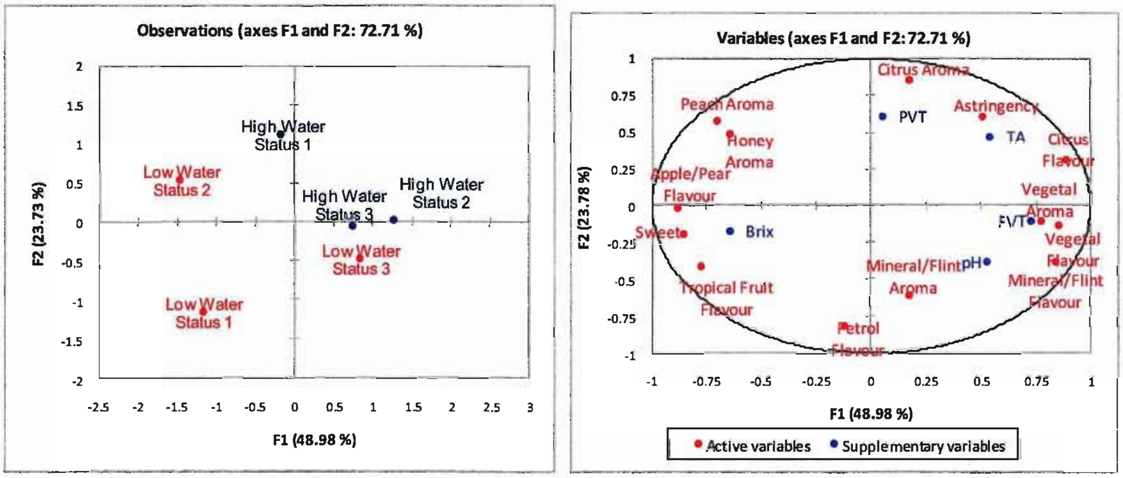

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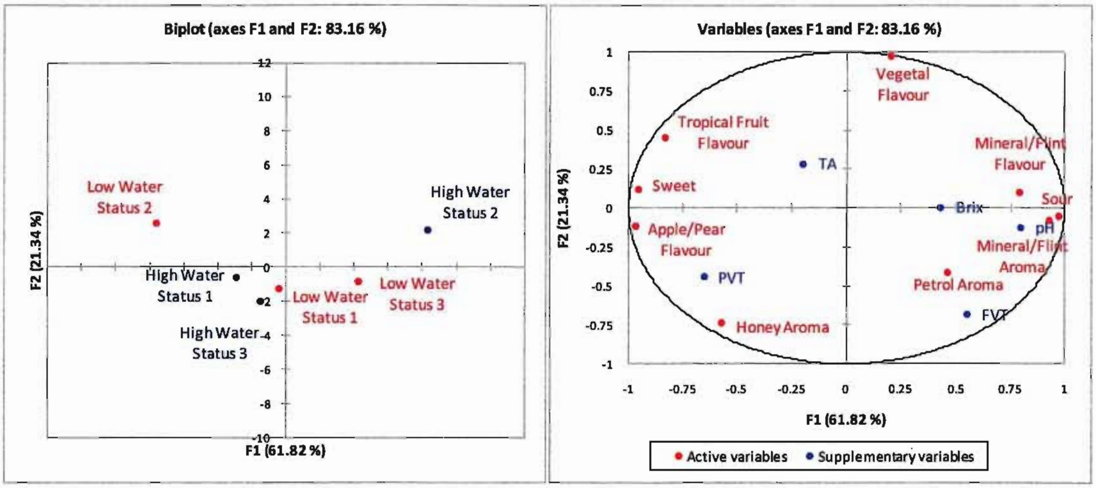
2005



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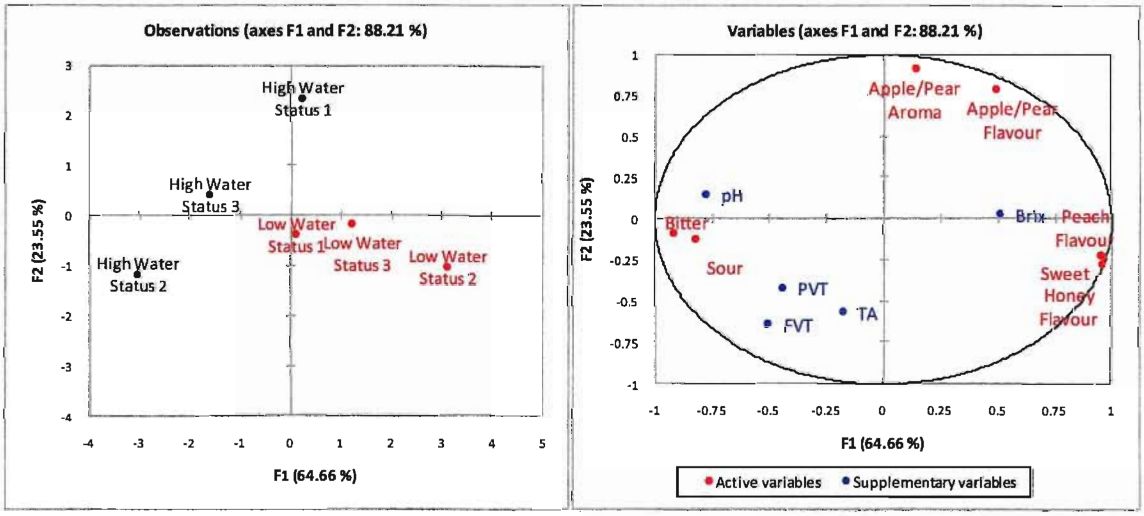

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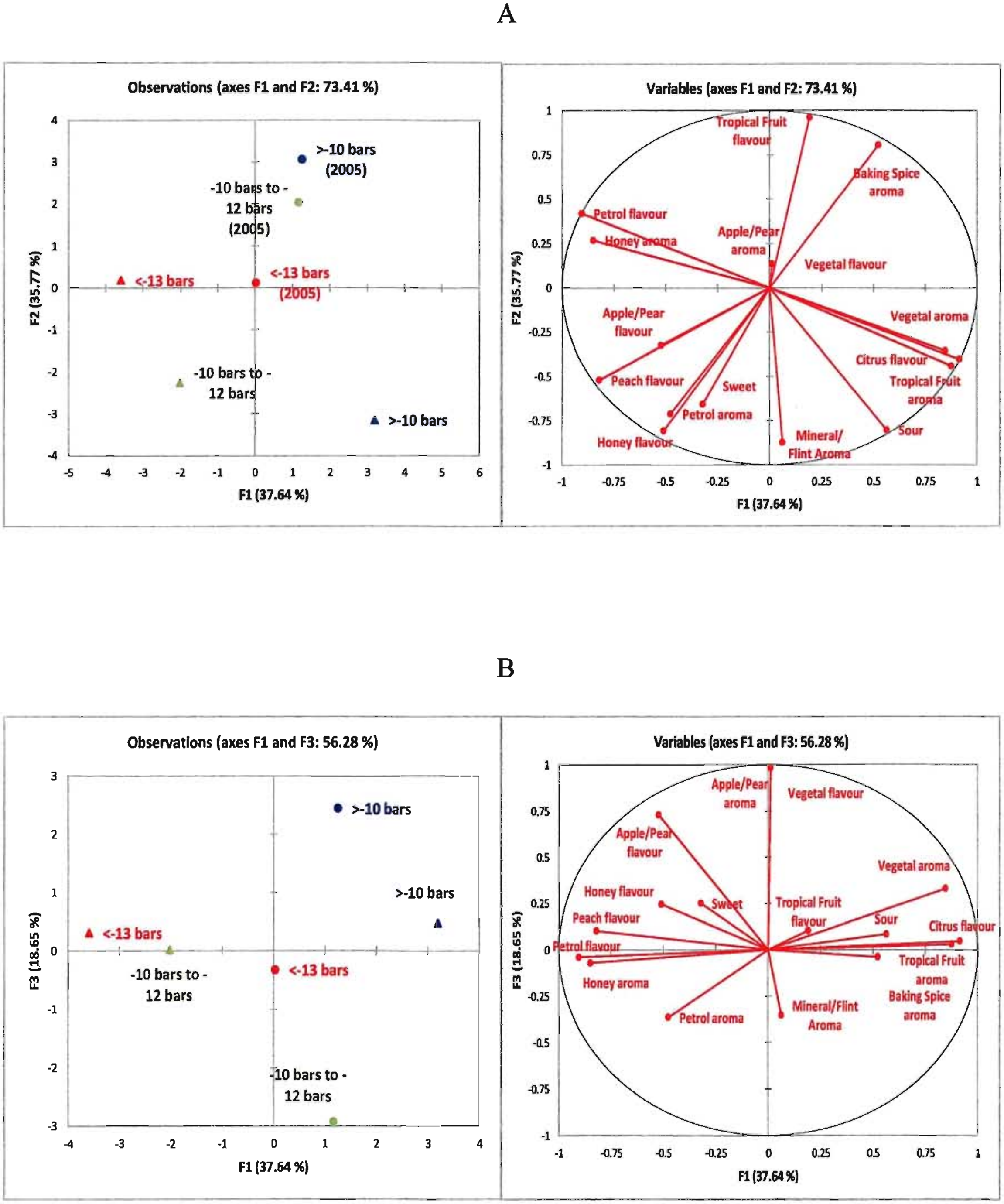

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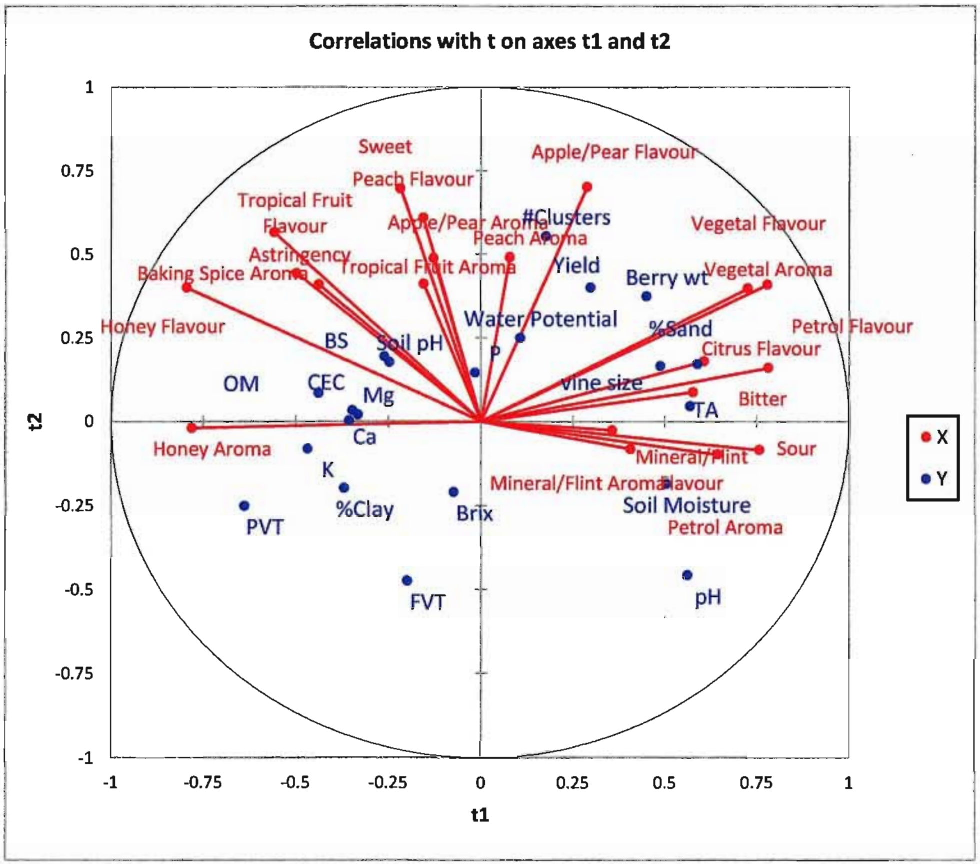

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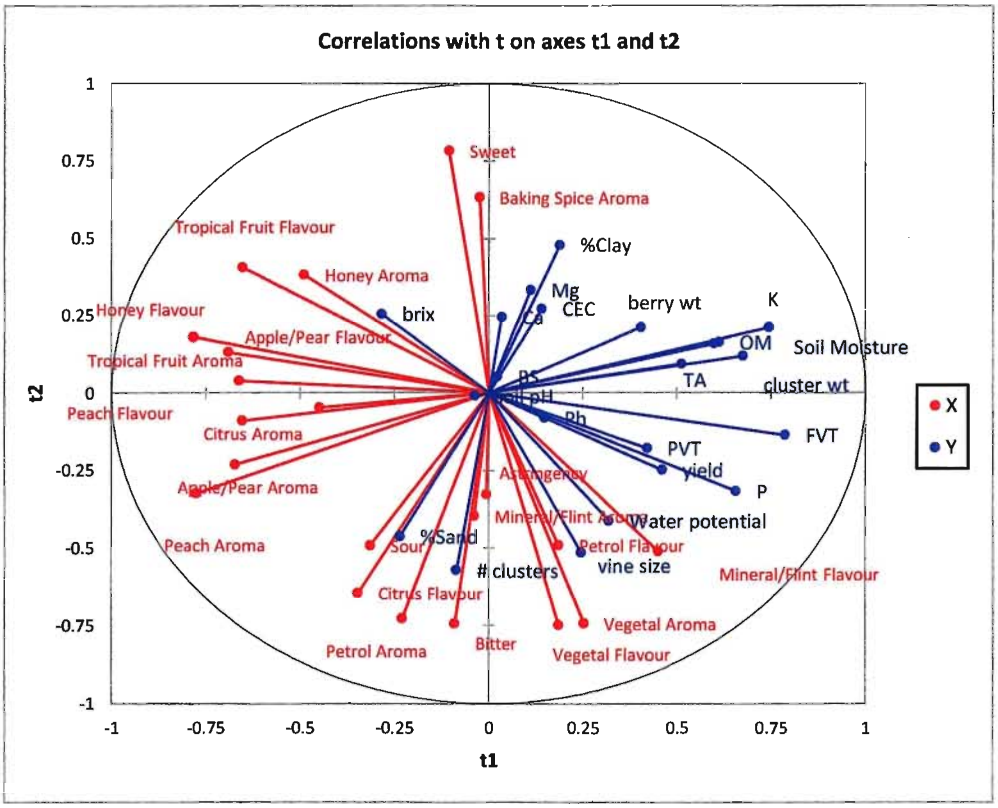

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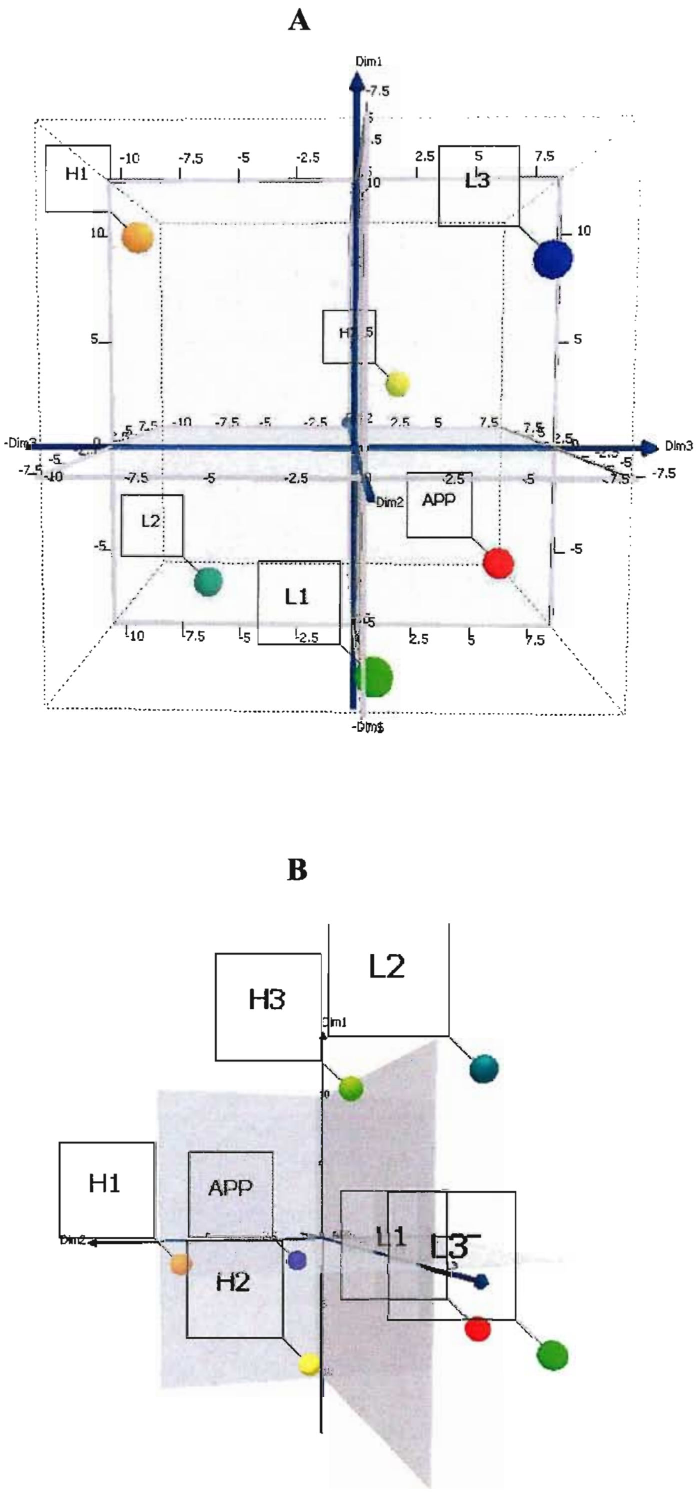

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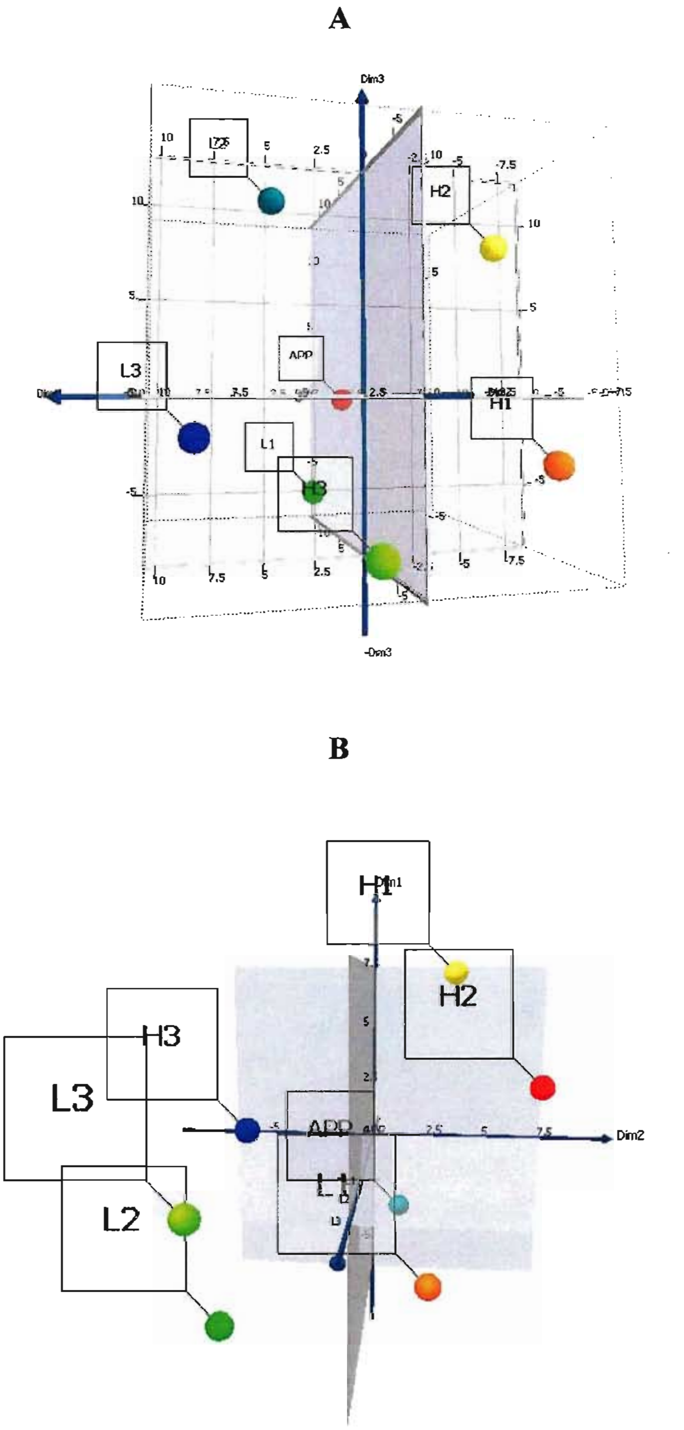

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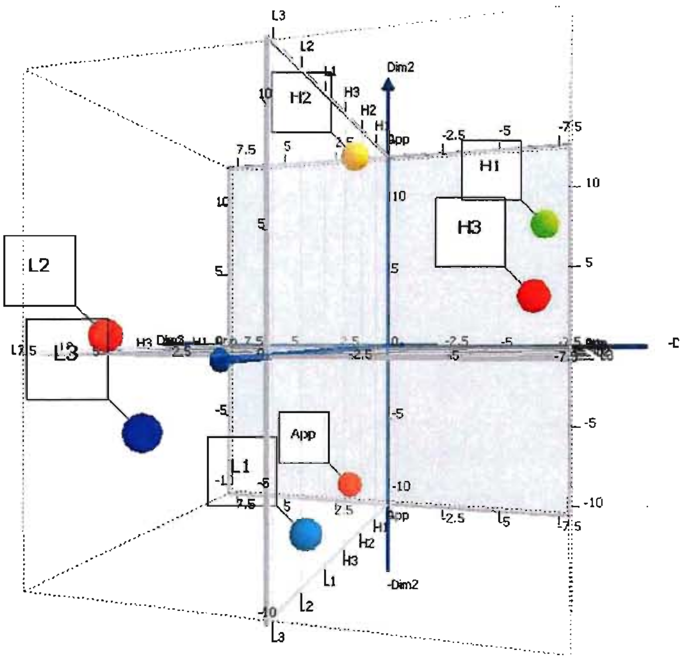
A



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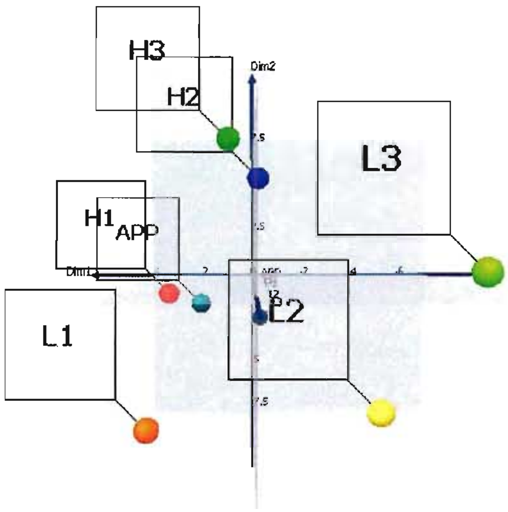

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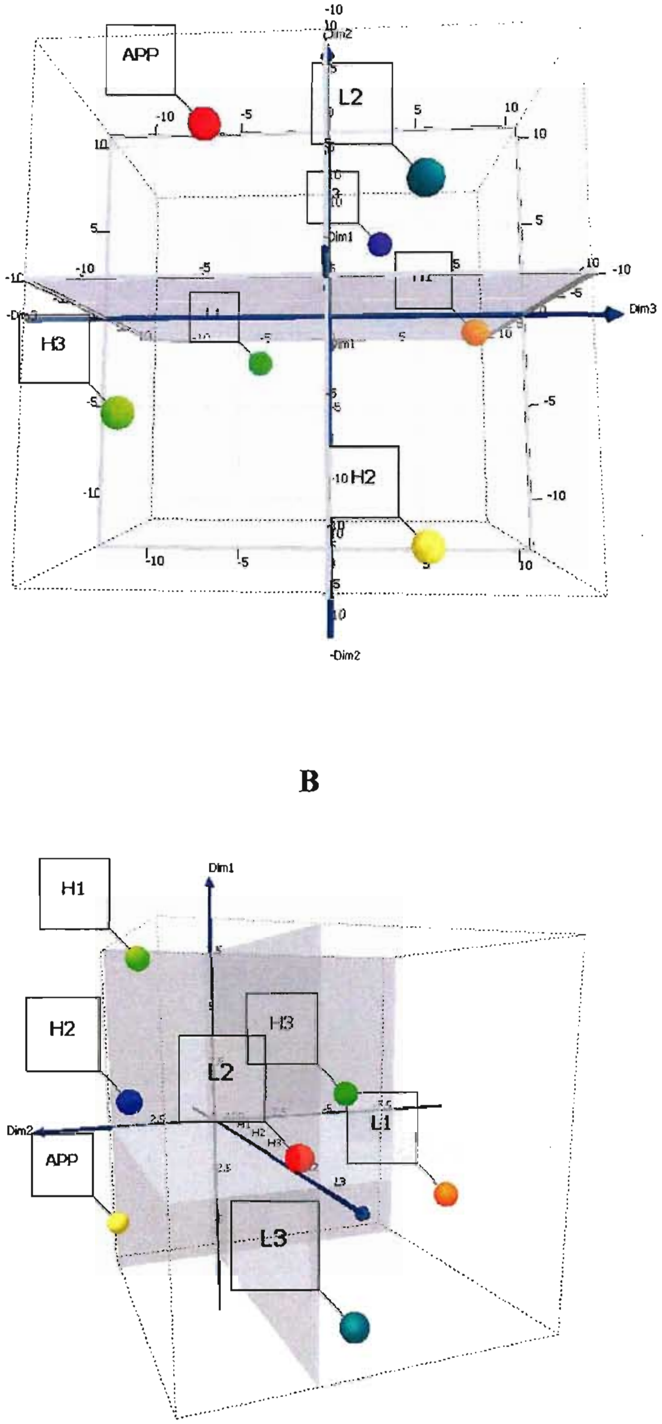
A



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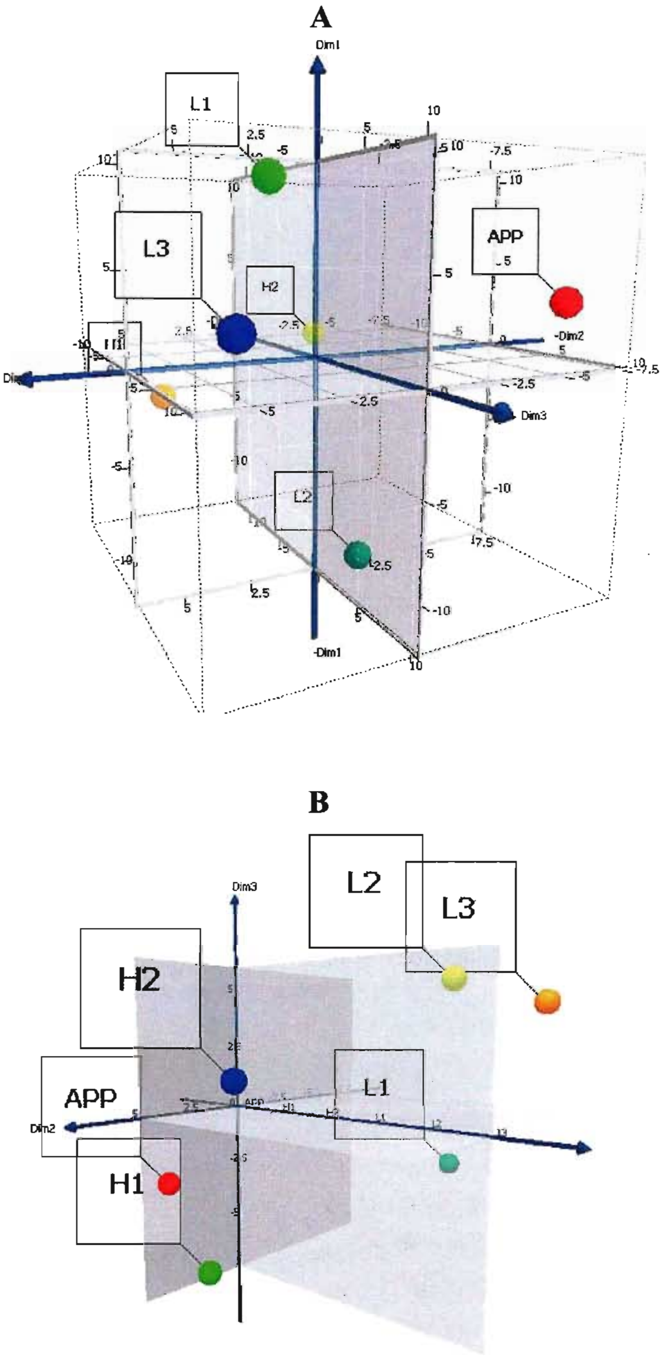

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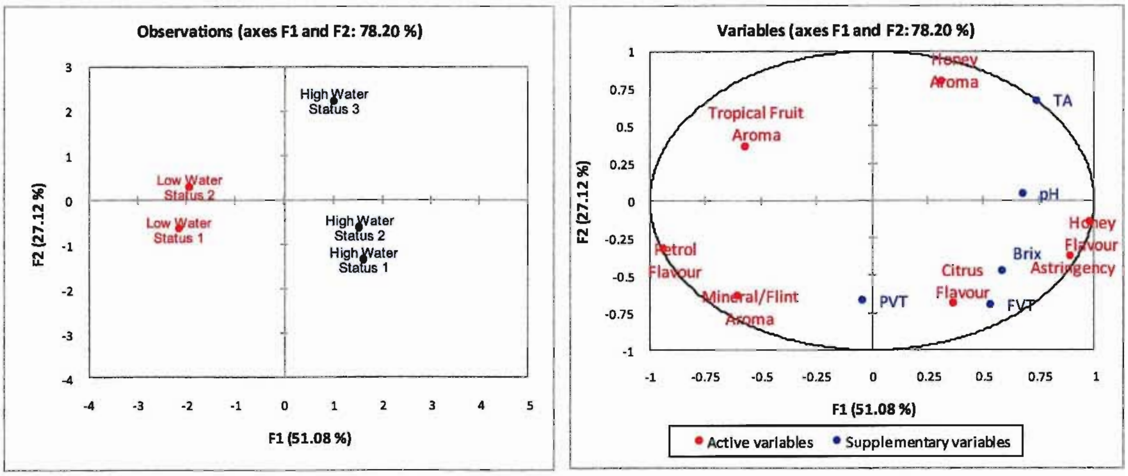
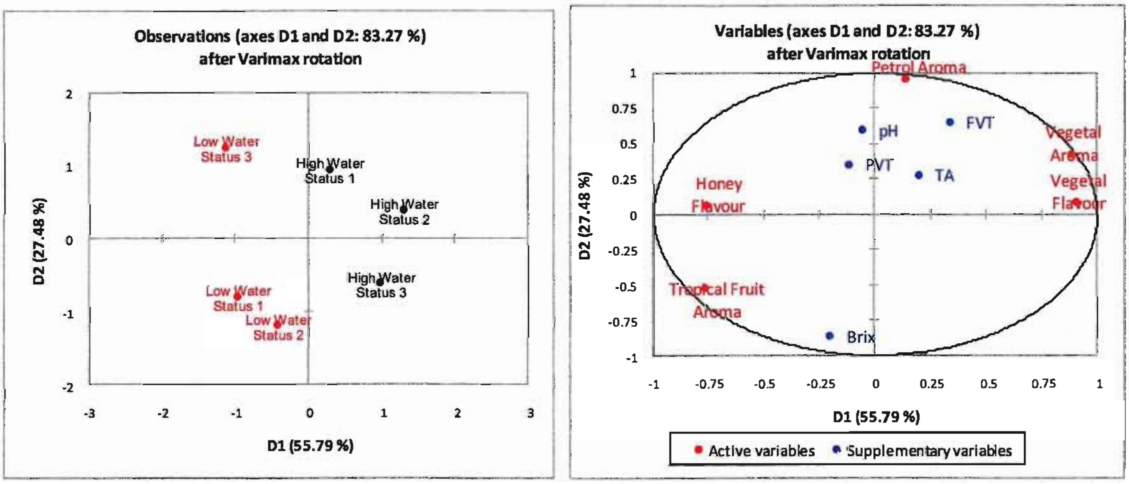
2005



2006



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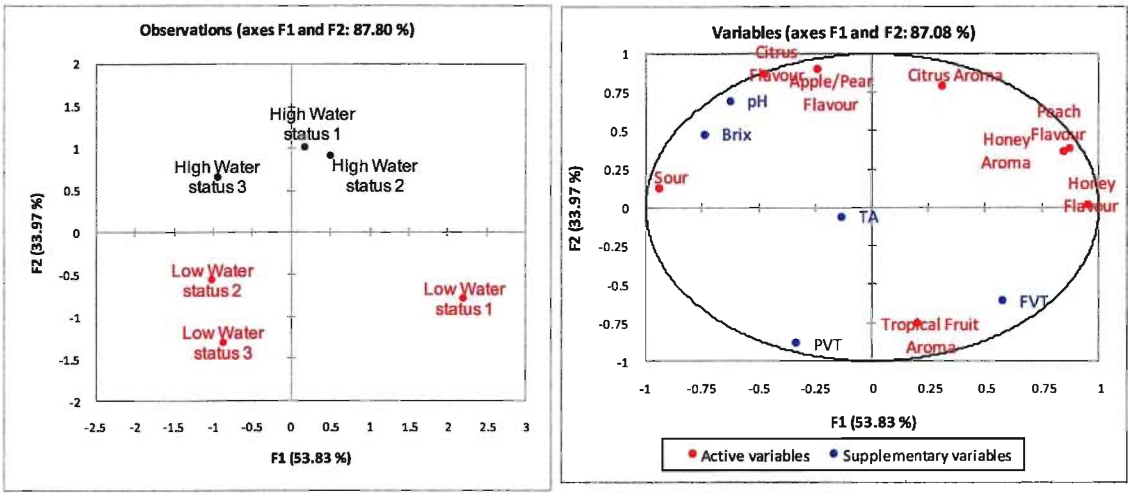
2005



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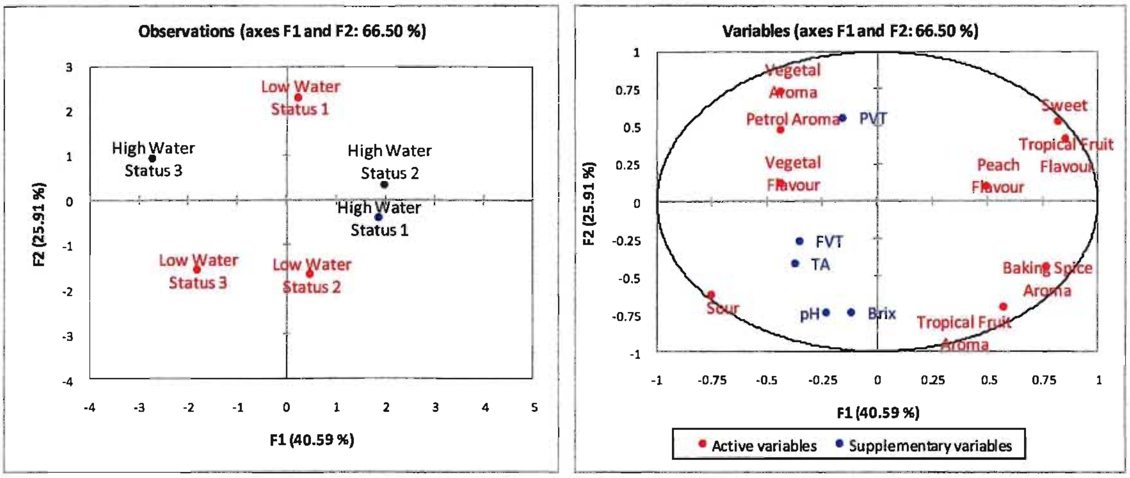

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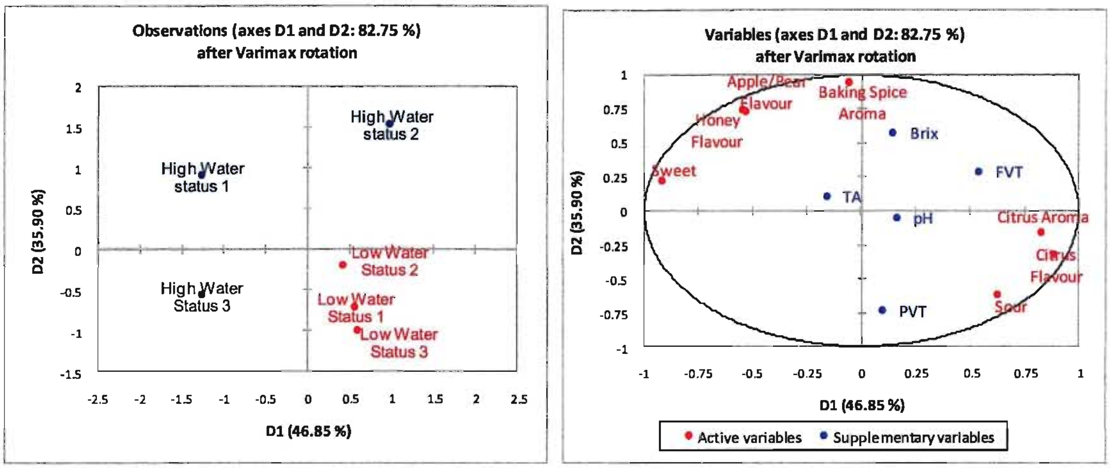
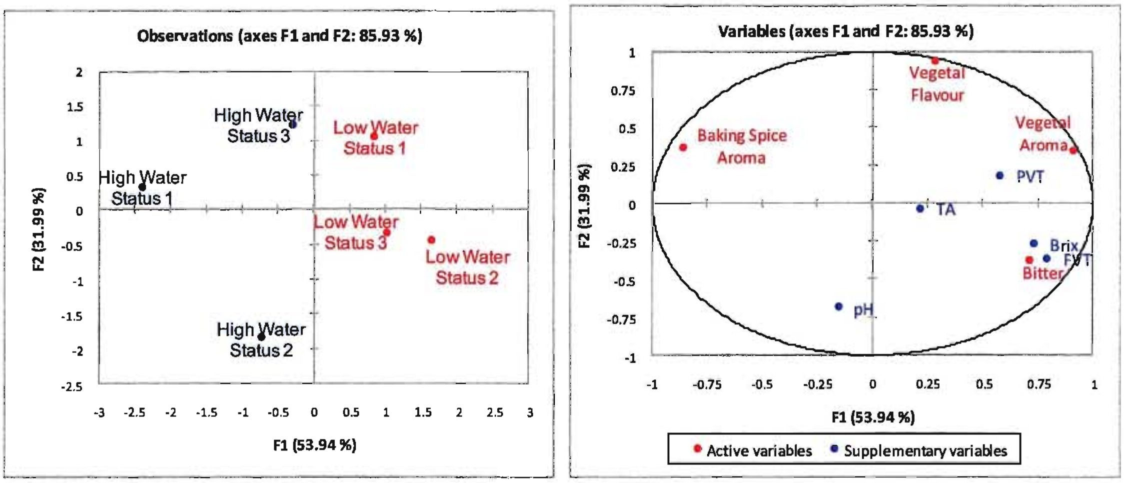


2006



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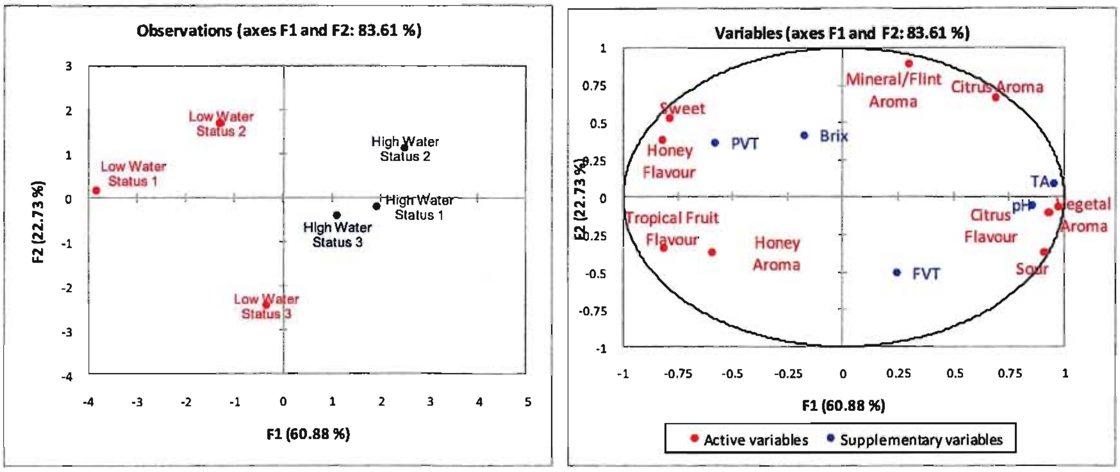

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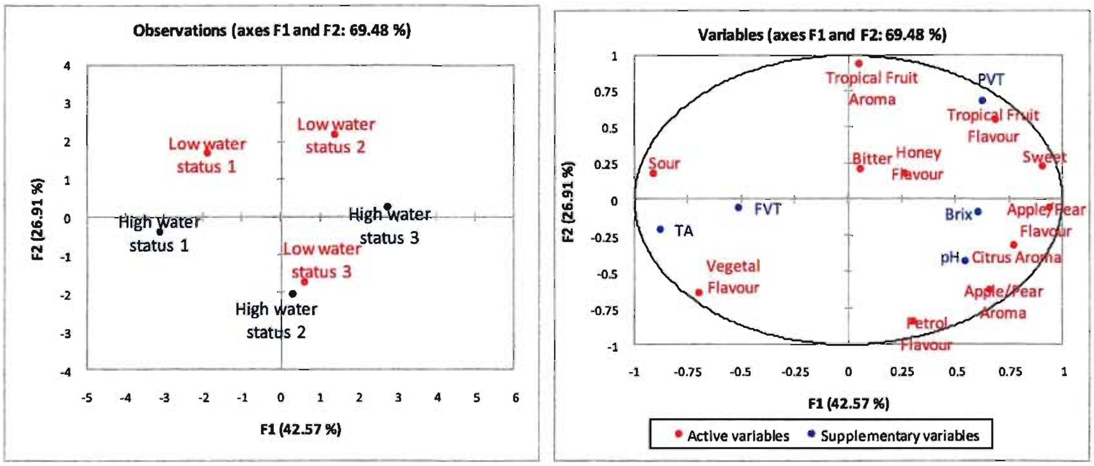

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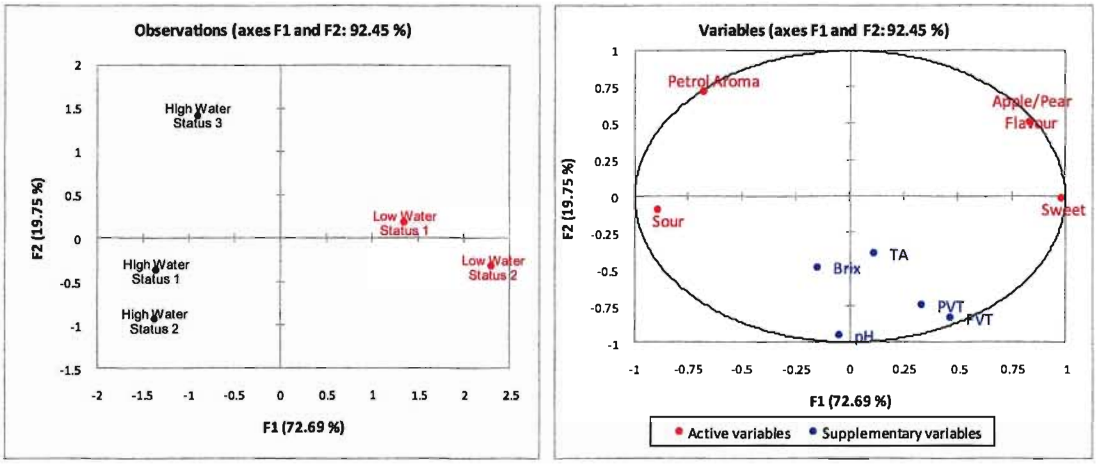
2005



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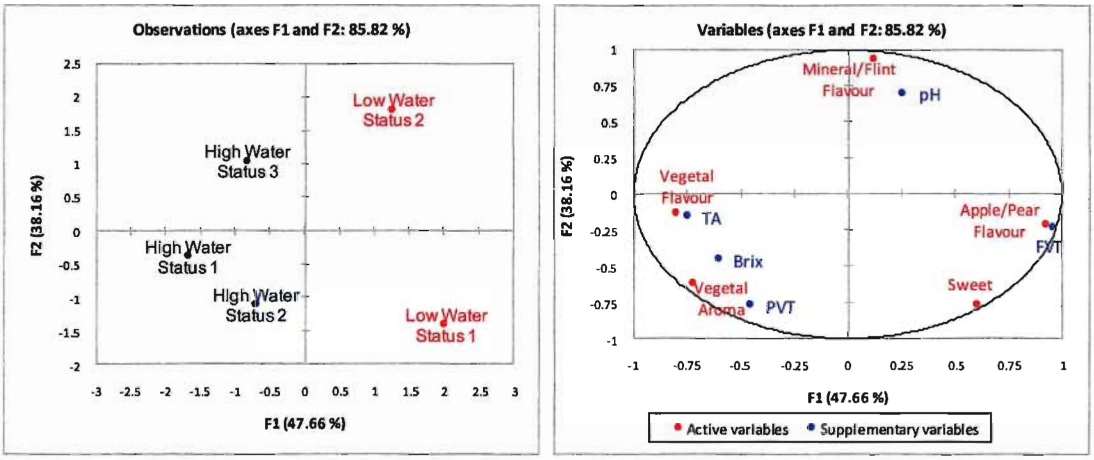

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Chapter 7: General Discussion and Conclusion

This chapter is in part of the following published paper:

Willwerth, J.J, Reynolds, A.G. and Lesschaeve, I. (2010). Terroir Factors: Their Impact in the Vineyard and on the Sensory Profiles of Riesling Wines. Les Facteurs du Terroir: Leur Impact dans le Vignoble et sur le Profil Sensoriel de vins de Riesling. Prog. Agric. Vitic. 8:159-168.

7.1 Introduction

The terroir concept can be defined as an interactive ecosystem, in a given place, including climate, soil, and the vine. Terroir is an important concept in the wine and food industry because it gives the product a "sense of place" which distinguishes it from other similar products. Traditional understanding is that soil primarily influences terroir; however evidence suggests that water availability and vine water status are the means by which the terroir affects wine style and quality (Koundouras et al. 1999, Morlat and Bodin 2006, Van Leeuwen and Seguin 2006). Vine water supply has been noted as a major factor in the terroir effect due to its impact on early budburst potential and potential vine vigour (Morlat et al. 2001). Grapes cultivated under mild water stress can improve berry composition (Matthews and Anderson 1988, Smart 1985) and mild water deficits have been shown to be a major factor in the terroir effect (Seguin 1983, Van Leeuwen et al. 2009). Many vineyards are variable in nature and do not exhibit homogeneous trends in terms of soil, vine performance or fruit quality. Spatial variability in soil, climatic conditions and other factors such as disease, have been associated with yields and some fruit composition variables (Bramley and Hamilton 2004, Cortell et al. 2005, Hall et al. 2002). Greenspan and O'Donnell (2001) found that spatial variability in vine vigour had an impact on yield, brix and water status. Cortell et al. (2007, 2008) studied a number of yield and fruit quality indices in Oregon Pinot Noir vineyards and found that vine vigour associated with soil and water availability had an impact on fruit composition, particularly phenolics. Bramley (2005) found that Cabernet Sauvignon vineyards in Coonawarra varied in a number of fruit composition variables and there was some consistency from year to year. While quality has been analysed through measuring chemical variables in fruit, there has not been a focus on wine produced from fruit harvested from vines of different water status. To this end, very few studies have examined sensory differences in wines made solely of vines of different water status. In terms of white wine production, the authors could not find any studies performed to date which used descriptive analysis. Through difference testing, Matthews et al. (1990) found that red wines of different water status had different sensory characteristics. Significant differences were found in terms of appearance, aroma, taste and flavour among different irrigation treatments. Through descriptive analysis, Chapman et al. (2005) found that Cabernet Sauvignon wines produced from vines of higher water status had more vegetal and less fruity aromas and flavours than vines with lower water status.

The Niagara Peninsula is known for its diverse soils, macroclimates and topographical features that further complicate the terroir effect. As a result, there are many distinct terroirs in the region and the potential to grow a variety of cultivars with high quality wines. Precision viticulture techniques, including global positioning systems (GPS) and geographic information systems (GIS), have become useful tools to study vineyard terroir and variability while keeping key environmental factors constant. Therefore these were used to accomplish the research objectives.

This study attempted to further understand the basis of terroir in the Niagara Peninsula by using Riesling vineyards representative of each VQA (Vintners Quality Alliance) sub-appellation. The specific primary objectives of this research were: (i) to demonstrate the influences of soil texture, soil water content, and vine water status on vine and fruit development within vineyard blocks and to delineate these terroir effects using GPS and GIS; and (ii) to elucidate the relationships between soil and vine water status and wine sensory properties. It was hypothesized that (i) consistent water status zones could be identified within vineyard blocks and, (ii) vine water status would play a major role in fruit composition and sensory characteristics of Riesling wine, whereas soil would play a role through its water holding capacity and water supply to the vine. This project had two distinct phases; the first phase examined spatial relationships of soil characteristics, vine performance (yield, vine size), plant water status, and fruit composition (including aroma compounds) using GPS and GIS technologies. The second phase consisted of the sensory characterization of wines produced from regions of different water status delineated through GIS through multiple sensory evaluation tasks. Finally, multivariate statistics and geostatistics were used to help elucidate relationships between terroir effects and wine sensory properties with the ultimate goal to create a model for the basis of terroir in Niagara Riesling vineyards.

7.2. Objective I. Elucidation of spatial trends within vineyards

General spatial trends. The growing seasons of 2005, 2006 and 2007 were quite typical for the Niagara Peninsula and ideal for studying terroir effects, particularly vine water status. All vintages had some dry periods during summer months, but 2005 and 2007 had prolonged drought periods during most of the growing season. Through the use of GPS and GIS technologies, the data collected from each vintage were depicted spatially and analysed to examine spatial trends and relationships. Vineyards varied in terms of soil texture and composition, and were depicted spatially. However, no real consistent relationships were found regarding many of these soil variables, particularly elemental composition. As hypothesized, consistent water status zones could be delineated within every vineyard and distinct regions could be categorized as "high" and "low" water status. This is in agreement with the findings of Acevedo-Opazo et al. (2008) who found that it was possible to assess spatial variability of vine water status within vineyards, even those small in size (<1 ha). In many cases, particularly in the hot and dry vintages, the "low" water status regions consisted of vines suffering moderate to high water stress. The spatial distribution of other variables such as soil moisture, vine size and berry weight were also temporally stable in many vineyards. Some strong relationships were consistently found between vine water status, vine size, and berry weight and were associated to soil moisture at times. Fruit composition was shown to vary within vineyard sites; however, spatial trends in general were not as temporally stable as vine water status or vine performance variables. This supports findings by Bramley (2005) who found that fruit quality indices at harvest were not as variable as yield variables. Temporal stability of certain variables such as monoterpenes was quite site specific. Yield was quite varied, especially in 2005 after a winter with significant cold injury in some of the vineyard sites. Therefore, as supported in the literature, cold injury can significantly impact the terroir effect. This is largely due to its impact on vine health and how winter injury leads to substantial vine to vine variation which in turn can impact vine performance and fruit quality. Therefore, these inconsistencies in some of the vineyards not only make it more difficult to study terroir but ultimately reduce wine quality and appropriate expression of the site influences.

Soil, vine water status, vine size and yield components. Generally, spatial relationships between vine water status, vine size, berry weight and yield were also stable from year to year. In terms of soil texture, higher soil moisture was generally found in areas of higher clay content. For the most part, these areas often had vines of higher water status but there may have been other interactive factors that possibly influenced vine water status other than just soil texture. Some inconsistencies between the different vineyards studied may have been a result in differences in rooting depth, soil depth, and gravel content as seen through soil pits or differences in drainage. Therefore, these factors cannot be ignored when looking at relationships between soil and vine water status. Research has generally found that vine water status has a large impact on the vegetative growth of the vine (Reynolds et al. 2006, Schultz and Matthews 1988). Some of the strongest relationships found were between vine water status and vine vigour. Leaf ψ and berry weights were lower in the hotter and drier vintages of 2005 and 2007. Generally, regions with lower water status were found to have smaller vine sizes and berry weights whereas areas of high water status had higher yields. Lower vine water status can help improve fruit quality since berry size is considered an important indication of grape and wine quality (Walker et al. 2005).

Effect of vine water status on fruit composition. Vine water status also had an impact on fruit composition in several vineyards but in some cases these were not consistent findings from year to year indicating random effects in terms of fruit composition for some variables. Generally, regions of high water status had lower soluble solids and higher titratable acidity likely due to a concentration effect of having smaller berries but it some cases higher sugars were found in regions of higher water status likely due to more sugar production from more leaf area and greater photosynthesis capability. In some vineyards, spatial distribution trends in berry monoterpene concentrations were temporally stable but only in a few cases for free volatile terpenes (FVT). For all vineyards studied, monoterpenes, both FVT and potentially volatile terpenes (PVT), were highest in the 2006 vintage. This suggests that periods of drought and subsequent low vine water status have negative effects on monoterpene concentrations. However, regions within vineyard sites with smaller berry weights seemed to have higher concentrations of FVT and PVT, reflecting the impact of skin-to-juice ratio. Therefore, it appears from these findings that either high or very low water status can be detrimental to concentration in monoterpenes. This supports research such as Peyrot des Gachons et al. (2005) in that mild water deficits can result in higher grape quality. While there were some good spatial relationships between vine water status and fruit composition, these relationships were not as strong as those between vine water status and other factors like berry weight and vine vigour. Many viticultural variables could be related to vine water status and vine size in many of the vineyard sites examined. Since water deficits in vines have been shown to reduce shoot growth (Kliewer et al. 1983) and canopy density (Smart 1974), low water status may have altered the canopy characteristics of the vine, ultimately leading to better leaf and fruit exposure to sunlight and improved fruit composition. Furthermore, many of the relationships between vine size and vine water status demonstrates that water status is greatly influenced by water supply together with evaporative demand of the canopy.

7.3.Objective II: Determining effects of soil and vine water status on sensory profiles of wines

Sorting tasks performed on wines from the 2005 and 2006 vintages indicated that wines of similar water status were shown to have similar sensory properties through sorting tasks. For many of the vineyards, the wine treatments were visibly separated into two groups based on vine water status. The separation of "low" and "high" water status wines was greater in the warmer and drier 2005 vintage than the cooler, wetter 2006 vintage. Descriptive analysis using a trained panel further indicated that water status had an effect on wine sensory profiles and also described these differences in terms of aroma and flavour attributes. Aroma and flavour attributes were significantly different between wines in both the 2005 and 2006 vintages. Comparing results from the sorting tasks and descriptive analysis lead to some interesting conclusions. In this study, similar findings were obtained with descriptive and sorting tasks, which is consistent with other research experiments (Preston et al. 2008). Yearly variations in some of the sensory attributes between high and low water status wines within a vineyard may be related to differences in the absolute water potential (ψ) values of the given year. Interestingly, there were common attributes that were found to be common in both vintages for wines of similar water status despite variations in the growing seasons.

Wines produced from vines with leaf ψ >-10 bars were found to have sensory profiles with the highest intensity ratings of *apple/pear*, *tropical fruit* and *vegetal* aromas and *citrus* flavours and the lowest *honey* and *petrol* aromas. On the contrary, wines that were made from vines <-13 bars were highest in *honey*, *petrol* and *tropical fruit* flavours and lowest in *baking spice*, *tropical fruit*, *vegetal*, *mineral/flint* aromas and *citrus* flavours. The sensory profiles of wines where the vines had some mild water deficit were highest in *honey*, *mineral/flint*, and *petrol* aromas and lowest in *vegetal* aroma.

The findings of this study support our hypothesis that vine water status has a substantial impact on the sensory properties of Riesling wines. It was demonstrated that variability of leaf water potential within vineyard sites can lead to wines that differ in their sensory profiles. These results support other studies that show the dependence on wine sensory attributes on vine water status such as those of Matthews et al. (1990) and Chapman et al. (2005) and advocates that vine water status is in fact a major determinant of the terroir effect. This supports other terroir-related studies which indicate that water availability and vine water status are important contributors to the terroir effect (Koundouras et al. 1999, Penavayre et al. 1991, Peyrot des Gachons et al. 2005, Seguin 1983, Van Leeuwen et al. 2009). This is one of the first studies in a New World wine region which supports this notion, which is very significant.

It does appear that there may be a quality threshold for optimum water status that could be potentially elucidated with consumer preference studies. Similar to the findings of Matthews et al. (1990), this research indicates that wines of different water status possess different sensory profiles without there being many differences in terms of basic fruit composition. This also supports other authors (Chapman et al. 2005) who state that soluble solids, titratable acidity and pH are generally arbitrary and not useful predictors of the sensory properties of a wine. Soluble solids are useful to predict potential ethanol in the final wine where titratable acidity and pH can be useful for winemaking considerations. However, aroma and flavours are not directly related to these variables.

This indicates that vine water status may have a strong influence on synthesis or degradation of aroma compounds or their precursors which is consequently impacting their sensory characteristics.

7.4. Objective III: Validation of sub-appellations

There were differences found in both the chemical composition and sensory characteristics of wines produced from different sub-appellations of the Niagara Peninsula. Through principal component analysis (PCA), specific sensory and chemical attributes were shown to be associated with clusters of different sub-appellations. Multivariate techniques such as PCA and partial least squares were useful to determine that many of the differences associated with the sensory profiles of the wines were related to soil texture, vine water status, vine size and yields. Finally, while each sub-appellation did have its unique sensory profile, wines were found to be generally grouped in terms of their regional designation ('Lakeshore', 'Bench' and 'Plains') within the Niagara Peninsula. Similar sensory profiles were found from these appellations which indicate that wines classified from their place of origin in the Niagara Peninsula should exhibit certain varietal characters despite different growing seasons assuming similar vinification methods were used. These wine typicities are important for a small, young, quality driven wine region in Canada. It allows for easier marketing and expansion domestically and internationally as the wines are distinct and recognizable. Further research can be done to explore other important cultivars as well as individual wine estates, to further understand terroir within the Niagara Peninsula and its sub-appellations.

7.5. Overall Conclusions

The findings of this research project support the notion of terroir as an interactive system related to soil, climate and the vine. Through the use of precision viticulture, within-site terroir-related effects could be studied while keeping mesoclimate and other climatic factors constant. Vineyards varied in terms of soil texture and composition. However, no real consistent relationships were found regarding many of these soil variables. Soil had some influence on vine growth and yield in select cases but its greatest impact was an indirect effect of water holding capacity and availability to the vine. This study demonstrated the complicated nature of soils and how useful conclusions cannot be made from one soil variable, but rather from multiple interactions. Some inconsistencies between the different vineyards studied may have been a result of differences in rooting depth, soil depth, and gravel content as seen through soil pits or differences in drainage. Therefore, these factors cannot be ignored when looking at relationships between soil and vine water status. The strongest relationships were those concerning soil moisture, vine water status, vine size, and berry weight. Differences in the sensory characteristic of wines could be related to vine water status. Vine water status was found to be a major contributor to the terroir effect as it had a major impact on vine size, berry weight and wine sensory characteristics. This is one of the most extensive studies elucidating the impact of vine water status on white wine sensory attributes and quality. Through sorting tasks and descriptive analysis vine water status had a profound impact on the sensory characteristics of Riesling wines. Consistent water status zones were found and these zones produced wines with different sensory profiles of which several attributes were similar across multiple vineyards across the Niagara Peninsula, Ontario. These differences were found without any vineyard manipulation or cultural practice imposed onto the vines, meaning that vine water status is a major factor of the terroir effect. Vines of different water status produced wines with distinct sensory profiles within vineyard sites but some attributes were found to be site or vintage specific. Since many attributes were similar across vineyards and vintages, examination of leaf water potential ranges of the wines gave a clearer explanation of the impact of water status on their sensory characteristics. Sensory profile differences were found with wines produced with grapes from vines that had no water deficit, mild water deficit and more severe water deficit. It does appear that there may be a quality threshold for optimum water status that could be potentially elucidated with consumer preference studies. Sensory attributes differed without there being differences in terms of basic fruit composition. Therefore, basic fruit composition does not appear to be a useful predictor for Riesling wine quality in the Niagara Peninsula. This is an important finding as many winemakers and growers rely on soluble solids as an indicator of quality and are paid higher prices according to sugar levels. It can be concluded that either severe water deficit or lack of water stress are not desirable for ultra-premium wine production with Riesling. Therefore, vine water status could be potentially a positive or negative determinant of terroir and is more than likely one of the largest factors impacting wine quality worldwide especially with climate change impacting many of the important wine regions.

Wines produced from 10 Riesling sub-appellations within the Niagara Peninsula differed in chemical and sensory composition. Each vineyard had a unique sensory profile but could be generally classified according to their broad geographic area. Many of the sensory differences could be related to soil texture, vine water status, and vine size through multivariate statistics.

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