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Spatial variability in Ontario Riesling Vineyards: I. Soil, vine water status and vine performance

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ABSTRACT

Aim: The major focus of this research was to explain the so-called terroir effects that impact grapevine yield components, berry composition, and wine varietal character. To elucidate potential contributors to the terroir effect, vine water status [midday leaf water potential (ψ)] was chosen as a major determinant. The hypothesis of this component of the study was that consistent leaf ψ zones could be identified within vineyard sites and that vine water status would play a major role in vine performance and yield components. Soil texture was anticipated to play a role indirectly through its water-holding capacity.

Methods and materials: To test this hypothesis, ten Riesling vineyards representative of each Vintners Quality Alliance of Ontario sub-appellation were selected within the Niagara Peninsula. These vineyards were delineated using global positioning systems and 75–80 sentinel vines were geo-referenced within a sampling grid for data collection. During the 2005–2007 growing seasons, leaf ψ measurements were collected bi-weekly from a subset of these sentinel vines. Data were collected on soil texture and composition, soil water content (SWC), vine performance and yield components. These variables were mapped using geographical information systems software and relationships between them were elucidated.

Results: Vineyards were variable in terms of soil texture, composition, nutrition, and moisture. However, in general, few consistent relationships with soil composition variables were found. As hypothesized, consistent leaf ψ zones were identified within vineyards in all three vintages. Some geospatial patterns and relationships were spatially and temporally stable within vineyards. In many cases, spatial distribution of leaf ψ was temporally stable within vineyards despite different weather conditions during each growing season. Spatial trends within vineyards for SWC and leaf ψ were temporally stable over the 3-year period for eight vineyards. Generally, spatial relationships between leaf ψ, SWC, vine size, berry weight and yield were also temporally stable. Some inconsistencies in spatial distribution of variables were attributable to winter injury.

Conclusions: Many viticultural variables such as leaf ψ, vine size, berry weight, and yield were spatially variable and, as hypothesized, consistent leaf ψ zones were identified within vineyards in three distinct vintages. Many geospatial patterns and relationships were determined and were temporally stable, and this temporal stability in these variables occurred despite different growing seasons. The strongest relationships were those concerning leaf ψ, SWC, vine size, and berry weight. No consistent relationships were found concerning soil composition. The most consistent soil variables that impacted vine performance and yield components were physical properties, particularly texture.

Significance and impact of the study: Soil had some indirect effects, but leaf ψ was more likely 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. Temporal stability is required for many practical geomatic applications to be initiated in vineyards, but it is also of importance to future research endeavors for this project as well as others.

KEYWORDS

Terroir, precision viticulture, vine water status, leaf water potential, soil water content, spatial and temporal variability

Supplementary data can be downloaded through: https://oeno-one.eu/article/view/2401

INTRODUCTION

Vine growth, yield, and fruit composition are highly influenced by water supply from the soil. Many variations in grape and wine quality can be attributed to soil-related differences from the so-called terroir effect. Traditional understanding is that soil primarily influences terroir; however, this has been controversial in research and is now regarded to be an amalgam of soil and environmental effects (van Leeuwen and Seguin, 1994; van Leeuwen and Seguin, 2006; van Leeuwen *et al.*, 2004; van Leeuwen, 2010). Some studies (Bader and Wahl, 1996; Noble, 1979; Wahl, 1988) found no consistent trends in sensory profiles of wine from different soil types while others (de Andres-de Prado *et al.*, 2007) indicated that soil effects did influence chemical and sensory properties in wine. The main influence soil has on wine sensory properties seems to be due to its physical properties, water-holding capacity, and drainage characteristics. It is difficult to define the best soil in terms of texture, soil depth or mineral content as high-quality wines are grown on diverse soils worldwide. Depending on the location, it is rarely possible to relate the quality of wines in terms of soil texture, soil type or minerals (Seguin, 1983; van Leeuwen *et al.*, 2004; van Leeuwen, 2010). In California, Noble (1979) evaluated the 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. Van Leeuwen *et al.* (2004) studied the impact of different soil textures and grape maturation of Bordeaux cultivars in France. Gravelly soils stopped shoot growth earlier in the growing season, titratable acidity values were low, soluble solids and anthocyanins were high, and berry size was small. Sandy soils produced 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 attributable to vine water status. Bader and Wahl (1996) used soils from different regions in Germany on one vineyard site to eliminate any climatic influences; they found that the soil effects on wine flavor were small and concluded that climate was more important than soil on wine sensory characteristics in a cool climate region but 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 Riesling 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 concentration. 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 high water-holding capacity, produced wines with lower color intensity and total phenols.

The effect of soil texture therefore seems 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. Variations in vine size and yield have been shown to be closely associated with variations in plant available water (Hall *et al.*, 2002; Lamb *et al.*, 2004; Cortell *et al.*, 2005). Seguin (Seguin, 1970; Seguin, 1975) first attempted to scientifically define the terroir effect through investigating chemical properties of soils in Bordeaux and its famous chateaux. Soil chemical composition did not have a specific influence on wine quality, however the soil's ability to regulate water supply to the vine via its physical properties was significant. 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) who demonstrated relationships between soil and wine sensory profiles using soil types from different sites within the Loire Valley.

Many soil effects on vine behavior are mediated through varying water content levels and their effects on leaf water potential (ψ) or stomatal conductance (Klepper, 1968; Seguin, 1983; Seguin, 1986; van Leeuwen and Seguin, 1994; van Leeuwen and Seguin, 2006; van Leeuwen *et al.*, 2004). Some studies indicate that plant water status is the means by which the terroir affects wine style and quality (Koundouras *et al.*, 1999; Choné *et al.*, 2001). In the Loire Valley, free-draining sandstone soils that provided water stress during fruit 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 accelerating budburst and increasing vine vigor (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 cultivar. They concluded that soil and climate effects were mediated through their influence on vine water status. In Ontario, low leaf ψ zones in Cabernet franc vineyards correlated spatially with anthocyanins and phenols and produced wines with more intense red and dark fruit aromas than those from high leaf ψ zones (Hakimi and Reynolds, 2010; Reynolds and Hakimi Rezaei, 2014c). Similar conclusions were reached for several Ontario Pinot noir vineyards (Ledderhof *et al.*, 2014). Zones in a Riesling vineyard with low leaf ψ likewise produced wines with more intense citrus characteristics that were attributable to higher monoterpene concentrations in the fruit (Marciniak *et al.*, 2013).

Vineyards have been shown to vary spatially in terms of soil, vine nutrition (Bramley, 2001; Davenport and Bramley, 2007; Reynolds and Hakimi Rezaei, 2014a), vegetative growth (Baldy *et al.*, 1996; Bramley *et al.*, 2011), yield, and fruit composition (Bramley, 2001; Reynolds *et al.*, 2007; Bramley *et al.*, 2011; Reynolds and Hakimi Rezaei, 2014b,c). 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; Reynolds and Hakimi Rezaei, 2014a–c) and variability (Bramley and Hamilton, 2004; Bramley, 2005) while keeping key environmental factors constant. Other studies that have utilized precision viticulture 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 higher percentage of clay contained 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 done to see how Niagara's unique terroir influences wine varietal character. Some studies performed in Ontario have indicated that vine size and soil texture were spatially associated with the fruit composition and sensory characteristics of wines (Hakimi and Reynolds, 2010; Marciniak *et al.*, 2013; Ledderhof *et al.*, 2014; Reynolds and Hakimi Rezaei, 2014a–c), but in some cases spatial patterns in yield, vine size, and berry composition were not temporally consistent (Reynolds *et al.*, 2007). Van Leeuwen (2010) states that soil and environmental conditions that moderate vine vigor through mild water deficit stress are important for high-quality wine production and influence the terroir effect. Therefore, this study attempted to further understand the basis of the terroir effect in Ontario vineyards. The specific objectives of this research were to demonstrate the putative influences of soil texture, soil water content, and vine water status on vine and fruit development within vineyard blocks, to delineate these terroir effects using geomatic technologies, and to elucidate relationships between soil and vine water status vs. vine performance. Data on berry composition are included in a companion article (Willwerth and Reynolds, 2020) and data describing sensory differences between wines from high and low water status zones in these vineyards were published in Willwerth et al. (2018).

MATERIALS AND METHODS

1. Site selection

In April 2005, ten Riesling vineyard sites were selected throughout the Niagara Peninsula in Ontario (Table 1). These sites were non-irrigated commercial vineyards and the vineyard blocks had heterogeneous soil types. Each site was also representative of a VQA sub-appellation. The details concerning soil and vineyard characteristics and vineyard management are given in Table 1. All vineyards 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 (72–80 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 GPS correction receiver with accuracy of 1–1.4 m was used in May 2005 to geo-reference each sentinel vine and to delineate the shape and size of each vineyard block.

It should be noted that ten vineyards were originally selected, and that data were collected from all ten, but due to disease and winter injury a full 3-year data set could only be compiled for seven vineyards.

2. Soil analysis

Once the sites and vineyard blocks were chosen, detailed soil mapping was carried out on a site-by-site basis. Soil samples (≈ 200 g) were collected using a 1-m soil probe from a subset of sentinel vines (every fourth vine; ≈20 vines/site) in June 2005. Soil analyses including pH, organic matter concentration (OM), elemental concentration,

TABLE 1. General features of Niagara Peninsula Riesling vineyards used for elucidation of terroir studies, 2005–2007.

Variable	Sites				
	Glenlake Vineyards (Lakelodge)	Lambert Farms	Reif Estate Winery	Chateau des Charmes	Paragon Estate Vineyards
Location	Niagara-on-the-Lake	Virgil	Virgil	St Davids	Jordan
VQA sub-appellation	Niagara Lakeshore	Four Mile Creek	Niagara River	St David's Bench	Creek Shores
Area of vineyard block (ha)	3.39 ha	0.81 ha	1.71 ha	1.68 ha	1.55 ha
Number of sentinel vines	74	75	74	75	74
Soil series [a]	Tavistock 15; c>B	Chinguacousy 19: B=B	Vineland 6; B=B	Toledo 7; B>B	Malton 1; B
Field capacity (%) [a]	39.3	38.0	38.0	43.3	43.0
Wilting point (%) [a]	8.7	13.3	6.0	16.3	18.3
Depth to base of B horizon (cm) [a]	64	52	83	59	45
Parent materials [a]	40–100cm reddish-hued loamy textures (c) over clay loam till (B)	Mainly reddish-hued clay loam till	Mainly reddish-hued lacustrine fine sandy loam & very fine sandy loam (B) 40–100cm reddish-hued loamy textures over clay loam till (B)	Mainly lacustrine silty clay	40–100 cm lacustrine silty clay over clay till loam
Soil drainage [a]	Imperfect	Imperfect to poor	Imperfect	Imperfect to poor	Poor
Clone	239 Gm	239 Gm	239 Gm	239 Gm	21B Weis
Rootstock	SO4	SO4	SO4	SO4	SO4
Vine age at initiation of trial (year planted)	9 years -1996	5 years -2000	22 years -1983	22 years -1983	7 years -1998
Vine spacing (m; row × vine)	2.5 × 1.5	2.74 × 1.22	3.0 × 1.3	2.5 × 0.9	2.3 × 1.2
Number of rows; vines per row	58 rows; 10,940 vines 42 @ 198v/r, 16 @ 164v/r	15 rows; 2400 vines 160 vines/row	14 rows; 4104 vines 12 @ 298 v/r, 2@ 264 v/r	47 rows; 7520 vines 160 vines/row	43 rows; 5800 vines 145 vines/row
Training system	Scott Henry	Scott Henry	4-arm Kniffin	Double Guyot	Double Guyot
Floor management	Clean cultivation	Alternate sod	Alternate sod	Clean cultivation	Alternate sod

Variable	Sites				
	Henry of Pelham	Myers Vineyard	Flat Rock Cellars (Nadja's Vineyard)	Cave Spring (Home Block)	Vailmont Vineyards (Vieni Estate)
Location	West St Catharines	Vineland	Jordan	Beamsville	Campden
VQA sub-appellation	Short Hills Bench	Lincoln Lakeshore	Twenty Mile Bench	Beamsville Bench	Vinemount Ridge
Area of vineyard block (ha)	1.57 ha	1.26 ha	0.92 ha	2.22 ha	1.26 ha
Number of sentinel vines	80	72	72	75	74
Soil series [a]	Beverly 8; c=B	Jeddo 1; B	Chinguacousy 11;C>B	Chinguacousy 14; c>B	Jeddo 1;B
Field capacity (%) [a]	No information	42.0	38.0	38.0	42.0
Wilting point (%) [a]	No information	15.3	13.3	13.3	15.3
Depth to base of B horizon (cm) [a]	45	44	52	52	44
Parent materials [a]	Mainly lacustrine silty clay	Mainly clay loam till	Mainly clay loam till (C) 40–100 cm lacustrine silty clay over clay loam till (B)	15–40 cm loamy textures over clay loam (c) Mainly clay loam till (B)	Mainly clay loam till
Soil drainage [a]	Imperfect to poor	Poor	Imperfect to poor	Imperfect to poor	Imperfect to poor
Clone	49 Colmar	21B Weis	21B Weis	21B Weis	21B Weis
Rootstock	3309	SO4	SO4	SO4	SO4
Vine age at initiation of trial (year planted)	7 years -1998	18 years -1987	5 years -2000	27 years -1978	7 years -1998
Vine spacing (m; row × vine)	2.5 × 1.2	3.0 × 1.5	2.3 × 1.2	2.5 × 1.5	2.5 × 1.2

[a]Kingston and Presant 1989.

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, consistent with Canadian Society of Soil Science (CSSS, 1993). Proportions (%) of sand, silt, and clay were also determined and the geospatial maps of each vineyard block were thereafter constructed from this information.

3. Soil water content and vine water status

Soil water content (SWC; %) and midday leaf ψ measurements were taken bi-weekly in each vineyard (every 10–14 days) from sentinel vines between the end of June and early September (beginning of fruit set to pre-harvest). SWC was measured using a portable time domain reflectometer (TDR) (Spectrum Technologies, Plainfield, IL) at a depth of 20 cm. On the same day, leaf ψ was determined using three leaves/vine on a subset of sentinel vines (≈ 18 vines) with a Scholander-type pressure chamber (Soil Moisture Corp., Santa Barbara, CA). Measurements were taken between 11.00 and 14.00 under full sun conditions consistent with Scholander (Scholander *et al.*, 1965).

4. Viticultural data collection

For each sentinel vine, data on the weight of cane prunings were collected annually as an estimate of vine vigor ("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 samples of 250 berries were taken for monoterpene concentration analyses. A large database was compiled annually on these sentinel vines for all vine performance and yield component variables.

5. 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). Interpolation maps were generated for all soil and viticulture variables using the inverse distance weighting interpolation to cartographically depict the spatial distribution of each variable within each vineyard. Soil water content and plant water status were mapped using seasonal means.

6. Statistical analysis

Linear and spatial correlations were determined between soil composition, soil texture, leaf ψ, SWC, vine performance and yield components for all vintages. Principal component analysis (PCA) was conducted using XLSTAT to elucidate relationships among soil variables, soil and vine 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. Spatial correlations were also determined using the statistical package provided by Vertical Mapper. Maps and the spatial correlations were used to evaluate temporal stability, examine spatial variation for selected variables in each season, and compare spatial relationships between correlated variables.

RESULTS

1. General comments

All results shown are from the 2005–2007 growing seasons. Three sites were omitted from this paper due to significant winter injury in 2004–2005 that substantially decreased yields [Lambert (LAM), Reif (REI), Vailmont (VLM)], and powdery mildew in 2006 (VLM). Figure 1 shows the meteorological data from the long-standing monitoring site in the Niagara Peninsula, Vineland Station, on temperature and rainfall events for each growing season. The growing seasons of 2005, 2006 and 2007 were not atypical for the Niagara Peninsula but varied substantially in terms of their mean reference evapotranspiration (ETref) values, which allowed their suitability for studying terroir effects, particularly those based upon vine water status. All vintages had dry periods during summer months but 2005 and 2007 had prolonged drought periods during most of the growing season (Grape Growers of Ontario, 2005; Grape Growers of Ontario 2006; Grape Growers of Ontario, 2007). The mean ETref values during the bloom to harvest period were 4.44 (2005), 2.26 (2006) and 5.39 (2007). Data collected from each vintage via GPS and GIS were depicted cartographically and analyzed to examine spatial trends and relationships. Soil texture maps from each vineyard block are depicted in Figure 2, while SWC, leaf ψ, vine size, yield, and berry weight maps from four example vineyard blocks

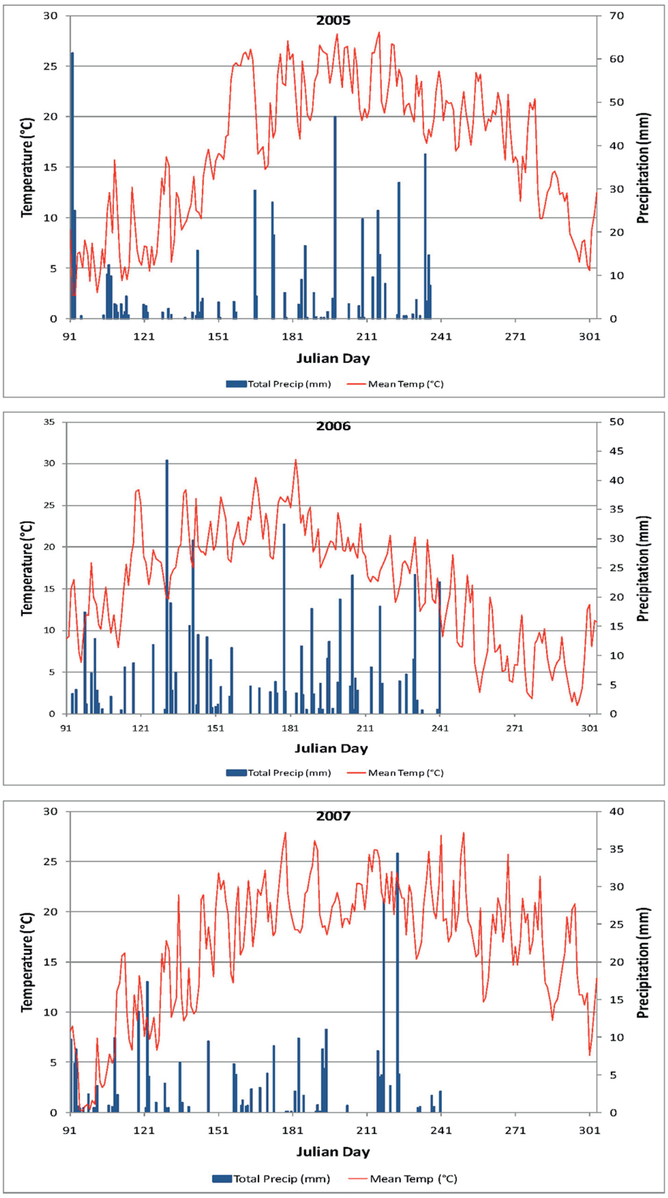

FIGURE 1. Climate data for 2005–2007, Vineland, ON.Location details: 43.150° north, 79.399° west, elevation: 127 m.

are depicted in Figures 3–10. All soil composition maps are found in Figures S1–S7. SWC, leaf ψ, vine size, yield, and berry weight maps from Paragon Vineyard (PAR), Henry of Pelham (HOP), and Flat Rock Cellars (FLR) are likewise located in Figures S8–S13.

2. Linear correlations

Correlations for each vineyard are depicted in separate Tables S1–S7. Soil variables (e.g. % sand and clay, pH, OM, CEC, BS, elements), SWC, and leaf ψ are presented as putative independent variables and vine size and yield components as dependent variables. As most soil variables are relatively stable, particularly in soils with high % clay, whereas variables such as yield components are inconsistent and subject to vicissitudes of annual weather patterns, it is not surprising that strong correlations were not abundant. Nonetheless, SWC and leaf ψ were frequently correlated to vine size and yield components.

Four vineyards were located in the eastern portion of the Niagara Peninsula (Niagara-on-the-Lake, St. Davids) and six in the western portion (St. Catharines, Jordon, Vineland, Beamsville). Among the east Niagara vineyards, at Glenlake Vineyards (GLK) the SWC was correlated with vine size in 2005 but was non-correlated in 2006 and 2007 (Table S1). Another positive correlation was soil potassium (K) vs. berry weight (2005). There were no relationships involving leaf ψ. Inverse correlations included the following: soil pH and calcium (Ca)(2007) and CEC (2005) vs. yield; soil phosphorus (P) (2005, 2006), soil K (2005) and Ca (2007) vs. cluster number; and soil Ca (2005), K (2006), and BS vs. berry weight (2005). At Chateau des Charmes (CDC), direct correlations included the following: SWC vs. yield (2005); leaf ψ vs. vine size (2005); SWC vs. berry weight (2007); and soil P (2005), OM (2006), and % sand (2007) vs. vine size (Table S2). Inverse correlations included the following: SWC vs. vine size (2007); leaf ψ vs. vine size (2005), yield (2006), and clusters (2007); % clay vs. vine size (2007); OM vs. yield (2005); and soil pH and Ca vs. berry weight (2006).

Among west Niagara vineyards, at PAR Vineyards, direct correlations included leaf ψ vs. berry weight (2005), and % sand and soil P vs. berry weight (2006; Table S3). Inverse correlations included the following: leaf ψ vs. clusters (2005) and berry weight (2006); soil P vs. vine size (2005); and OM (2005, 2006), soil P (2006), K (2005) and BS (2007) vs. berry weight. At HOP, no correlations were found between leaf ψ or SWC and yield in 2005 (Table S4). Positive correlations were as follows: SWC vs. yield, berry weight, and vine size (2007); and leaf ψ vs. berry weight (2007). The inverse correlation was soil P vs. yield (2006). At the Myers Vineyard (MYR), positive correlations were as follows: leaf ψ vs. vine size (2005) and berry weight (2007); SWC vs. berry weight (2006); % sand vs. vine size (2006, 2007); OM vs. vine size (2005–2007); soil pH vs. berry weight (2006); P vs. vine size (2006, 2007); Ca vs. berry weight (2006) and vine size (2005); and BS vs. berry weight (2006; Table S5). Inverse correlations included the following: SWC

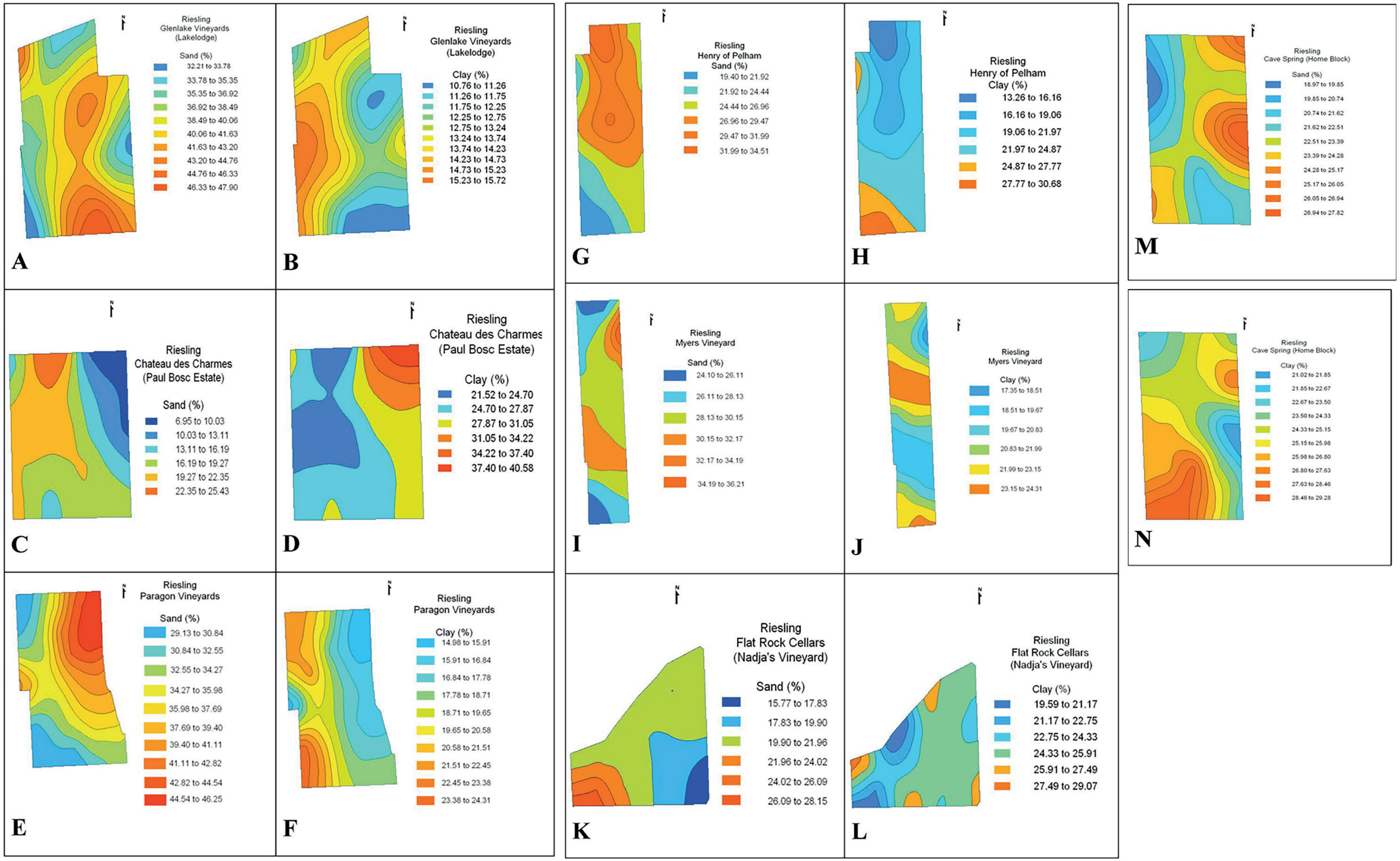

FIGURE 2. Spatial distribution of soil texture in 2005: A, C, E, G, I, K, M, sand (%); B, D, F, H, J, L, N, clay (%).
A,B, Glenlake Vineyard, Niagara-on-the-Lake, ON; C,D, Chateau des Charmes, St. Davids, ON; E,F, Paragon Vineyards, Jordan, ON; G,H, Henry of Pelham, St. Catharines, ON; I,J, Myers Vineyard, Vineland, ON; K,L, Flat Rock Cellars, Jordan, ON; M,N, Cave Spring Vineyards, Beamsville, ON.

vs. yield, clusters and vine size (2005); % clay vs. berry weight (2006); and OM vs. yield and clusters (2005). At FLR, positive correlations were as follows: SWC vs. yield (2005); P vs. yield (2007); and Mg vs. clusters (2006; Table S6). Inverse relationships were leaf ψ vs. vine size (2005) and yield (2006); and OM vs. yield (2005). At Cave Spring Cellars (CSC), positive correlations were as follows: SWC vs. berry weight (2005); OM (2005) and P (2006) vs. yield; and P and OM vs. berry weight (2005; Table S7). Inverse correlations were SWC vs. yield and clusters (2007); and soil Mg vs. yield (2007).

3. Spatial variability

3.1 Soil texture and composition

At the GLK site, there was some variation in soil texture (% sand and clay; Figure 2A,B) within the vineyard but not to the same extent as at other vineyards in the study. Soil pH was correlated with soil Ca content and the BS of the soil (Figure S1). OM and soil magnesium (Mg) were also correlated and spatially related. At CDC, the soils were quite variable in terms of texture (Figure 2C,D) and composition (Figure S2). Spatially, soil K and P varied tremendously and were very low in the northern section of the vineyard. Soil pH was spatially associated with Ca, CEC, and BS. OM was spatially related with P and K, and negatively correlated with Ca and BS. Soil Ca was negatively correlated with P and Mg but associated with CEC and BS. Soil K and P were spatially related.

At the PAR site, there was substantial variability in terms of soil texture (Figure 2E,F). The vineyard was likewise variable in terms of composition (Figure S3). Spatial relationships were found between soil texture and Mg, Ca and CEC. Spatially relationships were found between these variables and % clay and vice versa for % sand. Soil pH, Mg, Ca and CEC were all spatially related. OM, P and K were also associated with each other. The HOP vineyard was likewise quite variable in terms of soil texture (Figure

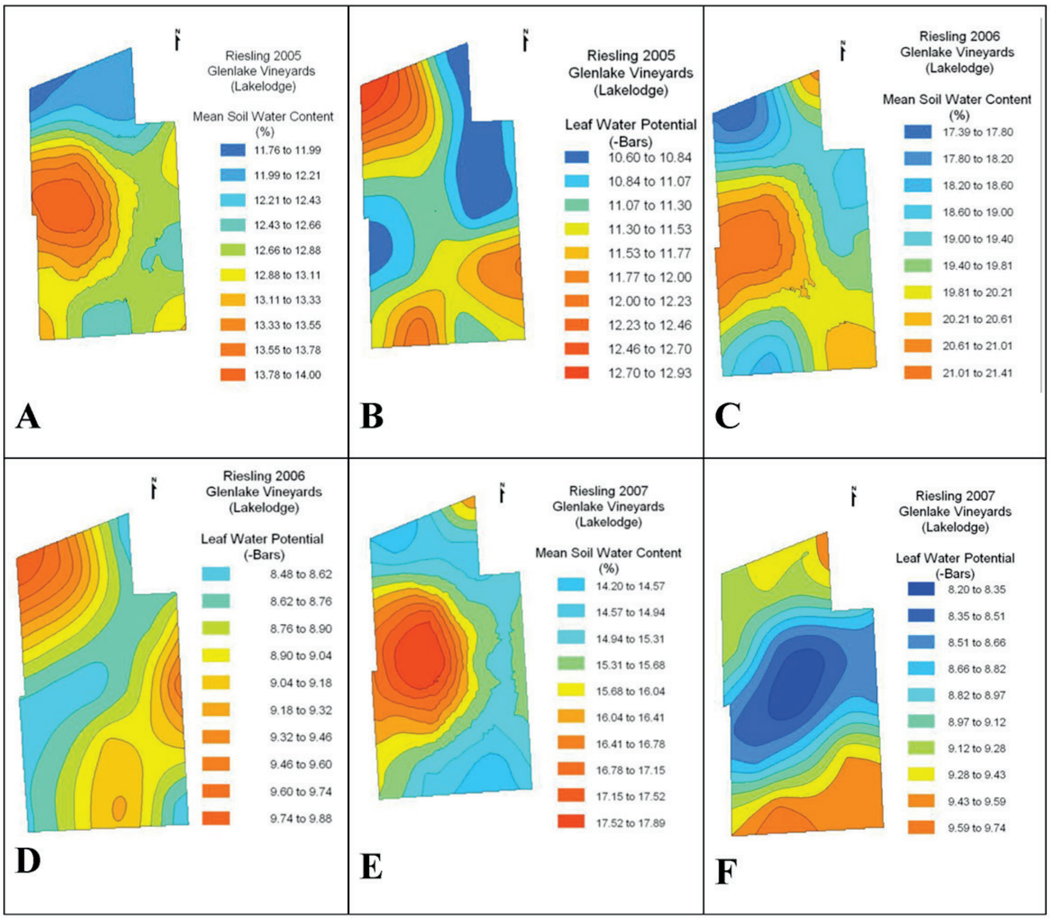

FIGURE 3. Spatial distribution of soil water content (%) and leaf water potential (1 MPa = 10 bars), Glenlake Vineyard, Niagara-on-the-Lake, ON.

Soil water content: A, 2005; C, 2006; E, 2007. Leaf water potential: B, 2005; D, 2006; F, 2007.

2G,H). Spatial relationships were found between soil pH, CEC and BS (Figure S4). For the MYR site, soil texture varied spatially within the block (Figure 2I,J). Spatial maps indicated that % sand and clay were inversely related, as expected. OM and CEC also had high variation. OM, soil K, P, and Ca plus BS were all positively associated (Figure S5). Soil Ca was also spatially related with soil pH and Mg, CEC, and Mg were also positively related. At FLR, soil texture (Figure 2K,L) varied within the vineyard site and was also spatially related with OM and K (Figure S6). Percent sand was positively associated with OM and K. OM was also related with P and K and inversely with BS. Soil pH was positively associated with Ca, CEC and BS but inversely related with K and Mg. Soil Mg and Ca were inversely related spatially. The CSC soils differed spatially within this vineyard in terms of texture (Figure 2M,N) and nutrients, especially Ca (Figure S7). Percent sand and clay were spatially related with OM. Percent clay was also associated with K, Ca and CEC. OM was related to K and inversely with Ca.

3.2 Soil water content and leaf ψ

Maps for four sites (GLK, CDC, MYR, CSC) are included in the main body of the paper (Figures 3–6) while the other three sites (PAR, HOP, FLR) are included in the Supplemental data (Figures S8–10). For the GLK site, consistent SWC (Figure 3A–C) and leaf ψ (Figure 3D–F) zones were found in 2005, 2006, and 2007 despite different weather conditions. Values were quite different in each season. For example, SWC was twice as high in 2006 and very few vines had leaf ψ readings < -1.0 MPa, whereas in 2005 all vines had readings below. The CDC vineyard was very consistent from year to year and spatial trends in many of the variables were temporally stable over the 3-year period of this study. Spatial trends in SWC were temporally consistent from 2006–07 with some differences observed in 2005 (Figure 4A-C). Very clear spatial trends in

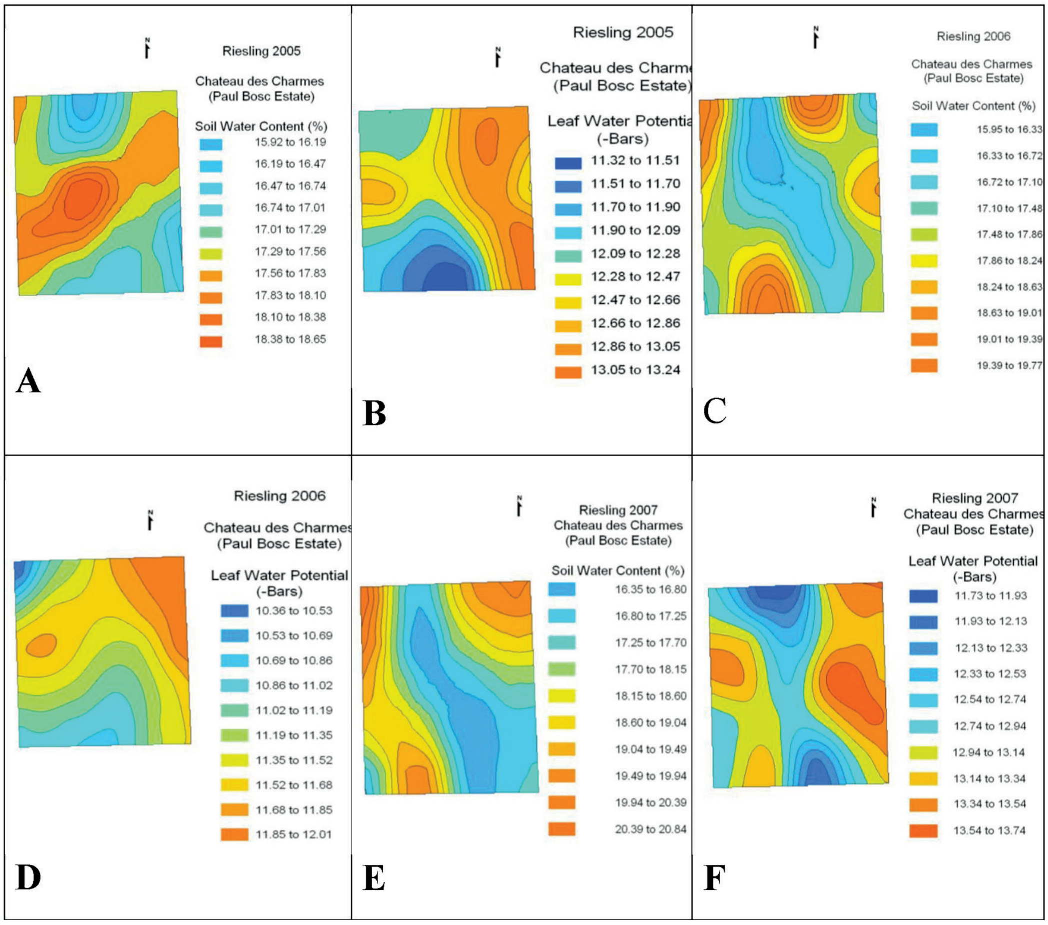

FIGURE 4. Spatial distribution of soil water content (%) and leaf water potential (1 MPa = 10 bars), Chateau des Charmes Vineyard, St. Davids, ON.

Soil water content: A, 2005; C, 2006; E, 2007. Leaf water potential: B, 2005; D, 2006; F, 2007.

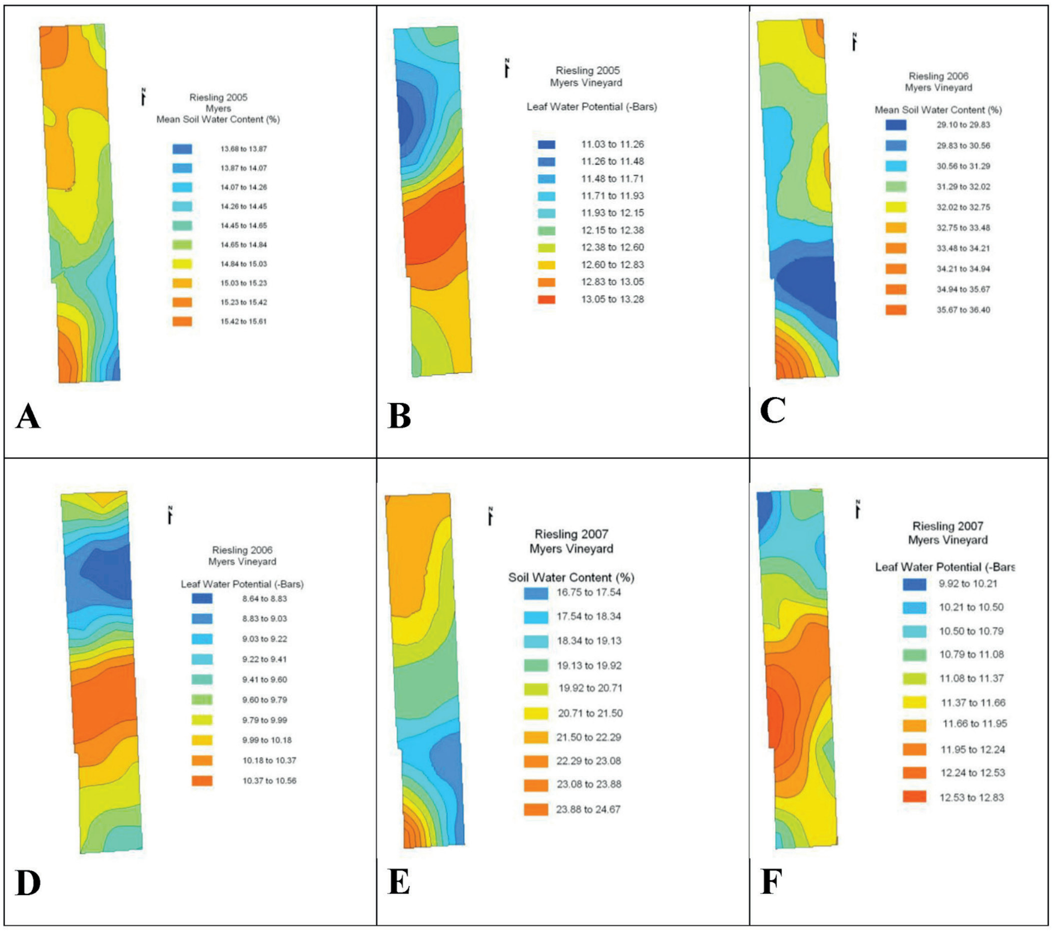

FIGURE 5. Spatial distribution of soil water content (%) and leaf water potential (1 MPa = 10 bars), Myers Vineyard, Vineland, ON..

Soil moisture: A, 2005; C, 2006; E, 2007. Leaf water potential: B, 2005; D, 2006; F, 2007

leaf ψ (Figure 4D-F) were observed. No clear relationship was found between leaf ψ and SWC at this site. This may be due to excessive soil tillage that could have interfered with proper contact of instrument probes with the soil. Furthermore, this was an established vineyard on heavy clay soil with a limited and shallow root system incapable of accessing water from deep in the soil profile; consequently, SWC was relatively high but leaf ψ was quite low in 2005 and 2007 (Figure 4).

The PAR site displayed spatial trends in SWC (Figure S8A–C) that were temporally stable from year to year. There were some consistent spatial trends in leaf ψ (Figure S8D–F) but no consistent relationship was observed between leaf ψ and SWC. There were also some strong relationships between OM and soil elemental concentrations and leaf ψ (Figure S3, Figure S8D–F). Sand-dominated zones were spatially associated with areas of lower leaf ψ while the opposite effect was found in clay-dominated zones (Figure 2E,F, Figure S8D–F). The HOP vineyard displayed some areas of temporal stability in terms of SWC (Figure S9A–C). This was also the case in terms of leaf ψ (Figure S9D–F). At the MYR site, SWC (Figure 5A–C) and leaf ψ (Figure 5D-F) were temporally stable and strong spatial relationships were found between these variables. Consistent leaf ψ zones were identified within vineyard sites in 2005–07. Spatial relationships in leaf ψ were temporally stable during each of the growing seasons. In the FLR vineyard, spatial trends in SWC were also temporally stable and strong relationships with leaf ψ were observed (Figure S10). Leaf ψ appeared to be temporally stable for the most part with consistent zones demonstrated each year (Figure S10D–F). At the CSC site, some areas of temporal stability were found in terms of SWC (Figure 6A–C) and leaf ψ (Figure 6D–F). There were also some relationships between these two variables. However, this site did not show the same magnitude of temporal stability for SWC and leaf ψ as other vineyards. The temporal

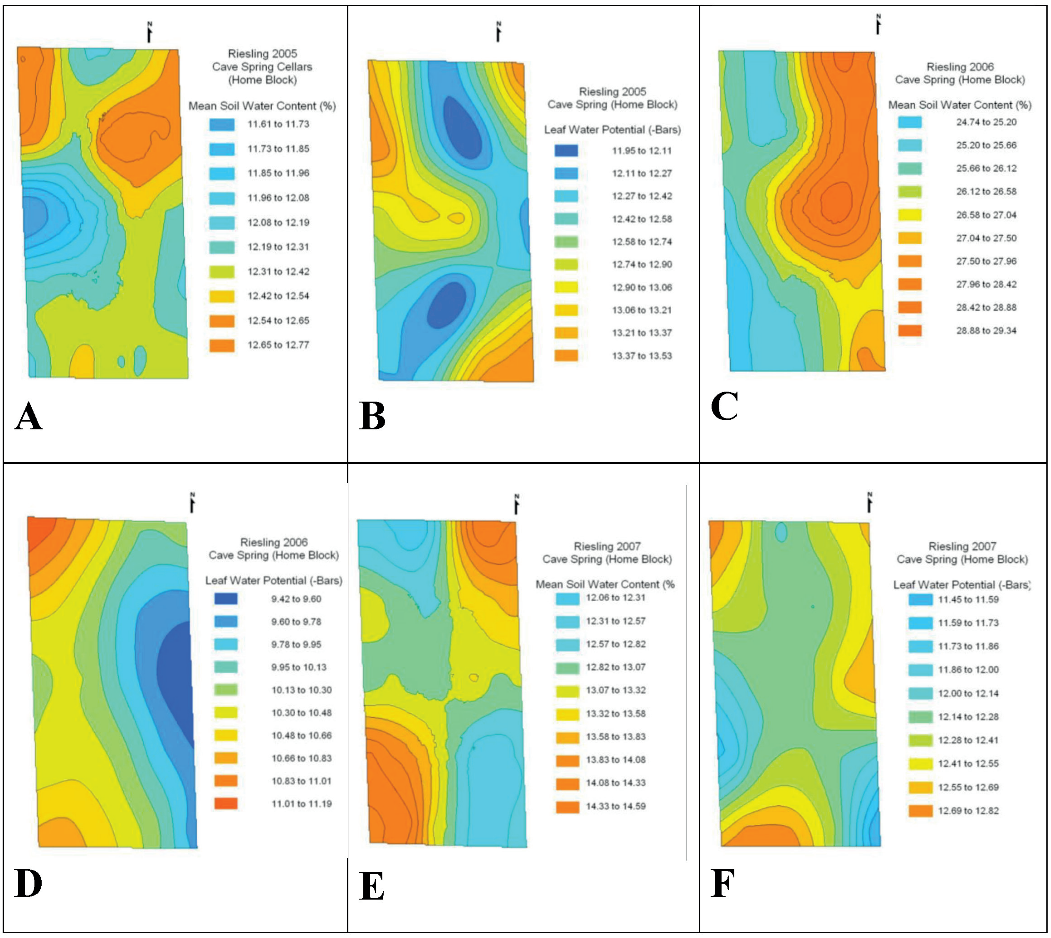

FIGURE 6. Spatial distribution of soil water content (%) and leaf water potential (1 MPa = 10 bars), Cave Spring Vineyard, Beamsville, ON.
Soil moisture: A, 2005; C, 2006; E, 2007. Leaf water potential: B, 2005; D, 2006; F, 2007

variation in spatial data may be a result of a change in soil hydrology due to extensive drainage tiling installed prior to the 2006 growing season. This not only would have impacted the drainage but also would have caused disturbance to the roots and rooting zone, all of which would impact water availability and uptake.

3.3 Vine size, yield and berry weight

Maps for four sites (GLK, CDC, MYR, CSC) are included in the main body of the paper (Figure 7–10) while the other three sites (PAR, HOP, FLR) are included in Supplemental data (Figure S11–13). At the GLK site, trends in vine size (Figure 7A–C) were temporally stable during the study. Strong relationships were found between leaf ψ, vine size, and SWC. Yield varied spatially and trends in yield were temporally stable from 2006–07 (Figure 7D–F). Yield varied substantially between 2005 and 2006/07 and this can be attributed to winter injury and crop loss caused by the severe 2004/05 winter. However, leaf ψ had some spatial relationships with yield. Spatial trends in berry weight were inconsistent across vintages but there were some relationships with leaf ψ (Figure 7G–I). For the CDC site, very clear spatial trends in vine size were observed (Figure 8A–C). Leaf ψ and vine size were spatially related, with areas of higher leaf ψ having higher vine size (Figure 4D–F and Figure 8A–C). There were some consistent trends in terms of yield and berry weight (Figure 8D–I). In general, areas of lower leaf ψ had lighter berry weights and lower yield. No spatial yield maps were created in 2006 due to the likelihood of inaccurate spatial trends associated with extensive fruit removal in sections of the vineyard because of sour rot infections.

At the PAR site, vine size and leaf ψ had some good relationships and spatial trends in vine size were consistent with the exception of 2005 where vine size was impacted by winter injury (Figure S11A–C). Yield also showed consistent spatial trends within this vineyard site and could

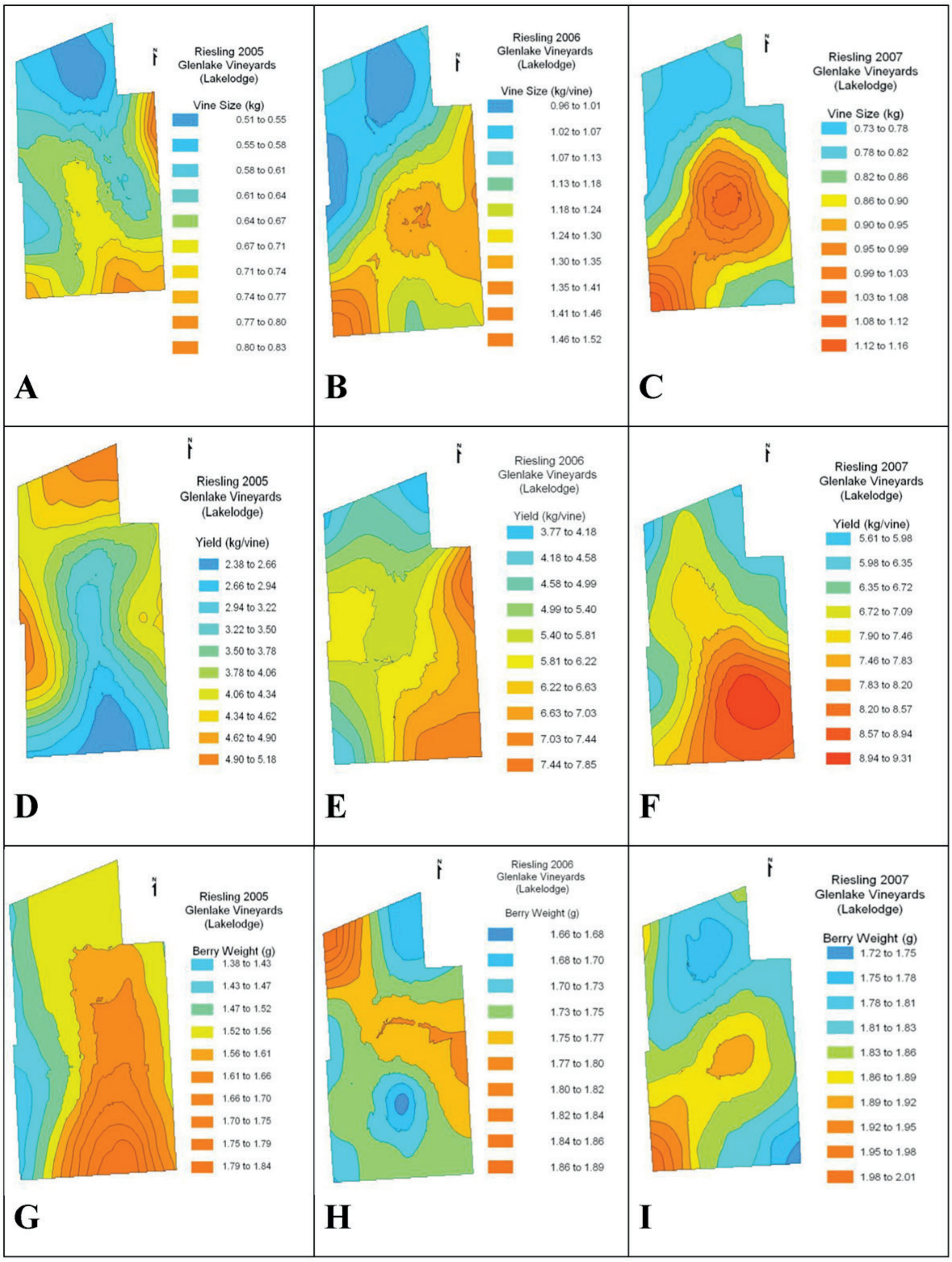

FIGURE 7. Spatial distribution of vine size (kg), yield per vine (kg) berry weight (g), Glenlake Vineyard, Niagara-on-the-Lake, ON.
Vine size: A, 2005; B, 2006; C, 2007. Yield per vine: D, 2005; E, 2006; F, 2007. Berry weight: G, 2005; H, 2006; I, 2007.

be associated with vine size and leaf ψ in many instances (Figure S11D–F). Similar to vine size, spatial variability was affected in 2005 by crop loss due to winter damage. Some consistent spatial trends in berry weight were observed in some areas with some association with leaf ψ (Figure S11G-I). For HOP, no vine size data were collected in 2005 but some areas of temporal stability were found in 2006–07 (Figure S12A–C). Some strong spatial relationships were observed between SWC, leaf ψ and vine size, especially in 2006–07 where vine size was smaller in areas of lower leaf ψ. Overall, lower vine size was observed in zones with lowest leaf ψ. In many other vineyards the opposite affect was found, where larger vines with more evaporative demand

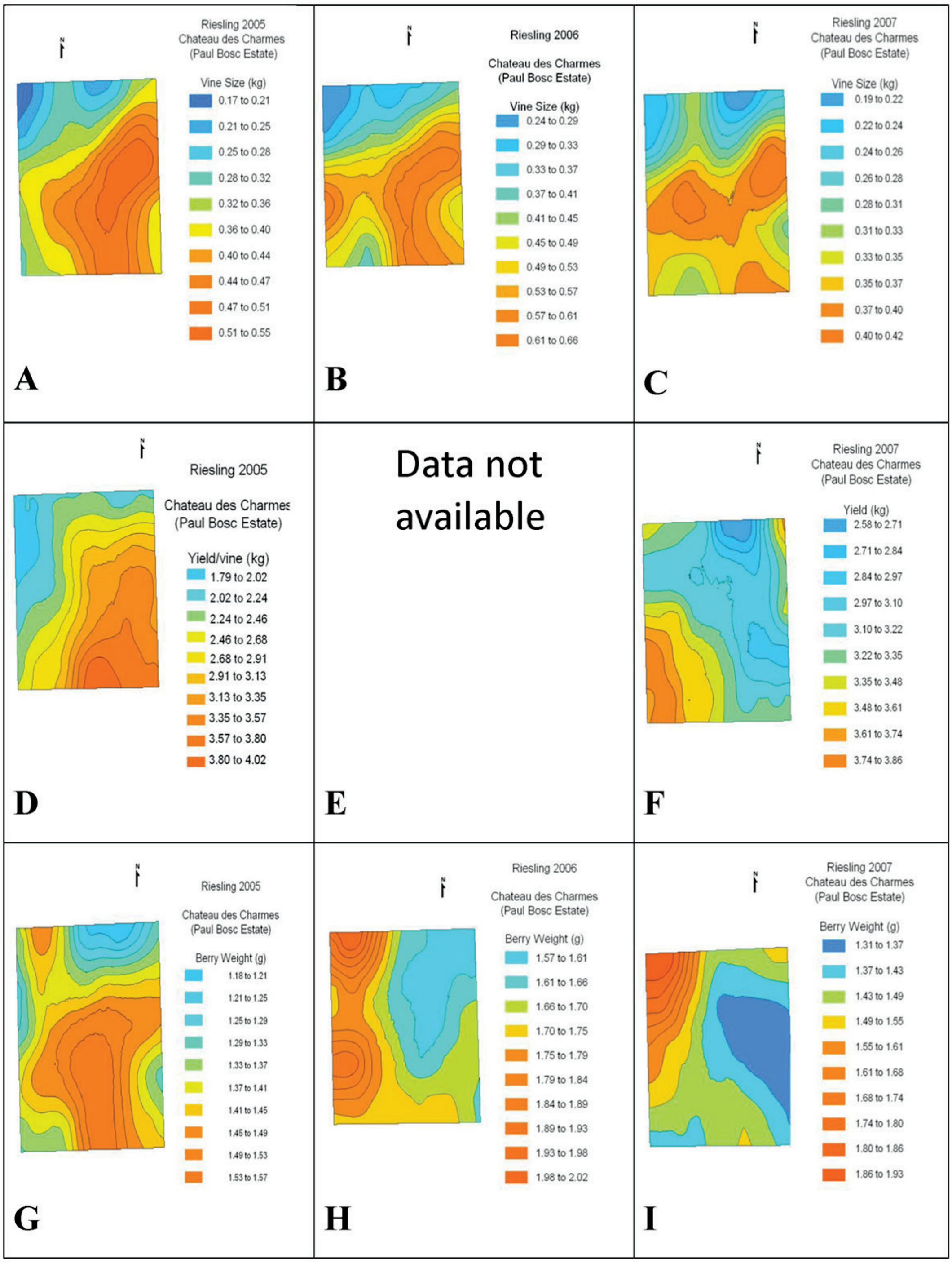

FIGURE 8. Spatial distribution of vine size (kg), yield per vine (kg) berry weight (g), Chateau des Charmes Vineyard, St. Davids, ON.
Vine size: A, 2005; B, 2006; C, 2007. Yield per vine: D, 2005; E, 2006; F, 2007. Berry weight: G, 2005; H, 2006; I, 2007.

were lower in leaf ψ. Yields varied spatially and some areas of temporal stability were observed but and some spatial relationships could be found with vine size and leaf ψ (Figure S12D–F). Yield was inversely correlated whereas vine size was positively related to water status. Spatial trends in berry weight were consistent from 2005–07 and some relationships were observed with SWC and leaf ψ (Figure S12G–I). Areas of higher leaf ψ and SWC were associated with areas of higher berry weights. At the MYR site, vine size spatial variability was temporally stable and strong relationships were found between these data and other variables (Figure 9A–C). Spatial patterns in yield components were likewise temporally stable with many highly significant correlations between

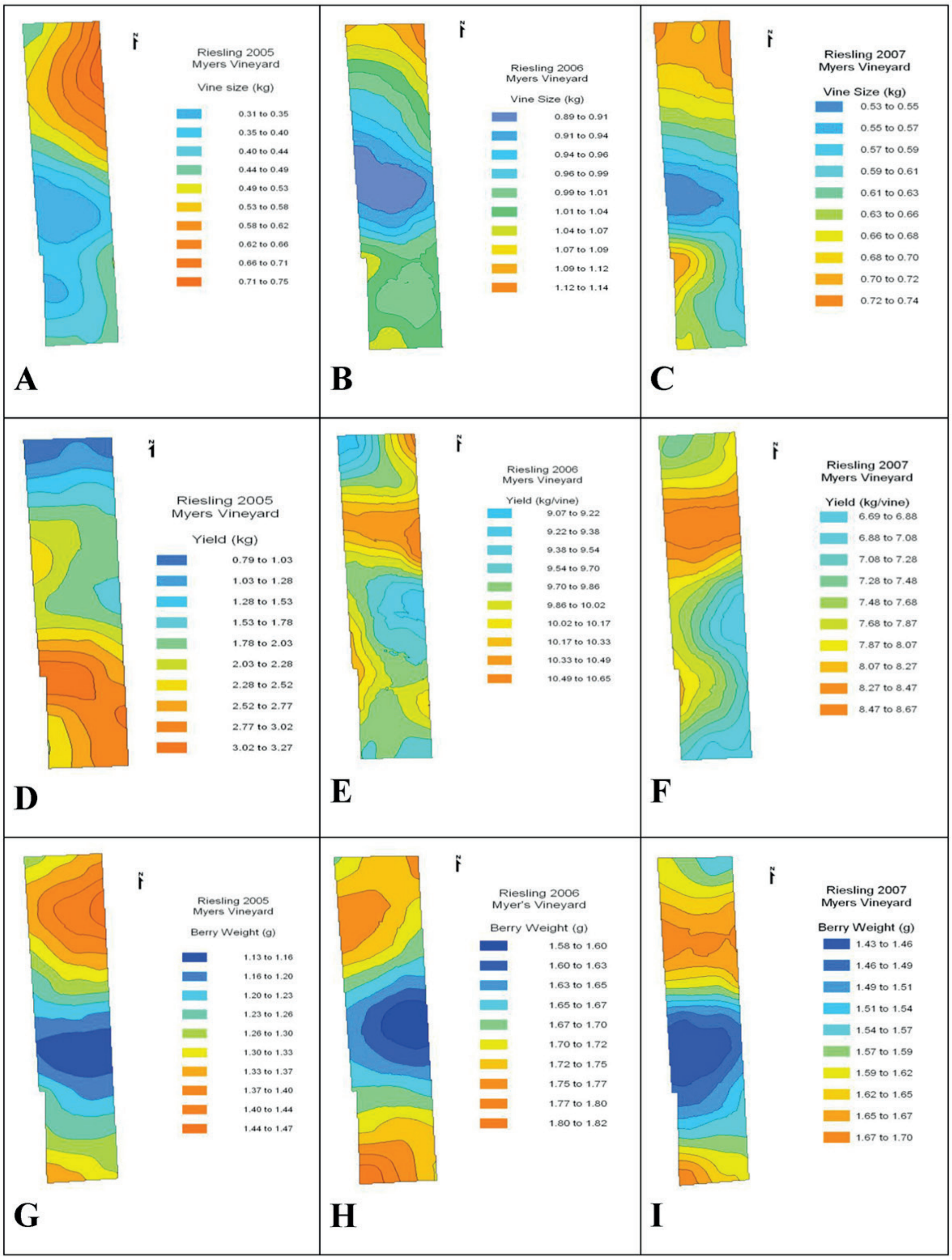

FIGURE 9. Spatial distribution of vine size (kg), yield per vine (kg) berry weight (g), Myers Vineyard, Vineland, ON.

Vine size: A, 2005; B, 2006; C, 2007. Yield per vine: D, 2005; E, 2006; F, 2007. Berry weight: G, 2005; H, 2006; I, 2007.

years. Higher yields were associated with areas of high leaf ψ and SWC (Figure 9D–F). Yield varied spatially but trends were temporally stable in 2006–07. Grapevine winter injury had a major impact on the spatial variation in yield in 2005, hence the substantial difference in spatial relationships compared to the other vintages. At FLR, vine size was the most temporally stable variable (Figure S13A–C). Yield spatial variability was observed but this was not consistent and appeared to be related to elevation and crop reductions due to winter injury than anything else (Figure S13D–F). Berry weight spatial trends were temporally stable from 2006–07 (Figure S13G–I).

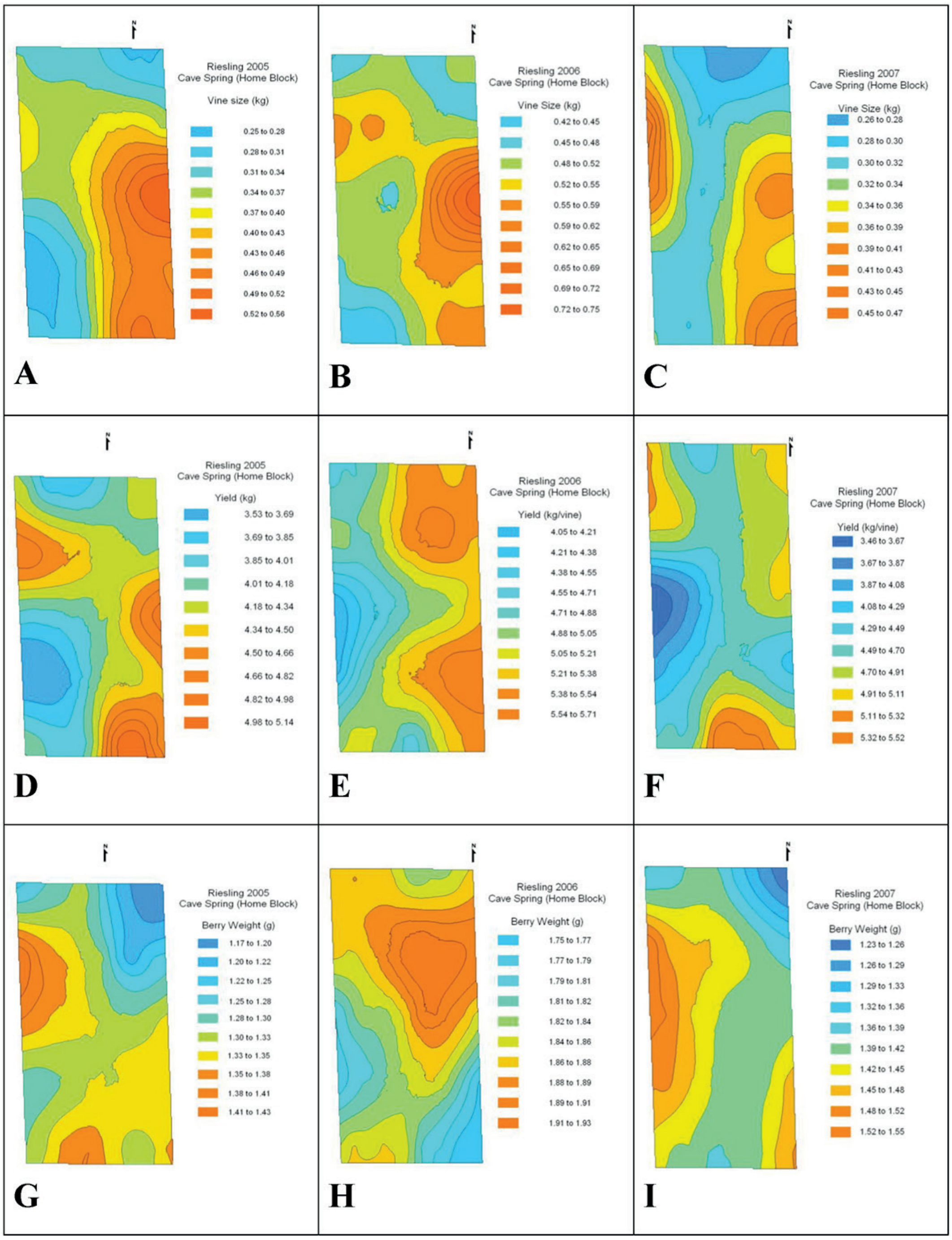

FIGURE 10. Spatial distribution of vine size (kg), yield per vine (kg) berry weight (g), Cave Spring Vineyard, Beamsville, ON.
Vine size: A, 2005; B, 2006; C, 2007. Yield per vine: D, 2005; E, 2006; F, 2007. Berry weight: G, 2005; H, 2006; I, 2007.

Strong relationships between berry weight, SWC and leaf ψ were found. Differences in berry weight spatial trends in 2005 can be associated with winter injury and differences in crop loads between vines with varying degrees of winter damage. At CSC, trends in vine size (Figure 10A–C) were temporally stable and consistent from 2005–07. Variability in yield (Figure 10D–F) was also consistent over the 3-yr period. In addition, there were some relationships between SWC, leaf ψ and berry weight (Figure 6, 10G–I).

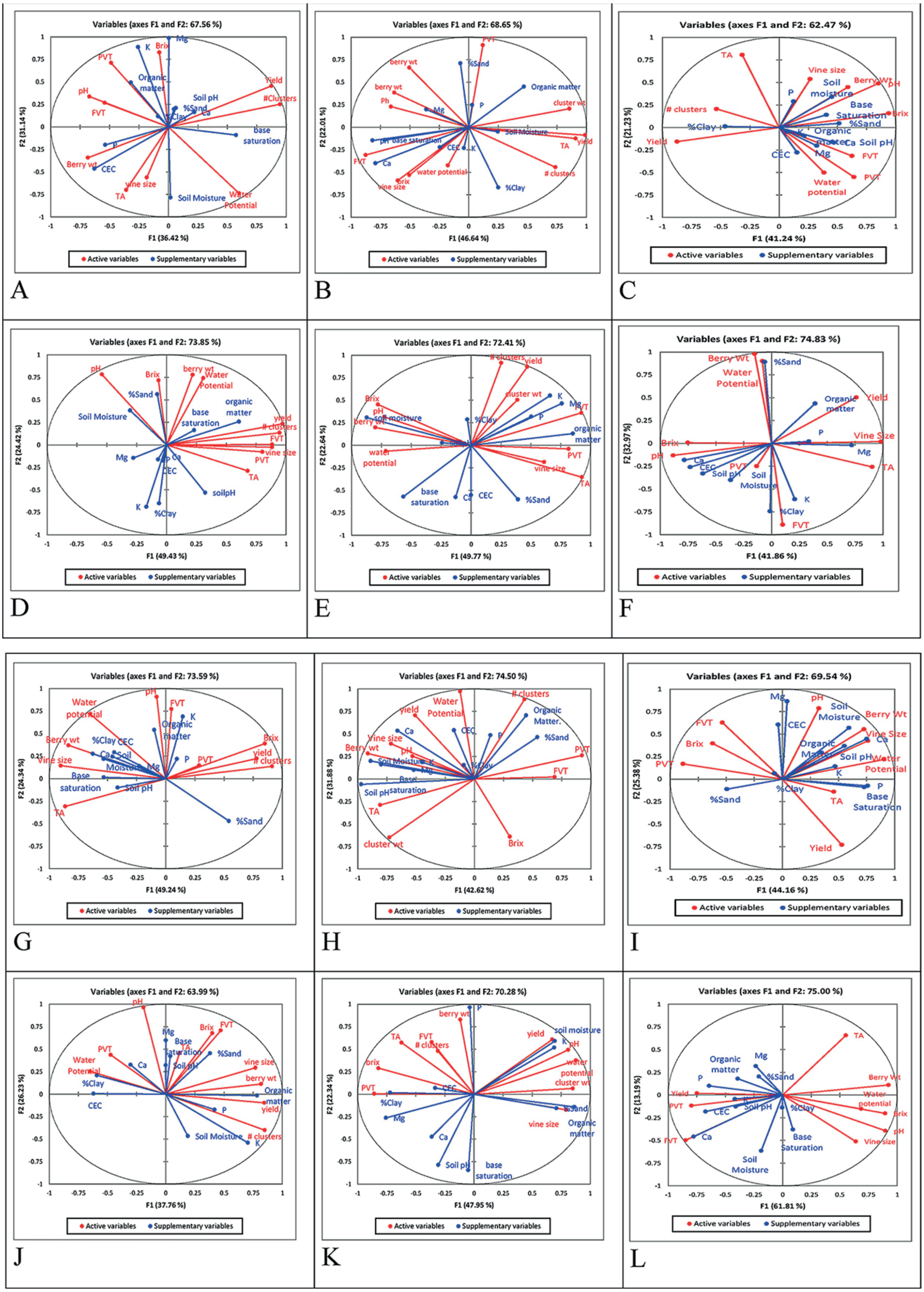

FIGURE 11. Principal components analysis of viticulture and soil variables, 2005–2007.
A–C: Glenlake Vineyards. D–F: Chateau des Charmes. G-I: Myers Vineyard. J–L: Cave Spring Vineyard.

4. Principal components analysis

Maps for four sites (GLK, CDC, MYR, CSC) are included in the main body of this paper (Figure 11) while the other three sites (PAR, HOP, FLR) are included in Supplemental data (Figure S14). In the GLK site in 2005, leaf ψ and SWC were correlated, as were vine size, berry weight and CEC (Figure 11A–C). In 2006, SWC and leaf ψ were not correlated but leaf ψ, vine size, Ca, and CEC were. SWC was highly correlated with yield and % clay whereas berry weight was correlated with % sand. In 2007, SWC, vine size, berry weight and % sand were all highly correlated and inversely correlated with yield. At CDC in all three vintages, leaf ψ was highly positively correlated with berry weight (Figure 11D–F). Vine size demonstrated positive correlations with OM as did yield in all vintages.

At the PAR site in 2005, SWC and leaf ψ were positively correlated with % clay, OM and yield, whereas berry weight, vine size and % sand were negatively correlated (Figure S14A–C). In 2006 and 2007 leaf ψ was positively correlated with vine size, berry weight and negatively correlated with OM, P and K. At HOP there were no clear positive correlations between SWC and leaf ψ (Figure S14D–F). Leaf ψ was positively correlated with berry weight in 2005 and 2006 but non-correlated in 2007. Yield was correlated with SWC in 2005 and CEC and Ca in 2005 and 2006. Vine size was correlated with OM in 2006 and 2007, with % sand in the wetter 2006 vintage, and with % clay in the drier 2007 vintage. For all three vintages at the MYR vineyard, leaf ψ, vine size, berry weight, SWC, CEC and Ca were all positively correlated with each other while being inversely correlated with % sand in the drier 2005 and 2007 vintages (Figure 11G–I). These relationships were also found with respect to yield in 2006 but not in 2005 or 2007. At FLR, SWC and leaf ψ were non-correlated in 2005 (Figure S14G–I). However, leaf ψ was positively correlated with K and % sand. In 2006 and 2007, leaf ψ and SWC were closely related, showing a higher positive correlation. Vine size was correlated with SWC in 2005–2006 but not in 2007. Leaf ψ was negatively correlated with yield but SWC was more correlated with yield. In 2005 and 2006 berry weight was correlated with % clay. It is conceivable that in a dry year, such as 2005, leaf ψ would be more negative in zones with highest % sand due to less water-holding capacity but in a wetter year more water would be available in zones with high % sand. For CSC in 2005, leaf ψ was highly correlated with % clay, CEC, and Ca, while being non-correlated with SWC (Figure 11J); it was also inversely correlated with yield, berry weight, and vine size. SWC, however, was highly correlated with % sand, vine size, yield, and P. In 2006, leaf ψ and SWC were both highly correlated as well as yield, vine size, yield, OM, and K (Figure 11K). Leaf ψ, vine size, and berry weight were highly correlated but inversely related to yield in 2007 (Figure 11L).

DISCUSSION

1. Spatial trends and relationships within vineyard sites

1.1 Soil texture and composition

Soil texture varied in all vineyard sites (Figure 2). The degree to which they varied in terms of % sand or clay ranged was due to the geological history of the Niagara Peninsula. The soils of the region are very diverse and complex due to several historical interglacial and glacial events and are therefore quite heterogeneous (Haynes, 2000). This variation in soil is consistent with 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 were inversely correlated. Soils higher in % sand were also higher in OM at a number of sites (e.g. CSC, FLR). Similar to the findings for texture, soil composition also varied within vineyard sites, and 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. Differences in pH within vineyards ranged from 0.5–1.5 indicating spatial variation. Soil Ca had a positive impact on soil pH in most of 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. Soil pH and BS were positively correlated but the relationship is not always linear (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, leading to K deficiencies in the vine due to this antagonistic effect. Some sites varied little spatially in K (GLK) whereas other vineyards had an almost six-fold difference (CDC). This was also found with K in other vineyards showing small spatial variations while others had large variations. The other macronutrients also varied spatially and to different extents. This provides justification for zone-specific nutrient management in Ontario vineyards, as some areas within sites were below adequate levels for grapevine nutritional requirements, where other regions were more than adequate (Ontario Ministry of Agriculture Food and Rural Affairs, 2007). In some vineyards, low vine size was found in K-deficient zones. Cellular K is crucial in plant biochemical processes, including carbohydrate production, protein synthesis, solute transport, and maintenance of plant water status. Lack of K reduces shoot growth, vine vigor, berry set and crop yields (Keller, 2016).

While individual vineyards exhibited wide spatial variation for many soil composition variables, no clear trends were found on their putative 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 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 that if the area zone of a vineyard displayed low concentrations of certain macronutrients then vine size and yield suffered in those instances. Petiole analysis indicating the nutrient status of the vine would perhaps have given clearer explanation of the impact of soil composition on vine performance or yield components but others have indicated that it is difficult to make implications about the impact of nutrients on the terroir effect (Reynolds and de Savigny, 2016; Reynolds *et al.*, 2007). Therefore, although vineyards varied in terms of soil composition, no obvious deficiencies were present, hence there was no clear impact of soil composition on vine performance or yield components.

In general, soil texture was related to SWC, and areas of higher % clay had higher SWC as expected. For the most part, these areas often had vines of higher 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 the result of differences in rooting depth, soil depth (Table 1), 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 and vine water status.

1.2 Soil and vine water status

The values of SWC varied based on the climatic conditions experience throughout each of the three growing seasons. As the sites were non-irrigated, the percentage of moisture in the soil can be attributed to rainfall and the physical properties of the soil. SWC values within sites were highest in 2006 followed by 2007 and were lowest in 2005. These trends were similar in terms of leaf ψ, which varied within all the vineyards studied. Leaf ψ was lowest in 2005 and highest in 2006. In white wine cultivars, leaf ψ values < -1.0 MPa are normally indicative of mild-to-moderate water stress, whereas values < -1.2 MPa might indicate more severe stress (van Leeuwen 2010). In each vintage there were areas within vineyards that had ψ values < -1.0 MPa, indicating some water stress evident (van Leeuwen, 2010). In every vineyard studied, consistent areas of differing leaf ψ values could be identified, and therefore distinct regions were delineated that could be categorized as “high” and “low” water status. This is consistent with 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 and 2007 vintages, the “low” water status regions consisted of vines experiencing moderate to high water stress (< -1.2 MPa). SWC varied spatially within all vineyard sites examined. Spatial trends within vineyards for vine leaf ψ were temporally stable over a 3-year period for eight vineyards. Spatial trends in SWC were found not to be as temporally stable as ψ but were still evident in many areas of these eight vineyards. Variation in SWC 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 (Table 1). Furthermore, some of the inconsistencies from year to year in terms of SWC could possibly be related to variables such as human disturbances of the soil (i.e. tilling, grape hoeing) leading to poor instrument contact with the soil.

2. Vine size and yield components

2.1 Vine size

Vine size was measured to determine the vegetative growth during the growing season as an estimate of “vine vigor”. There was spatial variation in vine size within vineyards and between many of the vineyards. This supports many other studies demonstrating that vineyards vary in terms of vine size (Bramley, 2001; Cortell *et al.*, 2007; 2008; Zerihun *et al.*, 2010; Reynolds and Hakimi Rezaei, 2014a) including Riesling vineyards within the Niagara Peninsula (Reynolds *et al.*, 2007; Marciniak *et al.*, 2014). Spatial trends for vine size were also stable within eight vineyard sites. Vine size values were much larger in 2006 than in 2007 or 2005. This is reflective of the 2006 growing season, when there was more rainfall during canopy development resulting in more available water from higher moisture levels. Water availability influences shoot growth. As SWC increases, vigor is stimulated and these can lead to higher vine size (Smart and Coombe, 1983). Not only was there higher vine size in vineyards in years characterized by more rainfall, but in all vintages, areas within vineyards with more SWC 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 size. Some of the strongest relationships in this study were between leaf ψ and vine size. Vine water status has a large impact on the vegetative growth of the vine (Reynolds *et al.*, 2006; Schultz and Matthews, 1988). Soil texture also had some influence on vine size: % percent sand was correlated with larger vines in some vintages and associated with each other and yields in many cases through PCA. Across all vineyards the strongest relationship was that vine components were positively correlated when sand >30% and clay content <20%. This is consistent with other studies in cool climate regions who found that soils higher in % sand had higher values of yield components (clusters/vine, yields) (Reynolds *et al.*, 2007; Reynolds and Hakimi Rezaei, 2014a,b).

2.2 Berry weight

Many of the same vineyard sites that demonstrated temporal stability for vine size and leaf ψ also had consistent spatial trends from year to year in regards to berry weight. Leaf ψ and berry weights were lower in the hotter and drier vintages of 2005 and 2007. SWC was also closely associated with berry weights all vineyards but varied slightly with different vintages. Generally, zones with lower leaf ψ had smaller vine sizes and berry weights whereas areas of high leaf ψ had higher berry weights. This supports findings by Cortell *et al.* (2008) who found that berry weights generally increased with vine size. 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 have been shown to lower berry size, especially if it occurs during the first phase of rapid berry expansion (Williams, 2000; Dry *et al.*, 2001). However any plant water deficit almost always limits berry size (Matthews and Anderson, 1988; Roby *et al.*, 2004). Lower water status reduced photosynthesis, resulting in less water and photosynthates being translocated to the berries (Carbonneau *et al.*, 1983). Lower vine water status can help improve fruit quality as berry size is considered an important indication of grape and wine quality (Walker *et al.*, 2005).

2.3 Yield

Yields varied within vineyards both spatially and temporally. Many precision agriculture studies have shown that yield can vary tremendously and with some temporally stability (Bramley and Hamilton, 2003, 2004). In this study, spatial trends in terms of yield were not as stable as leaf ψ, vine size, or berry weight but some trends were still found in several sites. Nonetheless, in five vineyard locations, trends in yields were temporally stable. Temporal inconsistency in spatial variability of yield was observed previously in the Niagara Peninsula where the authors found that yield spatial distribution varied temporally over four vintages in a Riesling vineyard (Reynolds *et al.*, 2007). In Australia, yields were found to be highly variable within vineyards but spatial patterns were temporally stable over a 3-year period (Bramley and Hamilton, 2004). The occasional lack of temporal stability in yield in Ontario vineyards can be explained by individual vine variations in fruit set, vine health, and frequent winter injury. Unlike warmer areas such as Australia, bud and/or vine cold injury can be the result of cold winters. This can lead to vines having similar growth but can differ in crop size. Therefore, yield estimations using precision viticulture techniques may be faced with substantial challenges in marginal grape production areas due to this annual variation.

Areas in vineyards with higher yields were often associated with vines of higher leaf ψ and SWC. Vineyards varied in yield, which was also due to vintage differences. Yields were highest in 2006, lower in 2007, and lowest in 2005. 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 from vines during the winter of 2004/2005. Some of the yield variation within certain vineyard sites, in general, in 2005 was directly related to widespread primary bud or woody tissue damage that occurred across Ontario, resulting in a lack of fruit production and reduced yields. Some vineyards (LAM, REI, VLM) in the study were dramatically impacted by this catastrophic event. Grape tonnage across the Niagara Peninsula in 2005 was reduced by two-thirds of an average harvest (Grape Growers of Ontario, 2006). In every vintage most of the variation in yield can be attributed to vine-to-vine differences in respect to the number of clusters on the vine as opposed to berry weight differences (Keller, 2016). However, there were still some strong relationships found between leaf ψ, SWC, vine size and yield. Particularly, larger vines on moister soils were associated with higher leaf ψ values and yields in many vineyards. Sandy soils often also had higher yields, which has been shown in other studies (Reynolds *et al.*, 2007).

3. Principal components analysis

PCA was used to help interpret the large data sets collected annually for each vineyard site. While some relationships are 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 the variables were further supported through PCA. In some cases, no relationships were found but there were few circumstances that led to contrary findings to spatial analysis. Aside from common soil associations (i.e. soil Ca and 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 SWC. Generally, more moisture was associated with clay-dominated areas of the vineyard while being lower in sand-dominated areas. Soil texture was associated with leaf ψ in some instances. Texture of the soil and OM demonstrated associations with vine size and yield. OM can impact vine size 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 (Seguin, 1970; Carey *et al.*, 2008). Variation in SWC due to water-holding capacity has been shown to strongly influence vine performance within vineyards (Hall *et al.*, 2002; Cortell *et al.*, 2005). In Germany, Wahl (1988) found that soil type did not impact many factors but yields varied between soils, which is in agreement with this study where sandier soils generally had larger yields than soils with higher % clay. It is also consistent with others, who found that soils higher in % sand had higher yield components (Reynolds *et al.*, 2007; Reynolds and Hakimi Rezaei, 2014a,b). In general, the most consistent findings through PCA were relationships concerning leaf ψ, vine size, and berry weight. In many of the vineyards, across all vintages leaf ψ, vine size and berry weight were closely associated. Reduction in vegetative growth is the most frequent consequence of water deficits (Kliewer *et al.*, 1983; Reynolds *et al.*, 2006; Schultz and Matthews, 1988; Williams, 2000). Similarly, water deficits typically reduce yields. The sensitivity to water deficits depends on phenological stage, so it is possible that some inconsistencies between vineyards or vintages could be related to water deficit timing; e.g., limited water supply during berry cell expansion can restrict berry size in both warm arid regions (Roby *et al.*, 2004) as well as cooler regions with frequent growing season precipitation (Reynolds and Hakimi Rezaei, 2014b; Balint and Reynolds, 2017). SWC was also associated with many of vine size and berry weight in some vineyards across the vintages but leaf ψ 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 through solely soil-based measurements, which are commonly recommended for monitoring water, and deciding upon when to irrigate horticultural crops in Ontario (Shortt and Verhallen, 2011).

CONCLUSIONS

Vineyards within the Niagara Peninsula were variable in terms of soil texture, composition, nutrition, and moisture. Furthermore, many viticulture variables such as leaf ψ, vine size, berry weight, and yield were spatially variable, and as hypothesized, consistent leaf ψ zones were identified within vineyards in three distinct vintages. Many geospatial patterns and relationships were determined and were temporally stable, and this temporal stability in these variables occurred despite different growing seasons. Generally, the strongest relationships were those concerning leaf ψ, SWC, vine size, and berry weight. No consistent relationships were found concerning soil composition. The most consistent soil variables that impacted vine performance and yield components were physical properties, particularly texture when sand content was high. Therefore, soil had some indirect effects, but leaf ψ was more likely 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. Temporal stability is required for many practical geomatic applications to be initiated in Niagara vineyards, but it is also of importance to future research endeavors for this project as well as others.

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