Journal of Applied Horticulture, 16(3): 167-192, 2014

Spatial variability in Ontario Cabernet franc vineyards III. Relationships among berry composition variables and soil and vine water status

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Abstract

The possible influence of vine water status upon berry composition was studied in ten commercial vineyard blocks of *Vitis vinifera* L. cv. Cabernet franc in the Niagara Peninsula, Ontario from 2005 to 2007. Soil texture, soil chemical composition, soil moisture and leaf water potential (ψ), as an indicator of vine water status, were determined on ≈ 80 sentinel vines in each vineyard. In each block, water status zones were identified in GIS-generated maps using leaf ψ and soil moisture measurements. Areas of low soil and vine water status were positively correlated linearly and spatially with areas of high Brix, color intensity, anthocyanins and phenols, and were negatively correlated with titratable acidity. In most vineyards, areas of high and low color intensity were positively correlated linearly and spatially with areas of high and low anthocyanins and phenols. Temporal stability was also noticeable for several variables including soil moisture, yield, berry weight, Brix, anthocyanins, and phenols. These data suggest that low soil moisture and low vine water status zones in vineyards are related to corresponding areas of superior berry composition. These data further suggest that precision viticulture techniques may be utilized in this region to delineate vineyard sub-zones of differing quality levels.

Key words: Global positioning systems, geographic information systems, precision viticulture, soil moisture, leaf water potential

Introduction

The first portion of this study addressed the spatial relationships between soil moisture, vine water status [based on leaf water potential (ψ)], and soil texture and composition (Reynolds and Hakimi Rezaei, 2014a), while a second paper focused upon those relationships between soil and vine water status, vine vigor, and yield components (Reynolds and Hakimi Rezaei, 2014b). In this third and final segment of the study, relationships between soil and vine water status and berry composition are addressed.

Geomatic technologies have been used in agriculture to enhance the precision in practices such as seeding, fertilization, lime application, spraying, and others (Robert, 2001). These management practices can be applied by utilizing yield monitors on harvesting equipment, global positioning systems (GPS) to continuously monitor position, and geographical information systems (GIS) to create yield maps by data interpolation. This process, frequently referred to as “precision agriculture”, has been widely applied to annual crops. Woody perennial crops such as grapes and tree fruits offer many added challenges: the trees or vines are not removed annually, costs of variable rate technology may not be justified, and spatial variability in yield or other variables may not be temporally stable due to fluctuating weather conditions, winter injury, bienniality, and other factors. Although traditional approaches to precision agriculture may not find application in vineyards, there are ways whereby geomatic technologies can be utilized. Collection of data, including yield, weight of cane prunings, fruit composition, and vine water status may demonstrate spatial correlations between those variables that might be used for economic gain. For example, low vigor zones delineated by GPS/GIS in a California Zinfandel vineyard were correlated with low vine water status and many berry composition metrics such as soluble solids and berry color (Greenspan and O’Donnell, 2001). Ultimately, this process can lead to the designation of zones of potentially superior wine quality. Proffitt *et al.* (2006) described a process that involves remote sensing, yield monitoring, creating yield and berry composition maps, soil sensing and subsequent map creation, and identifying zones for which differential management might be beneficial. These procedures might involve selective mechanical harvesting of regions of differing potential quality by controlling disposition of fruit into two or more containers.

The ability for geomatics to demonstrate spatial variability, spatial correlation, and temporal stability for a multitude of vineyard variables also allows it to be a powerful tool in understanding factors that determine berry composition and wine quality, *i.e.* the terroir effect. For example, low water status was shown to correlate with high monoterpene concentrations in Riesling in Ontario, as well as specific aroma and flavor descriptors in the wines (Willwerth *et al.*, 2010). Zones of low water status were also associated with desirable aroma and flavor descriptors in several Cabernet franc vineyards (Hakimi Rezaei and Reynolds, 2010a,b). The overall objective of this study was to test the hypothesis that soil and vine water status would be significant contributors to the terroir effect, insofar as they would be related spatially to a multitude of soil factors, yield, and fruit composition. The first portion of this study addressed spatial relationships between soil moisture, vine water status (based on leaf ψ), and soil texture and composition. The second focused upon those relationships between soil and vine water status, vine vigor, and yield components. In this final portion of the study, relationships between soil and vine water status and berry composition are addressed.

Materials and methods

Sites. Ten commercial vineyard blocks of Cabernet franc were selected for investigation, one each in the 10 sub-appellations of the Niagara Peninsula (Hakimi Rezaei and Reynolds, 2010a). Features of each vineyard including VQA sub appellation (Vintners' Quality Alliance; http://www.vqaontario.com/appellations), area of vineyard, number of sentinel vines, soil series, parental material, soil drainage, clone, rootstock, year of planting, vine spacing, and floor management were recorded for each vineyard (Hakimi Rezaei and Reynolds, 2010a,b). Area of vineyard blocks varied from 0.6 ha (Reif) to 2.6 ha (Hernder). Vine spacing varied from 2.0 m X 1.25 m (vine X row) at Vieni Estate to 3.0 m X 1.3 m at Reif. Training system was Guyot, pendelbogen, or Scott Henry. Floor management in some sites was clean cultivation while in others it was sod maintained in alternate rows. Rootstocks were 101-14, 3309 or SO4 and vine age varied from 7 to 18 years at the initiation of the trial. No changes in management were made at these sites during the study period.

GPS and GIS; water status categories. Details of the geomatic tools used in this project are described in Hakimi Rezaei and Reynolds (2010a,b). A Raven Invicta 115 GPS Receiver Raven Industries (Sioux Falls, SD, USA) (with 1.0 to 1.4 m accuracy) was used to delineate the shape of each vineyard block as well as to geolocate each sentinel vine. Using GIS programs MapInfo and Vertical Mapper (Northwood GeoScience, Ottawa, ON, Canada) water status zones were mapped based on vine leaf ψ values. Spatial correlation analysis was performed in Vertical Mapper, which gives an R value. All R-values > 0.8 were assumed to be particularly meaningful with respect to defining spatial correlations and temporal stability. For two independent variables sampled at a density of 80 observations per site (e.g. yield components, berry composition variables, vine size), R values of 0.330 and 0.269 were equivalent to p values of < 0.01 and 0.05, respectively; for a density of 20 observations per site (e.g. soil composition, leaf ψ), R values of 0.606 and 0.509 were equal to p values of < 0.01 and 0.05, respectively (Steel and Torrie, 1960).

Each vineyard block was separated into three zones of high, medium, and low water status (HWS, MWS, LWS, respectively). Grapes from each of these water status zones were harvested separately based on the leaf ψ map of each vineyard block in 2005 through 2007 and were used to make wine in 2005 and 2006 (for details on winemaking and sensory evaluation see Hakimi Rezaei and Reynolds, 2010a,b). Therefore, from each vineyard block, three wines (HWS, MWS and LWS) were made with three replicates of each in both years. These water status zones were also designated as treatment categories and compared with respect to yield components, vine size, and berry, must, and wine composition.

Soil sampling and composition: Soil samples were collected from every fourth vine with an auger from within the row, 40 to 50 cm away from the trunk. Soil was taken from a 0 to 45 cm depth and in total ≈ 350 g of a homogenized sample was taken. Depending on the area of each vineyard block, 15 to 20 soil samples were taken. Soil samples were analyzed using standard procedures [Canadian Society of Soil Science (CSSS), 1993].

Soil and vine water status: Soil moisture data (percent water by volume) were taken bi-weekly on five separate dates between late June and early September in the 2005 to 2007 growing seasons. Soil moisture was measured at each sentinel vine by time domain reflectometry using a Fieldscout TDR-300 soil moisture probe (Spectrum Technologies Inc., East Plainfield, IL, USA). Mean soil moisture for each sentinel vine was calculated from the five separate readings. Midday leaf ψ was determined on cloudless days between 1100h and 1600h for fully exposed, mature leaves of similar physiological stage that showed no evidence of damage. Overall, there were five sampling dates during the growing season; bi-weekly between late June and early September 2005 to 2007 for each site.

Berry analysis for Brix, titratable acidity and pH: Measurements were made during 2005 to 2007 seasons on 72 to 80 sentinel vines in each vineyard block. Prior to harvest in September/October, 100-berry samples were collected randomly from each experimental vine and stored at -25˚C until analysis. All berry samples and fruit were collected one day before commercial harvest. These samples were used to determine berry weight, soluble solids (Brix), pH, titratable acidity (TA), color intensity ($A_{420} + A_{520}$), hue (A_{420}/A_{520}), total anthocyanins, and total phenols. Frozen berry samples were thawed, weighed and placed in 250-mL beakers and then heated to 80˚C in a water bath (Fisher Scientific Isotemp 228, Fisher Scientific, Mississauga, ON, Canada) and held for one hour to dissolve precipitated tartrates. Samples were cooled to room temperature and juiced in an Omega 500 fruit juicer. The resulting juice was centrifuged at 4500 rpm for 10 minutes in an IEC Centra CL2 centrifuge (International Equipment Company, Needham Heights, MA, USA) to remove debris. The supernatant was retained for analysis of pH via an Accumet pH meter (model 25; Denver Instrument Company, Denver, CO, USA), TA with a PC-Titrate autotitrator (Man-Tech Associates, Guelph, ON, Canada) by titration with 0.1 *N* NaOH to an end point of pH 8.2, and Brix using an Abbé refractometer (model 10450; American Optical, Buffalo, NY, USA). The remaining juice was centrifuged with Model B-20 centrifuge (International Equipment Co. Needham Heights, MA, USA) at 12000 g for 10 minutes and stored at -25˚C for further analysis for color intensity, anthocyanins and phenols. Wine and must samples were analyzed using the aforementioned methods, except soluble solids which was not performed on wine samples.

Berry analysis for color intensity, anthocyanins, and phenols: After thawing to room temperature for several hours, color, anthocyanins and phenols were determined in berry samples. Color intensity and hue were determined using a modified method provided by Mazza *et al.* (1999). Color intensity and hue were calculated from absorbance values measured at 420 nm and 520 nm on an Ultrospec 2100 Pro UV/VIS spectrophotometer (Biochrom Ltd., Cambridge, UK). Undiluted juice, must and wine samples were measured in a 1-mm quartz cuvette and values were adjusted to 10-mm equivalents. The blank for juice and must samples was prepared using 120 g/L fructose, 120 g/L fructose and 10 g/L tartaric acid in distilled water as a zero absorbance. The blank for wine samples was a solution of 12% v/v ethanol and 10 g/L tartaric acid. Total anthocyanin concentrations in berries were determined using a modified version of the Fuleki and Francis (1968) pH shift method. The pH 1.0 and pH 4.5 buffer solutions were respectively prepared using 0.2M KCl with 0.2M HCl and 1M sodium acetate with 1M HCl in distilled water. One mL of each sample was diluted by 9 mL of both buffers separately and held in the dark for one hour. Subsequently, absorbance was measured at 520 nm in a 10-mm cuvette using a Biochrom Ultrospec 2100 Pro UV/Vis spectrometer against zero reference of appropriate buffer solution. The total anthocyanins concentration was calculated with the following formula:

Total anthocyanins (mg/L) = A_{520} (pH 1.0 - pH 4.5) X 255.75

Total phenols were estimated by colorimetric measurement of blue color caused by the redox reaction between reductant phenols and oxidant Folin-Ciocalteu reagent (VWR, West Chester, PA, USA) in an alkaline solution of sodium carbonate using the method of Singleton and Rossi (1965). Berry juice, must and wine samples were diluted in ratio of 1:9 with distilled water and one mL of diluted sample (or gallic acid standard) was added to a 100-mL volumetric flask containing ≈ 60 mL of distilled water, followed by 5 mL of Folin-Ciocalteu reagent and 15 mL of saturated 20% sodium carbonate, and distilled water to volume. Calibration standards were prepared by adding 0, 1, 2, 3, 5 and 10 mL of 5 g/L gallic acid stock solution to 100-mL volumetric flacks and diluting with distilled water to obtain 0, 50, 100, 150, 250, and 500 mg/L standards, which were used to create a standard curve. The calibration curve was used to calculate the total phenols in berry, must and wine samples, which were expressed in mg/L gallic acid equivalents.

Winemaking- must and wine analysis: Details of winemaking procedures are described in Hakimi Rezaei and Reynolds (2010a). All wines were produced by one winemaker according to standard procedures from the 2005 and 2006 vintages at Brock University's winery facilities. Wines were not made from the Morrison site in 2005 due to severe vine damage in the 2004-05 winter, nor could they be made from the Harbour and Vieni sites in 2006 due to severe powdery mildew. Each 20-L fermentation replicate from each site X water status category was based upon a sub-section of each of the three water status categories within each vineyard block. Must samples (250 mL) were collected from each site X water status category replicate and stored at -25 °C until analysis. Musts were analyzed for Brix, TA, pH, A_{420}, A_{520}, total anthocyanins, and total phenols in the same manner as the berries. Wine samples from each site X water status category fermentation replicate were likewise analyzed for TA, pH, A_{420}, A_{520}, total anthocyanins, and total phenols in the same manner as the berries and musts. Ethanol was determined using an Agilent 6890 series GC system gas chromatograph (Agilent, Wilmington, DE, USA) equipped with an Omegawax 250 fused silica (30.0 m x 250.00 µm x 0.25 µm) column. Wine samples or standards were diluted 1:10 with 2% 1-butanol as an internal standard.

Data analysis: Within each vineyard block, high, medium, and low water status zones were identified accordingly based on GIS- generated leaf ψ maps, and fruit were harvested separately from each zone for winemaking (Hakimi Rezaei and Reynolds, 2010a,b). Analysis of variance of berry composition was performed using the SAS statistical package version 8 (SAS Institute, Cary, NC, USA). The General Linear Models procedure (PROC GLM) was used. Duncan's multiple range test was used to separate the means for berry, must and wine composition data within each vineyard block, in accordance with the aforementioned HWS, MWS, and LWS categories. Correlation analysis was performed for each vineyard block as well as across the blocks for each year. Also, musts and wines from the MWS were compared with each other across sites to test the site effect. Principal component analysis (PCA) was also performed on the entire field-based data set (soil moisture, leaf ψ, yield components, vine size, berry composition) using XLSTAT 2008.

Results

Seasonal weather data for 2005-2007: The three seasons differed substantially with respect to growing degree days (GDD; base 10 °C) and precipitation. The sites also varied in GDD, with the 2005-07 means ranging from 1495 GDD (Buis, Niagara Lakeshore sub-appellation) to 1578 GDD (Harbour Estates, Creek Shores sub-appellation). The 2005 season was warmer than average with GDD averaging 1582 across the region. Precipitation in 2005 (426 mm; April to October) was close to average, but the period between May and late July was dry. The 2006 season was cool overall (1430 GDD) with mean precipitation of 472 mm that was evenly distributed throughout the growing season. Mean daily temperatures were below average throughout July and August. The 2007 season was drier than the preceding two years, with precipitation averaging 227 mm across the region, and GDD of 1583. Mean daily temperatures were > 20 °C throughout much of September.

Impact of vine water status on fruit composition

2005*:* Vine water status had limited impact on most berry composition variables in 2005, and for some variables, the putative impacts of vine water status were not entirely consistent (Tables 1, 2). Vine water status nonetheless had noteworthy effects on Brix values at four sites. At three sites (Hernder, George and HOP), higher Brix values were observed in the LWS categories, while at the Reif site, Brix was higher in the HWS category. Niagara-on-the-Lake sites were uniformly characterized by higher TA in the HWS category. Berry pH was affected at three sites; at the Château des Charmes (CDC) and HOP sites, higher pH was observed in the LWS category, while at the Reif site, pH was higher in the HWS category. Hue was increased at the CDC, George, and HOP sites in the LWS categories. Lower color intensity was observed at the George site in the LWS category. Higher anthocyanins were produced in the LWS category at the Buis and HOP sites; phenols were higher in the HWS category at the Harbour and George sites and lower at the HOP site.

2006. Vine water status had limited impact on most berry composition variables in 2006, and the apparent impacts of vine water status were not entirely consistent for many variables (Tables 1, 2). Higher Brix values were observed in the LWS category at the CDC and Harbour sites while at the Buis site, Brix was higher in the HWS category. TA was lower in the LWS category at the Buis and Harbour sites and higher at the Cave Spring site. Berry pH was lower at the Hernder site and higher at the Buis site in the HWS category. Areas of LWS had higher hue values at the Hernder site and lower values at the George site. Color intensity was higher in the HWS category at three sites (Hernder, Reif, Cave Spring), and lower at the Harbour site. Berry anthocyanins were only affected at the Hernder site in which low

Table 1. Impact of vine water status on berry composition of Cabernet franc in the Niagara Peninsula, ON, 2005-2007: Brix, titratable acidity, and pH. LWS, MWS, HWS: low, medium and high water status, respectively

Vineyard location	Soluble solids (Brix)				Titratable acidity (g/L)				pH			
	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.
2005												
Buis	21.2	20.9	20.7[b]	ns	8.1b	8.5b	8.9a	*[a]	3.50	3.48	3.47	ns
Ch des Charmes	23.3	23.1	22.9	ns	7.8b	8.2b	8.6a	*	3.58a	3.60a	3.55b	*
Hernder	21.0a	21.0a	20.2b	*	6.8b	7.3ab	8.0a	*	3.52	3.52	3.56	ns
Reif	21.0b	21.5ab	21.9a	*	9.9a	8.5b	9.4a	*	3.37b	3.46a	3.41ab	*
Harbour Estate	20.5	20.6	20.8	ns	8.1	9.2	9.3	ns	3.64	3.61	3.61	ns
George	21.6a	21.0b	21.1b	*	7.2	6.9	6.6	ns	3.59	3.58	3.59	ns
Cave Spring	23.8	23.7	24.2	ns	6.4	7.0	6.5	ns	3.62	3.66	3.63	ns
Henry of Pelham	22.2a	21.2b	21.0b	**	11.5	11.6	11.3	ns	3.68a	3.66ab	3.63b	*
Vieni Estate	22.3	22.1	22.6	ns	6.8	6.9	6.8	ns	3.65	3.63	3.61	ns
2006												
Buis	20.7ab	20.2b	20.8a	*	8.0b	7.8b	8.5a	*	3.53ab	3.47b	3.55a	*
Ch des Charmes	23.0a	22.3b	22.5b	*	9.1	8.9	8.7	ns	3.68	3.67	3.69	ns
Hernder	19.9	19.9	19.9	ns	7.8	7.5	7.5	ns	3.50a	3.47a	3.42b	*
Reif	21.9	21.8	22.0	ns	8.9	8.4	8.6	ns	3.53	3.55	3.51	ns
Harbour Estate	22.0a	22.0a	21.3b	*	11.0b	11.4a	11.6a	*	3.58	3.58	3.56	ns
George	20.0	20.2	20.4	ns	9.1	8.7	9.0	ns	3.43	3.49	3.40	ns
Cave Spring	22.9	23.4	24.0	ns	8.7a	8.6ab	8.3b	*	3.47	3.51	3.46	ns
Henry of Pelham	20.4	20.2	20.0	ns	10.4	10.0	9.9	ns	3.49	3.48	3.47	ns
Morrison	21.2	21.0	21.1	ns	10.1	9.9	9.8	ns	3.54	3.53	3.53	ns
2007												
Buis	22.6	23.0	23.1[b]	ns	7.6	7.4	7.5	ns	3.69a	3.64b	3.62b	**[a]
Ch des Charmes	26.2	30.2	26.7	ns	6.9b	7.3ab	7.6a	*	3.70	3.70	3.70	ns
Hernder	22.6	22.5	21.9	ns	4.8	4.9	4.7	ns	3.66b	3.71a	3.74a	**
Reif	24.0	23.9	24.5	ns	7.0b	7.5a	7.3a	*	3.73	3.66	3.73	ns
Harbour Estate	24.7a	23.9b	23.9b	*	7.1b	7.5b	8.3a	*	3.58	3.59	3.58	ns
George	24.7	24.9	24.3	ns	7.6b	7.8ab	7.9a	*	3.65	3.67	3.67	ns
Cave Spring	24.8	24.3	24.1	ns	6.6	6.5	6.3	ns	3.64a	3.61b	3.59b	*
Henry of Pelham	21.1	21.8	21.6	ns	7.3	7.0	7.0	ns	3.47	3.49	3.53	ns
Vieni Estate	23.0	22.4	23.1	ns	7.4	7.4	7.6	ns	3.59a	3.54b	3.52b	*
Morrison	25.0a	24.0b	23.4b	**	5.9	5.9	5.6	ns	3.74a	3.69b	3.67b	*

[a] *, **, ns: significant at $P \leq 0.05$, 0.01, or not significant, respectively. [b] Means in rows followed by various letters are significant at $P \leq 0.05$, Duncan's multiple range test.

anthocyanins were observed in the LWS category. Phenols were highest at the George and Morrison sites and low at the Hernder site in the LWS category.

2007: Differences between HWS and LWS categories were more widespread in 2007 and a greater modicum of consistency with respect to a possible effect of water status was present (Tables 1, 2). The LWS category had higher Brix at the Harbour and Morrison sites. TA was affected at four sites (CDC, Reif, Harbour, George) with lower TA in the LWS category. Berry pH was also affected at five sites; four sites (Morrison, Vieni, Cave Spring and Buis) had higher pH values, while the Hernder site had lower pH in the LWS category. Hue was affected by vine water status at five sites (Buis, Reif, Harbour, HOP, Vieni) whereby values were lower at the Buis and HOP sites in the LWS category, but highest at Reif, Harbour and Vieni. Vine water status altered color intensity at all sites except the CDC, Hernder and HOP sites; higher color intensity was observed in the LWS category at the Buis, Harbour, George, Cave Spring and Morrison sites, while the Reif and Vieni sites showed lower values. Anthocyanins were also affected at seven sites, in which higher anthocyanins were produced at the Buis, Harbour, George, Cave Spring, and Morrison sites, while lower values were observed at the CDC and Reif sites in the LWS category. Phenols were different at three sites; at the Buis and Morrison sites, higher values were observed in the LWS category, while at the HOP site, lower values were observed.

Impact of vine water status on must and wine composition: Vine water status did not have a substantial influence on must composition (data not shown). Vine water status did not impact must pH, Brix, hue, anthocyanins and phenols at any site in 2005; however, it affected TA at the Hernder and Reif sites whereby lower TA was observed in LWS vines at Hernder (4.7 vs. 6.6 g/L for HWS) while at the Reif site TA was higher in LWS musts (6.0 vs. 5.4 g/L in HWS). Color intensity was increased at the Harbour site in the HWS category in 2005 (0.9 vs. 0.4 in LWS). Vine water status did not alter must Brix, TA, pH, hue, anthocyanins and phenols in 2006; however, it increased color intensity at the Reif site in the LWS category (0.7 vs. 0.4 in HWS). Differences between wines resulting from vine water status were also minimal. Vine water status did not alter pH and hue in 2005 (Tables 3, 4). TA was highest at the Harbour site in the HWS category. LWS increased ethanol (Buis and CDC), color intensity (CDC and Vieni), anthocyanins (Harbour), and phenols (Hernder). In 2006, vine water status did not affect wine TA, ethanol, hue, anthocyanins and phenols; however, it increased pH at the George site in the HWS category and increased color intensity at the CDC site in the LWS category.

Table 2. Impact of vine water status on berry composition of Cabernet franc in the Niagara Peninsula, ON, 2005-2007: hue, color intensity, anthocyanins, and phenols. LWS, MWS, HWS: low, medium and high water status, respectively

Vineyard location	Hue				Color intensity				Anthocyanins (mg/L)				Total phenols (mg/L)			
	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.
2005																
Buis	0.41	0.44	0.44[b]	ns	20	18	20	ns	551a	478b	518ab	*[a]	1625	1555	1548	ns
Ch des Charmes	0.46a	0.43b	0.41c	*	19	21	21	ns	594	659	630	ns	1615	1850	1720	ns
Hernder	0.39	0.39	0.40	ns	18	19	18	ns	578	589	535	ns	1567	1480	1454	ns
Reif	0.38	0.40	0.38	ns	20	19	22	ns	605	594	669	ns	1337	1235	1269	ns
Harbour Estate	0.46	0.44	0.44	ns	13	14	16	ns	462	465	501	ns	697b	961b	1014a	*
George	0.40a	0.39ab	0.38b	*	17b	19a	19a	*	527	554	572	ns	673b	783a	859a	*
Cave Spring	0.38	0.38	0.39	ns	21	19	19	ns	587	563	603	ns	1668	1791	1858	ns
H. of Pelham	0.42a	0.40b	0.39b	*	20	18	19	ns	660a	611b	603b	*	2586a	1974b	1928b	*
Vieni Estate	0.41	0.40	0.40	ns	22	23	25	ns	663	661	693	ns	2300	2315	2444	ns
2006																
Buis	0.39	0.39	0.40	ns	22	19	21	ns	506	474	472	ns	1338	1288	1452	ns
Ch des Charmes	0.39	0.40	0.40	ns	20	18	19	ns	569	513	546	ns	1650	1526	1724	ns
Hernder	0.42a	0.40b	0.39b	*	13b	15a	16a	**	371b	436a	435a	**	1156b	1334a	1285a	*
Reif	0.42	0.41	0.43	ns	18b	17b	21a	*	473	488	545	ns	1699	1717	1886	ns
Harbour Estate	0.43	0.42	0.43	ns	17ab	18a	15b	*	499	558	430	ns	1171	1323	1273	ns
George	0.36b	0.37ab	0.39a	*	22	23	21	ns	426	440	433	ns	1683a	1818a	1409b	*
Cave Spring	0.37	0.37	0.37	ns	25b	26b	30a	*	686	690	747	ns	2644	2543	2524	ns
H. of Pelham	0.41	0.40	0.41	ns	18	17	16	ns	540	506	519	ns	1808	2024	1982	ns
Morrison	0.44	0.43	0.44	ns	13	14	13	ns	373	349	342	ns	1477a	1382ab	1245b	*
2007																
Buis	0.42b	0.40b	0.43a[b]	**[a]	19a	19a	16b	*	466a	524a	450b	*	1921a	1892a	1597b	**
Ch des Charmes	0.48	0.48	0.47	ns	29	27	32	ns	668b	632b	774a	*	2336	2219	2535	ns
Hernder	0.78	0.77	0.79	ns	13	14	12	ns	370	384	399	ns	1419	1497	1437	ns
Reif	0.49a	0.46b	0.50a	*	15b	17a	16a	*	425b	477a	473a	**	1987	2097	2051	ns
Harbour Estate	0.43a	0.42a	0.41b	*	23a	20b	21ab	*	575a	523b	543ab	*	1737	1766	1883	ns
George	0.43	0.44	0.43	ns	26a	23b	22b	**	637a	591b	459b	**	1873	1767	1766	ns
Cave Spring	0.39	0.38	0.39	ns	27a	25ab	24b	*	633a	584ab	574b	*	2342	2109	2157	ns
H. of Pelham	0.38b	0.40ab	0.42a	*	17	20	21	ns	451	501	503	ns	1184b	1512a	1419a	*
Vieni Estate	0.43a	0.41b	0.40b	*	19b	22a	24a	*	506	530	582	ns	1769	1879	2042	ns
Morrison	0.47	0.49	0.50	ns	15a	14ab	13b	*	468a	394b	376b	**	1511a	1397ab	1324b	*

[a] *, ns: significant at $P \leq 0.05$ or not significant, respectively. [b] Means in rows followed by various letters are significant at $P \leq 0.05$, Duncan's multiple range test

Table 3. Impact of vine water status on Cabernet franc wine composition in the Niagara Peninsula, 2005-2006. LWS, MWS, HWS: low, medium and high water status, respectively

Vineyard location	pH				Titratable acidity (g/L)				Ethanol (% v/v)			
	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.
2005												
Buis	3.34	3.35	3.36	ns	8.0	8.1	8.3[b]	ns	11.8a	11.7b	11.5c	*[a]
Ch des Charmes	3.62	3.69	3.66	ns	6.9	7.0	6.7	ns	12.6a	12.5b	12.3c	*
Hernder	3.59	3.59	3.50	ns	5.9	5.8	5.9	ns	11.2	11.0	11.1	ns
Reif	3.65	3.63	3.59	ns	5.9	5.8	5.9	ns	11.3	11.2	11.1	ns
Harbour Estate	3.85	3.77	3.79	ns	5.5b	5.6b	5.8a	*	10.2	10.4	10.4	ns
George	3.48	3.49	3.47	ns	5.7	5.7	5.9	ns	10.9	10.8	11.2	ns
Cave Spring	3.38	3.33	3.35	ns	6.1	6.4	6.1	ns	12.4	12.5	12.4	ns
Henry of Pelham	3.67	3.67	3.52	ns	5.3	5.7	5.8	ns	11.7	10.8	10.7	ns
Vieni Estate	3.57	3.51	3.57	ns	5.5	5.6	5.5	ns	10.7	10.4	10.4	ns
2006												
Buis	3.50	3.44	3.48	ns	6.1	6.4	6.4	ns	10.1	9.9	9.9	ns
Ch des Charmes	3.65	3.67	3.73	ns	6.0	6.0	5.9	ns	11.1	11.0	11.2	ns
Hernder	3.55	3.50	3.42	ns	5.7	5.9	6.1	ns	9.3	9.5	9.5	ns
Reif	3.63	3.63	3.58	ns	5.6	5.7	6.0	ns	10.8	10.9	11.0	ns
George	3.31b	3.32b	3.42a	*	7.9	6.7	6.3	ns	9.8	9.8	9.6	ns
Cave Spring	3.22	3.30	3.26	ns	7.1	7.1	6.8	ns	12.1	11.9	11.4	ns
Henry of Pelham	3.43	3.44	3.40	ns	6.1	6.5	6.6	ns	8.4	8.8	9.1	ns
Morrison	3.81	3.75	3.80	ns	5.2	5.3	5.3	ns	9.2	9.4	9.7	ns

[a] *, ns: significant at $P \leq 0.05$ or not significant, respectively. [b] Means in rows followed by various letters are significant at $P \leq 0.05$, Duncan's multiple range test.

Table 4. Impact of vine water status on Cabernet franc wine composition in the Niagara Peninsula, 2005-2006: hue, color intensity, anthocyanins, and phenols. LWS, MWS, HWS: low, medium and high water status, respectively

Vineyard location	Hue				Color intensity				Anthocyanins (mg/L)				Total phenols (mg/L)			
	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.
2005																
Buis	0.6	0.6	0.7[b]	ns	7.4	7.5	6.3	ns	242	195	232	ns	2268	2050	2333	ns
Ch des Charmes	0.7	0.7	0.7	ns	7.7a	7.2b	7.1b	*[a]	231	242	227	ns	1783	1849	1653	ns
Hernder	0.8	0.8	0.7	ns	5.1	4.9	5.2	ns	268	270	249	ns	1358a	1333a	1259b	*
Reif	0.9	0.8	0.8	ns	4.3	4.3	4.5	ns	273	275	264	ns	1450	1450	1346	ns
Harbour Estate	0.8	0.8	0.8	ns	4.1	4.6	4.0	ns	285a	274a	252b	*	914	913	819	ns
George	0.6	0.6	0.6	ns	5.5	5.6	6.3	ns	281	265	315	ns	1458	1422	1711	ns
Cave Spring	0.7	0.6	0.6	ns	7.5	7.7	6.7	ns	324	314	269	ns	1469	1221	1451	ns
Henry of Pelham.	0.7	0.6	0.7	ns	6.2	6.0	5.9	ns	283	265	268	ns	1467	771	925	ns
Vieni Estate	0.8	0.7	0.8	ns	4.5a	4.2b	3.9c	*	277	257	245	ns	1033	587	825	ns
2006																
Buis	0.6	0.5	0.5	ns	5.4	5.8	5.9	ns	155	164	165	ns	836	825	853	ns
Ch des Charmes	0.7	0.8	0.8	ns	6.8a	6.0b	6.4b	*	136	134	143	ns	1025	1014	1153	ns
Hernder	0.6	0.5	0.5	ns	5.3	5.8	5.9	ns	168	163	155	ns	1092	986	1231	ns
Reif	0.7	0.7	0.7	ns	6.1	6.6	7.3	ns	155	166	168	ns	1017	997	1078	ns
George	0.4	0.4	0.5	ns	8.8	7.9	6.2	ns	257	245	216	ns	1117	1069	1014	ns
Cave Spring	0.5	0.7	0.6	ns	12.9	11.2	10.8	ns	304	254	278	ns	1344	1228	1089	ns
Henry of Pelham	0.6	0.6	0.7	ns	4.8	5.5	5.8	ns	186	174	186	ns	1017	906	1028	ns
Morrison	1.0	1.0	1.1	ns	4.8	4.6	4.6	ns	81	96	105	ns	1003b	1253b	1369b	ns

[a] *, ns: significant at $P< 0.05$ or not significant, respectively. [b] Means in rows followed by various letters are significant at $P< 0.05$, Duncan's multiple range test.

Correlation analysis: Correlation analysis of soil factors vs. fruit composition for all sites in 2005 revealed that many soil and vine water status as well as soil composition variables were consistently linked with berry composition. Leaf ψ (absolute value; a.v.) negatively correlated with TA and positively correlated with Brix, color intensity, anthocyanins and phenols (Table 5). Other soil-based variables showing positive correlations with Brix, color intensity, anthocyanins and phenols included: % clay, CEC (additionally with berry pH), base saturation (BS), Ca (additionally with berry pH), and Mg (additionally with berry pH but not with phenols). Other noteworthy positive correlations included: soil moisture vs. TA and phenols; soil OM vs. pH; soil P vs. TA and phenols. Noteworthy negative correlations included % sand vs. Brix, pH, color intensity, anthocyanins and phenols; % clay and soil Mg vs. TA; OM vs. color intensity and phenols; soil P vs. Brix; soil K vs. Brix, pH and color intensity. Correlation analysis in 2006 once again revealed that many soil and vine water status as well as soil composition variables were consistently linked with berry composition, particularly color and phenolic analytes. Leaf ψ (a.v.) negatively correlated with TA (Table 5). Soil moisture positively correlated with color intensity, anthocyanins and phenols while negatively correlated with TA. Other noteworthy correlations involving color intensity, anthocyanins and phenols included those with: % clay (Brix, anthocyanins and phenols); CEC (color, anthocyanins and phenols); soil pH (anthocyanins and phenols); BS (Brix, anthocyanins, and phenols); soil Ca (color intensity, anthocyanins and phenols); soil Mg (color and phenols). Other positive correlations of note included: soil P vs. berry pH and TA; soil K vs. berry pH. Noteworthy negative correlations included: % sand vs. phenols; % clay vs. TA; soil OM vs. Brix and berry pH; BS vs. TA; P vs. Brix, color intensity, anthocyanins and phenols; K vs. color intensity, anthocyanins and phenols. In 2007 correlation analysis also showed that many soil and vine water status as well as soil composition variables were consistently linked with berry composition, particularly color and phenolic analytes. Leaf ψ (a.v.) was negatively correlated with TA; soil moisture negatively correlated with anthocyanins; % sand positively correlated with TA, while negatively correlated with color intensity (Table 5). Other positive correlations involving color and phenolic analytes included: % clay, CEC, and soil Ca vs. color intensity; Mg vs. color intensity and anthocyanins. Other positive correlations included: soil P and K vs. berry pH. Negative correlations included: % clay vs. TA; soil P and K vs. TA, color intensity, anthocyanins and phenols.

Multivariate relationships- Yield components, fruit composition, vine size and soil texture

2005: Relationships among yield components, fruit composition, vine size, and soil texture in 2005 are illustrated in Fig. 1. PCA explained 57.6% of the variability in the data in the first two dimensions. PC1 (36.1% of the variability) was most heavily loaded in positive direction with Brix, color intensity, anthocyanins, phenols and % clay and negatively loaded with vine size and % sand. PC2 (21.5% of the variation) was positively loaded with clusters/vine, yield, berry weight and pH. The third PC explained 16.3% of the variation (data not shown). Color intensity, anthocyanins and phenols were positively correlated and grouped in the lower right quadrant. Percent clay, Brix and pH were positively correlated and grouped together in the upper right quadrant. Yield, clusters/vine, berry weight, vine size and hue were grouped together in the upper left quadrant and highly positively correlated. TA, % sand and soil moisture also grouped together in the lower left quadrant and were positively correlated. Color intensity, anthocyanins and phenols negatively correlated with berry weight, vine size and hue, and % sand was highly negatively correlated with % clay.

The distribution of HWS, MWS and LWS categories at each site on the PCA plot illustrated that Hernder (MWS, LWS), CDC (HWS, MWS), HOP (LWS) and Vieni (HWS) were located in the lower right quadrant and associated with color intensity, anthocyanins and phenols. CDC (LWS), Vieni (MWS), and Cave Spring (HWS, MWS and LWS) were in the upper right quadrant and explained by Brix and % clay. HOP (HWS, MWS) and George were associated with yield, clusters/vine and pH.

Table 5. Overall correlations and associated *p* values of soil factors vs. fruit composition for Cabernet franc for ten Niagara Peninsula sites in 2005. Abbreviations: OM: organic matter; CEC: cation exchange capacity; SM: soil moisture.

Parameter	Sand (%)	Clay (%)	OM (%)	CEC (meq/100 g)	Soil pH	Base saturation (% Ca)	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	SM (%)	Leaf ψ (-MPa)
2005												
Brix	-0.469	0.5262	-0.0278	0.3998	0.2546	0.3441	-0.3069	-0.266	0.3872	0.3812	-0.0423	0.3554
	<.0001	<.0001	0.7268	<.0001	0.0012	<.0001	<.0001	0.0007	<.0001	<.0001	0.5953	<.0001
Berry pH	-0.300	0.1402	0.2619	0.1856	0.0768	0.0718	-0.0028	-0.1993	0.1729	0.2194	0.0372	0.0831
	0.0001	0.0770	0.0008	0.0188	0.3345	0.3672	0.9717	0.0115	0.0287	0.0053	0.6407	0.2960
Titratable acidity (g/L)	0.0875	-0.236	-0.078	0.1055	0.1942	0.0426	0.3811	0.1187	0.1295	-0.2168	0.3347	-0.250
	0.2715	0.0027	0.3266	0.1844	0.0139	0.5925	<.0001	0.1360	0.1027	0.0059	<.0001	0.0014
Color intensity	-0.286	0.3617	-0.1928	0.1744	0.1183	0.1722	-0.0887	-0.156	0.1636	0.1594	0.0015	0.2381
	0.0002	<.0001	0.0143	0.0270	0.1362	0.0289	0.2630	0.0475	0.0381	0.0435	0.9850	0.0024
Anthocyanins (mg/L)	-0.403	0.4355	-0.1140	0.2679	0.2735	0.3154	-0.0262	-0.1417	0.2673	0.2030	-0.0903	0.2801
	<.0001	<.0001	0.1511	0.0006	0.0005	<.0001	0.7419	0.0739	0.0006	0.0100	0.2559	0.0003
Phenols (mg/L)	-0.303	0.2963	-0.2095	0.2464	0.2053	0.2947	0.2301	-0.0055	0.2563	-0.0734	0.2329	0.2887
	0.0001	0.0001	0.0073	0.0017	0.0092	0.0002	0.0034	0.9450	0.0011	0.3560	0.0030	0.0002
2006												
Brix	-0.099	0.1749	-0.2167	0.1111	0.0429	0.01834	-0.1974	-0.1228	0.1105	0.0829	0.1390	-0.0901
	0.2050	0.0258	0.0055	0.1579	0.5858	0.8162	0.0116	0.1182	0.1603	0.2931	0.0768	0.2525
Berry pH	-0.0098	-0.003	-0.2655	-0.0502	-0.091	-0.1002	0.1798	0.3813	-0.0448	-0.1732	-0.0713	0.1334
	0.9011	0.9678	0.0006	0.5260	0.2515	0.2048	0.0220	<.0001	0.5710	0.0275	0.3674	0.0905
Titratable acidity (g/L)	0.0649	-0.3023	-0.021	-0.0969	-0.077	-0.2569	0.2045	-0.1238	-0.0854	-0.0449	-0.3216	-0.4542
	0.4102	<.0001	0.7870	0.2184	0.3306	0.0009	0.0088	0.1152	0.2785	0.5688	<.0001	<.0001
Color intensity	-0.0267	0.1303	0.0798	0.2092	0.0812	0.1431	-0.4813	-0.4769	0.1992	0.1684	0.3288	-0.0549
	0.7350	0.0974	0.3112	0.0074	0.3027	0.0685	<.0001	<.0001	0.0108	0.0316	<.0001	0.4859
Anthocyanins (mg/L)	-0.0484	0.1549	0.0319	0.2444	0.1802	0.2117	-0.4698	-0.3840	0.2531	0.0553	0.1887	0.0089
	0.5397	0.0483	0.6854	0.0017	0.0213	0.0067	<.0001	<.0001	0.0011	0.4832	0.0158	0.9105
Phenols (mg/L)	-0.3489	0.4150	0.0775	0.4566	0.4394	0.4043	-0.2977	-0.3385	0.4472	0.3416	0.3602	0.0011
	<.0001	<.0001	0.3256	<.0001	<.0001	<.0001	0.0001	<.0001	<.0001	<.0001	<.0001	0.9885
2007												
Brix	-0.044	0.1250	-0.0916	-0.0018	-0.1343	-0.0992	-0.0278	-0.0232	-0.0334	0.0483	-0.0753	0.0748
	0.5629	0.0954	0.2228	0.9807	0.0730	0.1885	0.7113	0.7582	0.6575	0.5206	0.3163	0.3199
Berry pH	0.0945	-0.0226	-0.0596	-0.0631	-0.0408	-0.0726	0.1570	0.3754	-0.0818	0.1051	0.0886	0.1056
	0.2082	0.7639	0.4275	0.4017	0.5876	0.3342	0.0358	<.0001	0.2769	0.1615	0.2382	0.1593
Titratable acidity (g/L)	0.1843	-0.1836	-0.0242	-0.0647	-0.0888	-0.1003	-0.3123	-0.2679	-0.0575	0.0135	-0.1301	-0.5302
	0.038	0.0142	0.7485	0.3909	0.2381	0.1830	<.0001	0.0003	0.4457	0.8583	0.0835	<.0001
Color intensity	-0.1546	0.1995	0.0613	0.1702	0.03808	0.1308	-0.3784	-0.2996	0.1779	0.1932	-0.1044	0.0185
	0.0387	0.0074	0.4148	0.0227	0.6128	0.0808	<.0001	<.0001	0.0172	0.0096	0.1642	0.8055
Anthocyanins (mg/L)	-0.0752	0.0791	0.0286	0.0986	-0.0268	0.0551	-0.3399	-0.2639	0.1051	0.1652	-0.1691	-0.092
	0.3171	0.2923	0.7041	0.1889	0.7216	0.4638	<.0001	0.0004	0.1614	0.0271	0.0237	0.2214
Phenols (mg/L)	0.0292	0.0433	-0.1453	-0.0185	-0.0016	0.0666	-0.3635	-0.2038	-0.0039	0.0604	-0.1335	-0.0891
	0.6981	0.5653	0.0553	0.8062	0.9827	0.3757	<.0001	0.0062	0.95810	0.4216	0.0748	0.2357

Harbour (HWS, MWS and LWS) was explained with berry weight, vine size, hue, and % sand. Buis and Reif (HWS, MWS and LWS) and Hernder (HWS) were associated with % sand and TA. Distribution was in general linked to both sub-appellation and water status--Harbour Estate (Creek Shores sub-appellation), Reif (Niagara River), George (Lincoln Lakeshore), and Buis (Niagara Lakeshore) sites were all on the left side of PC2 and exhibited high yield, clusters/vine, berry weight, vine size, TA and hue. CDC (St. David's Bench sub-appellation), HOP (Short Hills Bench), Hernder (Four Mile Creek), Cave Spring (Beamsville Bench) and Vieni (Vinemount Ridge) were all to the right of PC2 and explained by color intensity, anthocyanins, phenols, Brix, pH and % clay.

2006: Fig. 2 illustrates relationships among yield components, fruit composition, vine size, and soil texture in 2006. PCA explained 58.8% of the variability in the data set in the first two dimensions. PC1 (34.5% of the variability) was most heavily loaded in the positive direction with color intensity, anthocyanins, phenols and % clay, while negatively loaded with vine size, TA, hue, and % sand. PC2 (24.3% of variability) was positively loaded with Brix and pH and negatively loaded with clusters/vine, yield and berry weight. Color intensity, anthocyanins, phenols, % clay and Brix were positively correlated and grouped together in the upper right quadrant. These variables were negatively correlated with clusters/vine, yield, vine size and % sand. Soil moisture and berry weight were positively correlated in the lower right quadrant. TA, pH and hue were positively correlated in the upper left quadrant. Berry weight and soil moisture were negatively correlated with TA and hue. Percent sand was highly negatively correlated with % clay; Brix was highly negatively correlated with clusters/vine and yield and vine size was negatively correlated with color intensity, anthocyanins, phenols and % clay.

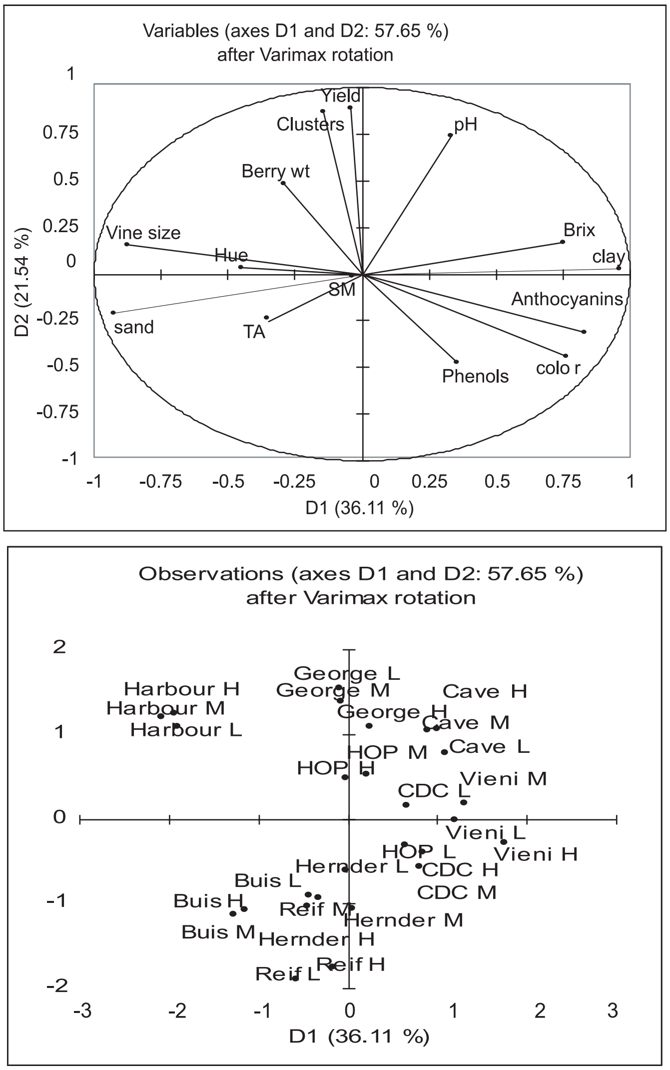

Fig. 1. PCA of field data. Cabernet franc. Niagara Peninsula. ON. 2005. CDC, HOP, Cave, and Harbour are abbreviations for Chateau des Chamies, Henry of Pelham, Cave Spring, and Harbour Estate sites, respectively.

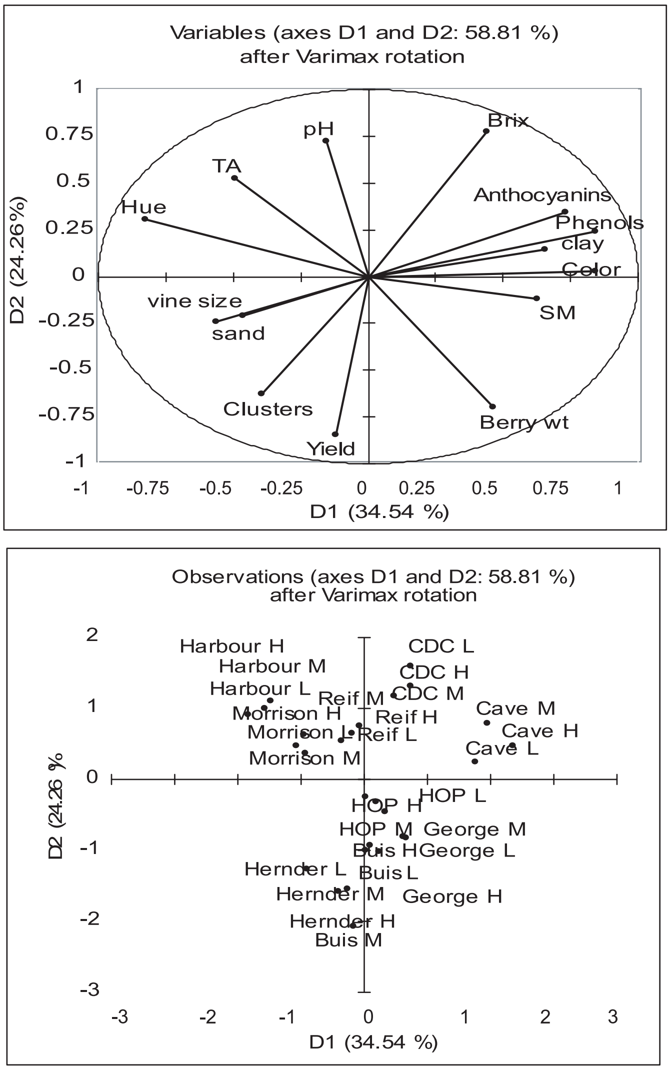

Fig. *2*. PCA of field data. Cabernet franc. Niagara Peninsula. ON. 2006. CDC. HOP, Cave, and Harbour are abbreviations for Chateau des Charmes, Henry of Pelham, Cave Spring, and Harbour Estate sites, respectively.

The distribution of water status categories at each site on the PCA plot showed that Cave Spring (all water status categories) and CDC (HWS, MWS and LWS) were explained with high color intensity, anthocyanins, phenols, % clay and Brix. CDC (LWS) was more closely associated with Brix than MWS and HWS. Hernder (HWS, MWS and LWS) and Buis (MWS) were associated with yield, clusters/vine, vine size and % sand. Hernder (LWS) was associated with clusters/vine, while its MWS and HWS categories were associated with yield. Reif, Harbour and Morrison were explained by hue, TA and pH; among these three sites Harbour was more intense in the above mentioned attributes as it was further away from the center of the plot. George and HOP (HWS, MWS and LWS) were explained by soil moisture and berry weight. The third PC explained 17.3% of the variability in the data set (data not shown). Morrison and Harbour (HWS, MWS and LWS) both were explained such that Morrison was associated with vine size, clusters/vine and hue, while Harbour was associated with yield and % sand (data not shown).

2007: Relationships among yield components, fruit composition, vine size, and soil texture in 2007 are illustrated in Fig. 3. The PCA explained 58.7% of the variability in the data set in the first two dimensions. PC1 (31.6% of the variance) was most heavily loaded in the positive direction with color intensity, anthocyanins, phenols, TA and Brix while negatively loaded with clusters/vine and hue. PC2 (27.1% of the variability) was positively loaded with clusters/vine, yield, berry weight, TA and % sand and negatively loaded with % clay. Similar to 2005 and 2006, color intensity, anthocyanins, phenols and Brix were highly positively correlated in the lower right quadrant. Berry weight and TA were highly positively correlated in the upper right quadrant. Clusters/vine, yield, berry weight and % sand were positively correlated in the upper left quadrant; hue, soil moisture, pH and clay were also positively correlated in lower left. Yield and clusters/vine were negatively correlated with color intensity, anthocyanins, phenols and Brix. TA was negatively correlated with pH and hue. Percent clay was also negatively correlated with berry weight and yield. However, vine size, pH, soil moisture and hue were not explained well in the first two dimensions.

The distribution of water status categories at each site of the PCA plot showed that CDC and Cave Spring (HWS, MWS and LWS), Vieni (HWS) and George (MWS, LWS) were explained by color intensity, anthocyanins, phenols and Brix; among these sites CDC was more and George was less intense in these attributes based on their relative positions. George (HWS) and Reif (MWS) were

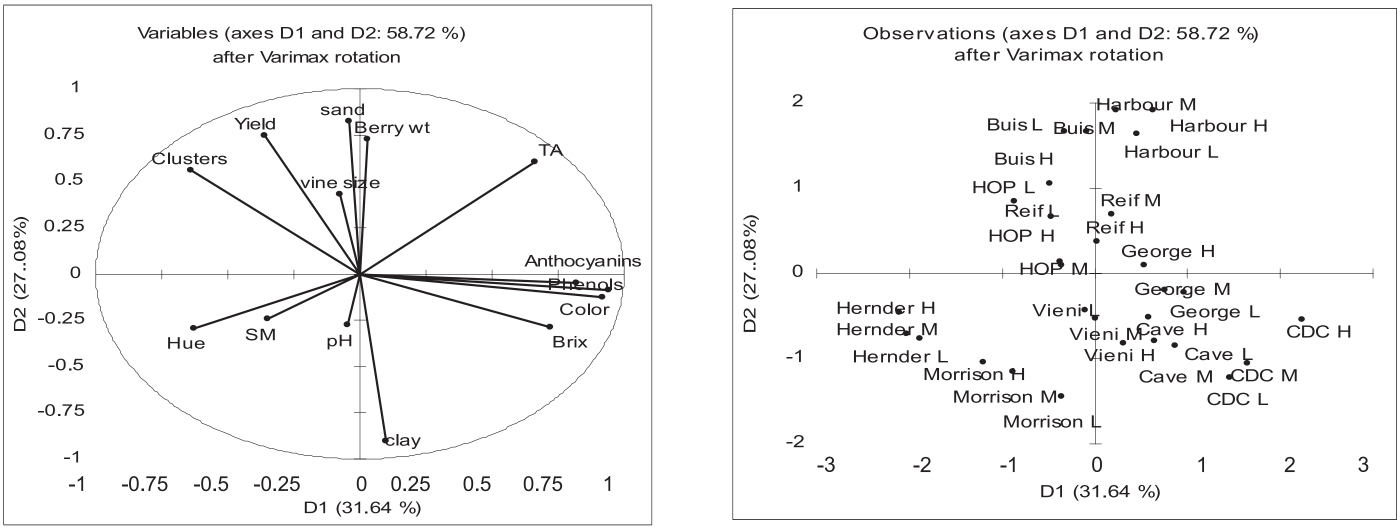

Fig. 3. PCA of field data. Cabernet franc. Niagara Peninsula. ON. 2007. CDC, HOP, Cave, and Harbour are abbreviations for Chateau des Charmes, Henry of Pelham, Cave Spring, and Harbour Estate sites, respectively.

Table 6. Spatial correlations 2005-2007—Yield, vine size, berry composition, soil moisture. Relationships with WP refer to absolute values. Abbreviations: Antho: anthocyanins; BWT: berry weight; SM: soil moisture; TA: titratable acidity.

Buis								
	Antho	BWT	Brix	Color	pH	Phenols	SM	TA
BWT 05	-0.49**							
06	-0.51**							
07	-0.52**							
Brix 05	0.85**	-0.51**						
06	-0.25	0.54**						
07	0.57**	-0.31*						
Color 05	0.95**	-0.41**	0.87**					
06	0.81**	-0.36**	-0.16					
07	0.90**	-0.54**	0.35**					
pH 05	0.03	-0.33**	0.04	-0.18				
06	-0.69**	0.60**	0.54**	-0.55**				
07	-0.55**	0.42**	-0.43**	-0.36**				
Phenols 05	0.84**	-0.73**	0.82**	0.79**	0.06			
06	0.40**	0.04	0.32*	0.72**	-0.24			
07	0.65**	0.65**	0.40**	0.75**	0.01			
SM 05	-0.36**	0.77**	-0.50**	-0.26*	-0.35**	-0.64**		
06	0.38**	-0.05	-0.02	0.70**	-0.44**	0.76**		
07	0.65**	-0.20	0.84**	0.50**	-0.65**	0.43**		
TA 05	-0.60**	0.15	-0.69**	-0.59**	-0.28*	-0.37**	0.28*	
06	-0.57**	0.19	0.30*	-0.29*	0.57**	0.07	0.01	
07	0.58**	-0.54**	0.70**	0.45**	-0.33**	0.39**	0.39**	
Vine size 05	-0.25	0.51**	-0.61**	-0.63**	-0.16	-0.59**	0.34**	0.52**
06	-0.53**	0.66**	0.29*	-0.57**	0.66**	-0.42**	-0.62**	0.05
07	-0.20	0.26*	-0.55**	0.07	0.56**	0.07	-0.54**	-0.46**
Leaf ψ 05	-0.01	-0.25	0.27	0.23	0.28	0.10	-0.27	-0.55*
06	0.30	-0.43	-0.46	0.18	-0.16	-0.22	-0.03	-0.25
07	0.16	-0.03	-0.50*	0.44	0.38	0.44	-0.20	-0.17
Yield 05	-0.23	0.14	0.41**	0.34**	-0.26*	0.09	-0.12	-0.64**
06	0.25	-0.35**	-0.49**	-0.06	-0.36**	-0.49**	-0.50**	-0.58**
07	-0.49**	0.45**	-0.86**	-0.26*	0.64**	-0.25	-0.67**	-0.54**

explained with lower intensity in TA. Harbour (HWS, MWS and LWS) was associated with % sand, berry weight and vine size. Buis (HWS, MWS and LWS) was associated with % sand, yield and vine size. HOP (HWS, MWS and LWS) and Reif (LWS) were associated with yield, vine size and clusters/vine. HOP (LWS) had higher clusters/vine than its HWS and MWS counterparts based on their relative positions. Hernder and Morrison (HWS, MWS and LWS), and Vieni (LWS) were associated with pH, soil moisture, and hue and low TA. PC3 explained 16.3% of variability (data not shown). Morrison and Hernder sites were explained better in PC3. Morrison (LWS) was explained with high pH, Brix, and phenols; Morrison (MWS) was associated with % sand, hue, clusters/vine, and vine size while its HWS category was explained by berry weight and yield. Hernder (HWS, MWS and LWS) was also associated with hue, clusters/vine as well as % sand.

Overall, in the hot and dry years of 2005 and 2007, the relationships among the various attributes were explained much better compared to the wet season of 2006.

Spatial variability in yield and fruit composition

Spatial correlation: Spatial maps of soil moisture and leaf ψ as well as some soil composition variables are in part I of this study, while those for yield components and vine size are in part II. Spatial maps for all berry composition variables across all sites and vintages are found in Fig.s 7 to 15. Spatial correlations for leaf ψ, soil moisture, vine size, yield, berry weight, and all berry composition variables are in Table 6. Since the specific hypotheses of this study were that soil moisture and vine water status would be the major drivers of the *terroir* effect, spatial relationships involving all these variables are described. Moreover, a major group of target variables that could arguably be associated with the *terroir* effect in red winegrape cultivars involve color intensity, anthocyanins, and phenols, and therefore they and their spatial relationships with other metrics are emphasized. Finally, cluster exposure, canopy microclimate, and other features of vineyards that impact berry composition are linked

Table 6. contd . Spatial correlations 2005-2007—Yield, vine size, berry composition, soil moisture.

	Antho	BWT	Brix	Color	pH	Phenols	SM	TA
Chateau des Charmes								
BWT 05	-0.42**							
06	-0.32*							
07	0.10							
Brix 05	0.12	0.01						
06	0.22	-0.48**						
07	0.61**	-0.32*						
Color 05	0.94**	-0.56**	0.23					
06	0.71**	-0.67**	0.38**					
07	0.91**	-0.12	0.66**					
pH 05	0.54**	0.16	-0.01	0.25				
06	-0.05	-0.12	0.34**	-0.08				
07	-0.11	-0.38**	0.30*	-0.15				
Phenols 05	0.93**	-0.56**	0.23	0.95**	0.39**			
06	0.61**	-0.52**	0.40**	0.79**	0.08			
07	0.45**	-0.58**	0.61**	0.69**	0.15			
SM 05	0.45**	-0.34**	-0.31*	0.40**	0.26*	0.42**		
06	-0.14	-0.22	0.16	-0.04	-0.09	0.04		
07	-0.45**	-0.24	0.09	-0.35**	0.35**	-0.13		
TA 05	0.52**	-0.58**	-0.12	0.64**	-0.10	0.56**	0.69**	
06	0.31*	-0.43**	0.25	0.42**	-0.34**	0.20	-0.15	
07	0.66**	0.40**	0.35**	0.43**	0.03	-0.17	-0.27*	
Vine size 05	-0.22	0.45**	-0.46**	-0.36**	0.18	-0.41**	0.19	0.06
06	-0.25	0.61**	-0.18	-0.56**	0.30*	-0.35**	-0.40**	-0.38**
07	0.21	0.82**	-0.25	0.04	-0.47**	-0.47**	-0.43**	0.42**
Leaf ψ 05	-0.03	-0.27	-0.19	0.12	-0.32	0.01	0.05	0.27
06	0.02	-0.02	-0.04	-0.10	-0.09	-0.25	-0.10	0.17
07	-0.15	0.01	0.20	0.02	-0.03	0.13	0.53*	-0.10
Yield 05	-0.40**	-0.25	0.06	-0.22	-0.60**	-0.31*	-0.10	-0.03
06	-0.49**	0.16	0.05	-0.48**	0.60**	-0.22	0.06	-0.60**
07	-0.39**	0.53**	-0.66**	-0.55**	-0.29*	-0.79**	-0.25	0.14
Hernder								
BWT 05	-0.61**							
06	0.35**							
07	-0.09							
Brix 05	0.85**	-0.45**						
06	-0.47**	-0.33**						
07	0.36**	-0.39**						
Color 05	0.86**	-0.59**	0.78**					
06	0.67**	0.35**	0.11					
07	0.81**	-0.28*	0.63**					
pH 05	-0.12	0.02	0.10	-0.23				
06	-0.17	-0.30*	0.14	-0.18				
07	-0.04	-0.16	0.43**	-0.10				
Phenols 05	0.78**	-0.77**	0.60**	0.76**	-0.37**			
06	0.84**	0.32*	-0.63**	0.46**	-0.07			
07	0.66**	-0.43**	0.59**	0.84**	0.11			
SM 05	-0.24	0.12	-0.56**	-0.31*	-0.48**	-0.07		
06	0.32*	0.35**	-0.36**	0.12	-0.44**	0.32*		
07	0.20	0.14	0.12	0.36**	-0.03	0.37**		
TA 05	-0.75**	0.47**	-0.76**	-0.61**	0.06	-0.55**	0.16	
06	-0.24	-0.63**	0.25	-0.29	-0.05	-0.17	0.08	
07	0.86**	-0.11	0.39**	0.84**	-0.07	0.60**	0.12	
Vine size 05	-0.61**	0.54**	-0.34**	-0.52**	0.25	-0.64**	0.02	0.41**
06	-0.30*	-0.17	0.22	0.08	0.07	-0.21	-0.25	-0.07
07	-0.68**	0.39**	-0.39**	-0.72**	-0.01	-0.61**	-0.19	-0.72**
Leaf ψ 05	0.54*	-0.48	0.44	0.38	-0.30	0.65**	0.18	-0.66**
06	-0.40	-0.14	0.01	-0.64**	-0.10	-0.37	0.05	0.02
07	-0.01	-0.23	0.11	0.36	-0.69**	0.25	0.19	0.07
Yield 05	0.34**	0.02	0.41**	0.32*	-0.01	-0.09	-0.22	-0.47**
06	-0.31*	0.49**	0.13	-0.12	0.04	-0.27*	-0.09	-0.48**
07	-0.15	0.36**	-0.44**	-0.50**	-0.15	-0.55**	-0.49**	-0.24

to vine size, and consequently spatial relationships involving vine size are herein described.

Clear spatial relationships were particularly evident between leaf ψ, berry weight, Brix, and the various phenolic analytes (Table 6). An example of these relationships is presented for the CDC site (Figs. 4-6). In 2005 (Fig. 4) and 2006 (Fig. 5), leaf ψ was lowest in the north end of the block. These zones were consistent with zones of low berry weight, high Brix, and high berry color intensity, anthocyanins, and phenols. In 2007, the zones of low leaf ψ expanded into two distinct regions, and these regions were again spatially related to areas of low berry weight and high Brix, berry color intensity, anthocyanins, and phenols (Fig. 6).

Niagara-on-the-Lake sites: Spatial maps for these sites [Buis (maps A-C), CDC (D-F), Hernder (G-I), Reif (J-L)] are as follows: Brix and TA (Fig. 7), anthocyanins and color (Fig. 9), phenols (Fig. 11), and all spatial correlation coefficients for these and other variables are in Table 6. Spatial maps for all berry composition variables showed similar relationships with soil moisture and occasionally with leaf ψ across sites and vintages. Variables with significant positive spatial correlations with soil moisture included Brix (Buis 2007; Reif 2006), TA (Buis 2005, 2007; CDC 2005; Reif 2005), pH (CDC 2005, 2007; Reif 2007), anthocyanins (Buis 2006-07; CDC 2005; Hernder 2006), color intensity (Buis 2006-07; CDC 2005; Hernder 2005), and phenols (Buis 2006-07; CDC 2005; Hernder 2006-07). Inverse spatial correlations with soil moisture included Brix (Buis 2005; Hernder 2005-06; Reif 2005, 2007), TA (Reif 2007), pH (Buis 2005-07; Hernder 2005-06; Reif 2005), anthocyanins (Buis 2005; Reif 2005, 2007), color (Buis 2005), and phenols (Buis 2005). Leaf ψ (a.v.) was positively correlated spatially with anthocyanins (Hernder 2005) and phenols (Hernder 2005), and was inversely correlated with Brix (Buis 2007; Reif 2005), TA (Buis 2005; Hernder 2005), pH (Hernder 2007), and color (Hernder 2006).

Numerous spatial relationships were apparent between color and phenolic analytes vs. other variables. Color intensity was positively correlated

Table 6. contd Spatial correlations 2005-2007—Yield, vine size, berry composition, soil moisture.

	Reif							
	Antho	BWT	Brix	Color	pH	Phenols	SM	TA
BWT 05	-0.29*							
06	-0.32*							
07	-0.26*							
Brix 05	0.70**	0.15						
06	0.50**	-0.10						
07	0.39**	-0.24						
Color 05	0.88**	-0.43**	0.42**					
06	0.86**	-0.22	0.39**					
07	0.87**	-0.28*	0.52**					
pH 05	0.51**	0.08	0.67**	0.27*				
06	-0.37**	0.14	0.14	-0.58**				
07	-0.44**	0.37**	-0.14	-0.63**				
Phenols 05	0.62**	-0.46**	0.22	0.78**	0.12			
06	0.60**	-0.10	0.58**	0.67**	-0.40**			
07	0.70**	-0.15	0.53**	0.77**	-0.25			
SM 05	-0.40**	-0.13	-0.53**	-0.11	-0.44**	0.07		
06	-0.16	0.02	0.31*	-0.13	0.30	-0.18		
07	-0.49**	0.47**	-0.41**	-0.50**	0.54**	-0.24		
TA 05	-0.47**	-0.27*	-0.74**	-0.23	-0.64**	-0.25	0.54**	
06	-0.01	-0.05	-0.02	0.23	-0.43**	0.06	0.18	
07	0.53**	-0.35**	0.67**	0.75**	-0.63**	0.58**	-0.49**	
Vine size 05	-0.41**	-0.01	-0.50**	-0.31*	-0.49**	-0.41**	0.43**	0.78**
06	-0.13	0.01	0.25	-0.15	0.26*	-0.14	0.19	-0.16
07	-0.26*	0.21	-0.17	-0.27*	0.20	-0.02	0.21	-0.07
Leaf ψ 05	-0.42	-0.17	-0.55*	-0.23	-0.31	-0.23	0.30	0.37
06	-0.36	0.22	0.25	-0.25	0.26	-0.07	0.60**	0.10
07	-0.13	0.38	-0.16	0.01	-0.02	-0.18	0.42	-0.01
Yield 05	-0.09	0.42**	0.30*	-0.16	0.07	-0.06	-0.26*	-0.54**
06	-0.27*	-0.01	-0.32*	-0.15	0.09	-0.42**	0.13	-0.07

	Harbour Estate							
BWT 05	-0.03							
06	0.36**							
07	-0.15							
Brix 05	0.58**	0.05						
06	0.74**	0.37**						
07	0.62**	-0.23						
Color 05	0.46**	0.37**	0.13					
06	0.55**	0.19	0.34**					
07	0.77**	-0.49**	0.49**					
pH 05	0.07	-0.60**	0.21	-0.60**				
06	0.19	0.35**	0.56**	-0.28*				
07	0.69**	-0.04	0.51**	0.30*				
Phenols 05	0.22	-0.30*	-0.38**	0.30*	0.07			
06	0.07	-0.36**	-0.31*	0.56	-0.59**			
07	0.46**	-0.30*	-0.02	0.38**	0.34**			
SM 05	-0.65**	0.19	-0.42**	-0.13	-0.22	-0.33*		
06	-0.37**	-0.37**	-0.30*	-0.45**	0.13	-0.28*		
07	0.27*	-0.42**	0.35**	0.55**	0.09	-0.16		
TA 05	-0.52**	0.18	-0.60**	0.28*	-0.44**	0.35**	0.23	
06	-0.08	-0.51**	-0.38**	0.49**	-0.77**	0.78**	-0.20	
07	-0.21	-0.50*	-0.29*	0.10	-0.27*	0.61**	0.08	
Vine size 05	-0.16	0.54**	-0.23	0.26	-0.47**	-0.13	0.26	0.23
06	-0.38**	0.58**	-0.42**	0.07	-0.38**	-0.10	0.41**	0.35**
07	0.32*	-0.16	-0.05	0.02	-0.24	-0.14	0.41**	0.39**
Leaf ψ 05	-----[a]	-----	-----	-----	-----	-----	-----	-----
06	0.36	0.52*	0.46	-0.16	0.63**	-0.56*	0.32	-0.70**
07	-----[a]	-----	-----	-----	-----	-----	-----	-----
Yield 05	-0.03	0.38**	-0.09	0.26	-0.34**	0.17	-0.30*	0.46**
06	-----[b]	-----	-----	-----	-----	-----	-----	-----
07	-----[a]	-----	-----	-----	-----	-----	-----	-----

with Brix (Buis 2005, 2007; Hernder 2005), TA (Hernder 2007; Reif 2007), berry anthocyanins (Buis 2005-07; CDC 2005-07; Hernder 2005-07; Reif 2005-07), and phenols (Buis 2005-07; CDC 2005-07; Hernder 2005, 2007; Reif 2005-07), and inversely with vine size (Buis 2005-06; CDC 2005-06; Hernder 2007) and berry weight (CDC 2005-06). As expected, anthocyanins were also spatially correlated with Brix (Buis 2005, 2007; Hernder 2005; Reif 2005), TA (Hernder 2007), and phenols (Buis 2005-07; CDC 2005-07; Hernder 2005, 2006; Reif 2007), as well as soil Ca (Hernder 2005; data not shown), and inversely with Ca, berry weight, and TA (Hernder 2005). Phenols were correlated inversely with berry weight (Buis 2005) and positively with Brix (Buis 2005-07). Several spatial correlations were also apparent amongst vine size, yield, berry weight, Brix, TA, and pH. Vine size was positively correlated with TA (Hernder 2005; Reif 2005) and pH (Reif 2006), and inversely with Brix (Hernder 2005, 2007; Reif 2005), TA (Hernder 2007), pH (Reif 2005), anthocyanins (Hernder 2005-07; Reif 2005, 2007), color (Hernder 2005, 2007; Reif 2005, 2007), and phenols (CDC 2005-07; Hernder 2005, 2007; Reif 2005).

Jordan, Vineland, Beamsville sites:. Spatial maps for these sites [Harbour (maps A-C), George (D-F), Cave Spring (G-I), HOP (J-L)] are as follows: Brix and TA (Fig. 8), anthocyanins and color (Fig. 9), phenols (Fig. 12). Maps for the last two sites (Vieni and Morrison) are not shown due to missing data in 2005 (Morrison, due to winter injury) and 2006 (Vieni, due to powdery mildew). All spatial correlation coefficients for these and other variables are in Table 6. Soil moisture displayed positive spatial correlations with Brix (Harbour 2007; Cave Spring 2006; HOP 2005), TA (Vieni 2005, 2007), pH (George 2006-07), anthocyanins (Harbour 2007; Cave Spring 2005; HOP 2005), color (Harbour 2007; HOP 2005-06), and phenols (George 2006-07; HOP 2005-06; Morrison 2006), and inverse correlations with Brix (George 2005, 2007; Vieni 2005, 2007), TA (George 2006; Cave Spring 2005, 2007; Morrison 2006), anthocyanins (George 2005; HOP 2007; Vieni 2005), color (George 2007; Cave Spring 2005; HOP 2007; Vieni 2005),

Table 6. contd 3 Spatial correlations 2005-2007—Yield, vine size, berry composition, soil moisture

	Antho	BWT	Brix	Color	pH	Phenols	SM	TA
George								
BWT 05	-0.79**							
06	-0.45**							
07	-0.81**							
Brix 05	0.36**	-0.32*						
06	0.24	0.15						
07	0.75**	-0.56**						
Color 05	0.93**	-0.81**	0.17					
06	0.17	-0.08	-0.06					
07	0.84**	-0.57**	0.81**					
pH 05	0.14	-0.03	0.38**	-0.05				
06	-0.24	0.34**	0.28*	0.64**				
07	-0.17	-0.17	-0.41**	-0.61**				
Phenols 05	0.68**	-0.64**	0.28*	0.72**	0.04			
06	-0.03	0.13	0.01	0.76**	0.73**			
07	0.73**	-0.57**	0.37**	0.45**	0.20			
SM 05	-0.45**	0.36**	-0.54**	-0.20	-0.37**	-0.31*		
06	-0.12	0.36**	0.54**	0.24	0.59**	0.47**		
07	0.06	-0.13	-0.31*	-0.35**	0.70**	0.46**		
TA 05	-0.42**	0.36**	0.35**	-0.40**	-0.10	-0.16	0.25	
06	0.06	-0.08	-0.11	-0.49**	-0.76**	-0.49**	-0.51**	
07	0.12	0.23	0.15	0.34**	-0.51**	0.01	-0.10	
Vine size 05	-0.62**	0.64**	-0.39**	-0.45**	-0.46**	-0.48**	0.72**	0.37**
06	0.10	0.20	0.69**	-0.02	0.28*	-0.02	0.50**	-0.19
07	-0.56**	0.82**	-0.45**	-0.44**	-0.13	-0.41**	0.04	0.53**
Leaf ψ 05	-0.01	0.12	0.58*	-0.11	0.05	-0.14	-0.05	0.56*
06	-0.07	0.08	-0.34	0.55*	0.32	0.55*	0.01	-0.13
07	0.60**	-0.76**	0.29	0.47	0.09	0.43	-0.03	-0.31
Yield 05	-0.51**	0.55**	-0.49**	-0.29*	-0.44**	-0.48**	0.75**	0.28*
06	-0.44**	0.46**	0.24	0.07	0.46**	0.07	0.58**	-0.45**
07	-0.75**	0.90**	-0.45**	-0.47**	-0.32*	-0.67**	0.31*	0.22
Cave Spring								
BWT 05	0.25							
06	0.30*							
07	-0.62**							
Brix 05	0.62**	-0.11						
06	0.63**	0.41**						
07	0.14	0.09						
Color 05	0.16	-0.79**	0.17					
06	0.76**	0.49**	0.73**					
07	0.87**	-0.64**	0.17					
pH 05	0.41**	0.04	0.62**	-0.07				
06	0.19	0.32*	0.47**	0.17				
07	-0.39**	-0.01	0.46**	-0.47**				
Phenols 05	-0.17	-0.75**	0.10	0.75	-0.02			
06	0.64**	-0.09	0.24	0.33**	0.19			
07	0.33**	0.11	0.82**	0.35**	-0.06			
SM 05	0.40**	0.80**	0.16	-0.56**	0.17	-0.52**		
06	0.16	0.40**	0.54**	0.59**	0.20	-0.27*		
07	0.03	0.47**	-0.06	-0.10	-0.22	0.21		
TA 05	-0.66**	-0.32*	-0.75**	0.22	-0.55**	0.40**	-0.48**	
06	-0.44**	-0.36**	-0.14	-0.24	0.18	0.01	-0.10	
07	-0.25	-0.18	0.24	-0.02	0.31	-0.11	-0.55**	
Vine size 05	0.29*	0.72**	-0.05	-0.48**	-0.02	-0.46**	0.68**	-0.21
06	0.21	0.55**	0.50**	0.40**	0.29*	-0.21	0.45**	-0.24
07	-0.67**	0.65**	-0.18	-0.57**	0.07	-0.28*	0.32*	0.10
Leaf ψ 05	-0.01	0.01	-0.41	0.16	-0.22	-0.02	-0.12	0.38
06	-0.39	-0.33	-0.38	-0.58*	-0.06	0.01	-0.63**	0.16
07	0.48	-0.76**	0.20	0.57	0.13	0.04	-0.59	0.45
Yield 05	-0.30*	-0.09	-0.53**	0.21	-0.47**	0.03	-0.10	0.40**
06	-0.36**	-0.44**	-0.55**	-0.49**	-0.54**	-0.15	-0.48**	-0.02
07	-0.15	0.45**	-0.29*	-0.08	-0.59**	-0.02	0.24	-0.24

and phenols (Cave Spring 2005-06; HOP 2007; Vieni 2007). Leaf ψ (a.v.) was correlated with Brix (George 2005), TA (George 2005; Vieni 2007), anthocyanins (George 2007), color (George 2006), and phenols (George 2006) and negatively correlated with color (Cave Spring 2006; Morrison 2006).

Color intensity was spatially correlated with berry weight (Cave Spring 2006), Brix (George 2007; Cave Spring 2006; HOP 2005-06; Vieni 2005, 2007; Morrison 2006-07), TA (HOP 2006), anthocyanins (Harbour 2005, 2007; George 2005, 2007; Cave Spring 2006, 2007; HOP 2005-07; Vieni 2005, 2007; Morrison 2007), and phenols (Harbour 2007; George 2005-07; Cave Spring 2005-07; HOP 2005-07; Vieni 2005, 2007; Morrison 2007), and inversely to berry weight (George 2005, 2007; Cave Spring 2005, 2007) and pH (Cave Spring 2007). Anthocyanins were correlated with Brix (Harbour 2007; HOP 2005; Morrison 2006-07) and phenols (Harbour 2007; George 2005, 2007; HOP 2005, 2007; Morrison 2006-07), and inversely to yield (George 2007, Morrison 2006-07), berry weight (George 2005, 2007), and TA (Cave Spring 2005-06) Phenols were positively correlated with Brix (Cave Spring 2007; HOP 2005-07, Vieni 2005, 2007), TA (Harbour 2007), and anthocyanins (Vieni 2005, 2007), and also inversely to yield (HOP 2005, 2007), berry weight (Cave Spring 2005, Vieni 2005), and TA (2006 George). There were also several spatial relationships among vine size, yield, berry weight, Brix, TA, and pH; for example, vine size displayed positive spatial correlations with Brix (George 2006; Morrison 2007), TA (Harbour 2007; George 2005, 2007; HOP 2005-07; Morrison 2007), pH (Morrison 2006-07), anthocyanins (Harbour 2007), color (George 2005, 2007), and phenols (Morrison 2007), and was inversely correlated to Brix (George 2005, 2007; HOP 2005, 2007; Morrison 2006), TA (Morrison 2006), anthocyanins (George 2005, 2007; Morrison 2006), color (Morrison 2006-07), and phenols (George 2005, 2007).

Temporal stability. Correlation analysis describing temporal stability is in Table 9. Brix was temporally consistent

Table 6. contd Spatial correlations 2005-2007-Yield, vine size, berry composition, soil moisture

Henry of Pelham								
	Antho	BWT	Brix	Color	pH	Phenols	SM	TA
BWT 05	-0.22							
06	0.51**							
07	0.05							
Brix 05	0.88**	-0.44**						
06	0.08	0.01						
07	0.18	-0.24						
Color 05	0.97**	-0.08	0.82**					
06	0.67**	0.57**	0.45**					
07	0.85**	0.17	0.09					
pH 05	0.20	-0.70**	0.36**	0.01				
06	-0.22	0.02	0.34**	-0.11				
07	0.29*	-0.26*	0.65**	0.05				
Phenols 05	0.76**	-0.48**	0.90**	0.75**	0.22			
06	0.07	0.40**	0.60**	0.49**	0.31*			
07	0.55**	-0.27*	0.39**	0.44**	0.18			
SM 05	0.54**	-0.38**	0.60**	0.51**	0.06	0.50**		
06	0.12	0.13	0.09	0.27*	0.09	0.35**		
07	-0.56**	0.09	-0.07	-0.57**	-0.11	-0.55**		
TA 05	-0.15	0.62**	-0.39**	-0.03	-0.56**	-0.39**	-0.43**	
06	-0.15	0.40**	0.22	0.30*	0.27*	0.51**	0.28*	
07	0.08	0.59**	-0.49**	0.22	-0.25	-0.32*	0.01	
Vine size 05	-0.28*	0.62**	-0.45**	-0.15	-0.64**	-0.31*	-0.46**	0.64**
06	0.12	0.41**	-0.16	0.17	0.16	-0.17	0.02	0.29*
07	0.36**	0.70**	-0.28*	0.31*	-0.18	-0.17	-0.11	0.64**
Leaf ψ 05	-0.04	-0.53*	0.26	-0.10	0.34	0.41	0.05	-0.25
06	0.05	0.13	0.25	0.38	-0.05	0.14	-0.21	0.01
07	-0.34	-0.10	-0.38	-0.44	-0.26	-0.41	0.44	0.19
Yield 05	-0.20	0.21	-0.45*	-0.24	0.07	-0.68**	-0.12	0.25
06	0.27*	-0.12	0.33**	0.46**	-0.14	0.13	-0.15	-0.17
07	-0.16	0.63**	-0.76**	-0.04	-0.58**	-0.47**	0.23	0.72**
Vieni								
BWT 05	-0.54**							
06	-----^{b}							
07	-0.25							
Brix 05	0.83**	-0.67**						
06	-----	-----						
07	0.41**	0.28*						
Color 05	0.92**	-0.54**	0.90**					
06	-----	-----	-----					
07	0.79**	-0.22	0.44**					
pH 05	-0.01	-0.34**	0.07	-0.18				
06	-----	-----	-----	-----				
07	-0.44**	0.37**	0.42**	-0.43**				
Phenols 05	0.81**	-0.73**	0.80**	0.79**	0.21			
06	-----	-----	-----	-----	-----			
07	0.66**	-0.25	0.58**	0.75**	-0.24			
SM 05	-0.29*	0.06	-0.40**	-0.42**	-0.04	-0.10		
06	-----	-----	-----	-----	-----	-----		
07	-0.13	-0.26*	-0.27*	-0.10	-0.05	-0.27*		
TA 05	-0.36**	-0.05	-0.25	-0.27*	-0.16	-0.18	0.35**	
06	-----	-----	-----	-----	-----	-----	-----	
07	0.05	-0.07	-0.35**	-0.31*	-0.26*	-0.40**	0.42**	
Vine size 05	-0.33**	0.66**	-0.34**	-0.37**	-0.25	-0.59**	-0.01	-0.24
06	-----	-----	-----	-----	-----	-----	-----	-----
07	-0.05	0.51**	-0.15	-0.35**	0.12	-0.49**	0.05	0.48**
Leaf ψ 05	0.11	0.28	0.09	0.07	-0.09	0.02	-0.20	-0.15
06	-----	-----	-----	-----	-----	-----	-----	-----
07	-0.06	0.24	-0.25	-0.43	0.05	-0.47	0.35	0.81**
Yield 05	0.03	0.09	0.19	0.26*	-0.61**	-0.27*	-0.31*	0.04
06	-----	-----	-----	-----	-----	-----	-----	-----
07	-0.31*	0.15	-0.17	-0.05	-0.01	-0.05	-0.18	-0.38**

spatially only at the CDC location over the 2005-2006 vintages, and in the 2006-2007 vintages, it was only consistent at the Harbour site (Table 7). At all other sites, spatial distribution differed substantially across vintages, and sometimes showed inverse temporal correlations between seasons. Berry TA was temporally consistent at three locations in both the 2005-06 seasons as well as the 2006-07 seasons, particularly at the Harbour site. pH showed temporal consistency in four sites (2005-06) and five sites (2006-07). Color intensity was consistent three locations (2005-06), and four locations (2006-07), particularly at the Hernder site in the 2006-2007 vintages. Anthocyanins were spatially consistent at four sites (2005-06) and at six locations (2006-07), particularly at the Cave Spring site in 2005-2006, and at both the Hernder and Morrison sites in 2006-07. Phenols were consistent at five sites (2005-06) and four sites (2006-07), most notably CDC over all three vintages, while at HOP phenols were particularly consistent in the 2005-2006 vintages and at Harbour they were particularly consistent in the 2006-2007 vintages.

Discussion

This investigation was initiated to identify major factors that contribute to the *terroir* effect, *i.e.* the impact of site upon berry composition and wine varietal typicity, in the vineyards of the Niagara Peninsula in Ontario. It was hypothesized, consistent with Seguin (1986), that the main factors would be indirectly soil-texture based, but it was specifically hypothesized, consistent with van Leeuwen (2010), van Leeuwen and Seguin (1994), van Leeuwen *et al.* (2004), and van Leeuwen *et al.* (2009) that the *terroir* effect would be based upon soil moisture, vine water status, or both. These hypotheses were for the most part proven in this and the companion papers. Distinct spatial patterns in soil texture, soil moisture, and leaf ψ were demonstrated. Spatial patterns in soil moisture were consistently temporally stable, and leaf ψ spatial variability was also occasionally temporally stable. Temporal variations in their spatial patterns were likely influenced by the volatile precipitation patterns typical of the region. Spatial correlations

Table 6. contd.. Spatial correlations 2005-2007—Yield, vine size, berry composition, soil moisture

Morrison								
	Antho	BWT	Brix	Color	pH	Phenols	SM	TA
BWT 05	-----[b]							
06	-0.62**							
07	-0.30*							
Brix 05	-----	-----						
06	0.41**	-0.01						
07	0.77**	0.11						
Color 05	-----	-----	-----					
06	0.04	0.20	0.70**					
07	0.88**	-0.58**	0.52**					
pH 05	-----	-----	-----	-----				
06	-0.48**	0.25	-0.56**	-0.49**				
07	0.82**	0.11	0.84**	0.55				
Phenols 05	-----	-----	-----	-----	-----			
06	0.57**	-0.29*	0.48**	0.05	-0.11			
07	0.79**	-0.15	0.71**	0.75**	0.73**			
SM 05	-----	-----	-----	-----	-----	-----		
06	0.08	-0.01	0.25	0.17	-0.17	0.38**		
07	0.08	0.16	0.19	-0.16	0.13	-0.24		
TA 05	-----	-----	-----	-----	-----	-----	-----	
06	0.24	-0.54**	-0.21	-0.22	-0.30*	-0.10	-0.38**	
07	-0.48**	0.59**	0.03	-0.55**	-0.17	0.26*	0.09	
Vine size 05	-----	-----	-----	-----	-----	-----	0.09	-----
06	-0.44**	0.36**	-0.53**	-0.26*	0.50**	0.05	0.13	-0.31*
07	0.07	0.82**	0.49**	-0.26*	0.51**	0.27*	0.07	0.46**
Leaf ψ 05	-----	-----	-----	-----	-----	-----	0.70**	-----
06	0.16	-0.17	-0.27	-0.53*	0.34	0.28	0.19	0.03
07	0.39	0.28	0.38	0.19	0.43	-0.13	0.40	0.14
Yield 05	-----	-----	-----	-----	-----	-----	-----	-----
06	-0.29*	0.48**	0.23	-0.17	0.33**	-0.30*	-0.31*	-0.45**
07	-0.71**	-0.04	-0.76**	-0.42**	-0.85**	-0.52**	-0.52**	0.11

*, **: Significant at $p \leq 0.05$ or 0.01 (boldfaced values), respectively. [a] Correlation coefficients were non-determinable.

existed between soil moisture, leaf ψ, soil physical and composition variables, yield components, and berry composition.

Impact of vine water status on fruit composition: The role of vine water relations as an important driver of the *terroir* effect, particularly upon fruit composition, was established by both Seguin (1986) and van Leeuwen *et al.* (2004, 2009). It is likely that the effects of climate and soil on fruit composition are mediated through their influence on vine water status (van Leeuwen *et al.*, 2004). Generally, coarse-textured gravelly soils with exceptional drainage or shallow, fine-textured soils with low growth potential will lead to mild water stress, and in red wine cultivars, this will consequently result in higher Brix and anthocyanins, and lower berry weights, vine size, and TA (van Leeuwen, 2010; van Leeuwen and Seguin, 1994; van Leeuwen *et al.*, 2004; 2009). Work with Cabernet franc in St. Emilion underscored the importance of low leaf ψ during the veraison to harvest period in terms of ultimate wine quality. Sites with low vine water status had fruit with highest Brix, anthocyanins, and phenols (van Leeuwen and Seguin, 1994). Similar conclusions were reached from work conducted in Greece on

Table 7. Temporal correlations 2005-2007 for ten Cabernet franc sites in the Niagara Peninsula in Ontario. Abbreviations: Antho: anthocyanins; SM: soil moisture; TA: titratable acidity

2005-2006											
Site	Antho	BWT	Brix	Color	pH	Phenols	SM	TA	Vine size	Leaf ψ	Yield
Buis	0.42**	0.62**	-0.10	0.52**	0.06	0.31*	-0.34	0.08	0.66**	0.14	-0.25
Cave	0.68**	0.76**	0.04	-0.02	0.37**	0.14	0.45**	0.05	0.73**	0.22	0.65**
CDC	0.34**	0.31*	0.50**	0.54**	0.59**	0.69**	0.56**	0.35**	0.58**	0.40	-0.34
George	0.29*	0.11	0.22	0.41**	-0.63	0.22	0.50**	0.20	0.76**	-0.28	0.69**
Harbour	0.10	-0.31	-0.12	0.14	0.29*	0.32*	0.50**	0.75**	0.55**	0.65**	-----[a]
Hernder	-0.51	-0.08	0.23	-0.18	0.04	-0.53	0.42**	0.35**	0.16	0.83**	0.07
HOP	-0.20	0.21	0.21	-0.01	0.46**	0.76**	0.53**	-0.25	0.10	0.03	0.25
Morrison	-----[a]	-----	-----	-----	-----	-----	0.52**	-----	-----	0.24	-----
Reif	-0.09	0.11	-0.51	-0.07	-0.21	0.26*	0.84**	-0.15	0.60**	0.39	-0.38
Vieni	-----[a]	-----	-----	-----	-----	-----	0.59**	-----	-----	0.44	-----
2006-2007											
Site	Antho	BWT	Brix	Color	pH	Phenols	SM	TA	Vine size	Leaf ψ	Yield
Buis	0.03	-0.03	-0.21	0.10	0.56**	0.25	0.82**	0.01	0.86**	-0.40	0.41**
Cave	-0.23	0.84**	-0.05	-0.29	0.27*	0.38**	0.68**	0.32*	0.48**	0.50*	0.27*
CDC	0.54**	0.78**	0.13	0.53**	-0.12	0.81**	0.78**	0.30*	0.82**	-0.09	0.68**
George	0.15	0.43**	-0.27*	0.27*	0.47**	0.18	0.45**	0.02	0.68**	0.45	0.59**
Harbour	0.53**	0.70**	0.70**	0.19	-0.01	0.88**	0.41**	0.68**	0.36**	0.66**	-----[a]
Hernder	0.83**	0.39**	-0.17	0.75**	0.10	0.13	0.59**	-0.64	0.10	0.04	-0.12
HOP	0.47**	0.21	-0.04	0.09	0.39**	-0.15	0.71**	-0.14	0.36**	0.47	0.58**
Morrison	0.68**	0.45**	-0.53	-0.25	0.37**	-0.22	0.71**	-0.53	0.68**	0.17	0.05
Reif	0.33**	0.34**	-0.30	0.33**	-0.11	0.40**	0.87**	-0.04	-0.03	0.84**	0.56**

Table 7. contd. Temporal correlations 2005-2007 for ten Cabernet franc sites in the Niagara Peninsula in Ontario. Abbreviations: Antho: anthocyanins; SM: soil moisture; TA: titratable acidity

					2005-2007						
Site	Antho	BWT	Brix	Color	pH	Phenols	SM	TA	Vine size	Leaf ψ	Yield
Buis	0.46**	-0.07	0.70**	0.25	0.26*	-0.13	-0.14	-0.45	0.75**	-0.45	-0.26
Cave	-0.21	0.79**	0.49**	0.47**	0.71	-0.04	0.62**	0.01	0.44**	-0.12	0.47**
CDC	-0.11	0.22	0.09	0.31*	0.05	0.74**	0.69**	-0.06	0.45**	-0.05	-0.13
George	0.28*	0.67**	0.33**	-0.09	-0.43	0.39**	0.44**	0.15	0.91**	0.08	0.66**
Harbour	0.05	-0.03	-0.06	0.31*	0.50	0.57**	0.57**	0.70**	0.42**	0.47	----[b]
Hernder	-0.38	0.29*	0.26*	-0.04	-0.08	-0.24	-0.10	0.24	0.06	0.11	0.14
HOP	-0.50	0.64**	0.33**	-0.26	0.59	-0.14	0.59**	0.19	0.55**	-0.40	0.20
Morrison	-----[a]	-----	-----	-----	-----	-----	0.55**	-----	-----	0.65**	-----
Reif	0.27*	0.35**	0.52**	0.41**	-0.03	0.17	0.67**	-0.17	-0.15	0.36	-0.19
Vieni	0.26*	0.57**	0.53**	0.45**	0.20	0.41**	0.66**	-0.10	0.35**	0.66**	0.05

*, **: Significant at $P \leq 0.05$ or 0.01 (boldfaced values), respectively. Significant inverse correlations are not indicated.

[a] Data were missing due to powdery mildew (Harbour, Vieni 2006) and winter injury (Morrison 2005).

[b] Correlation coefficients were non-determinable.

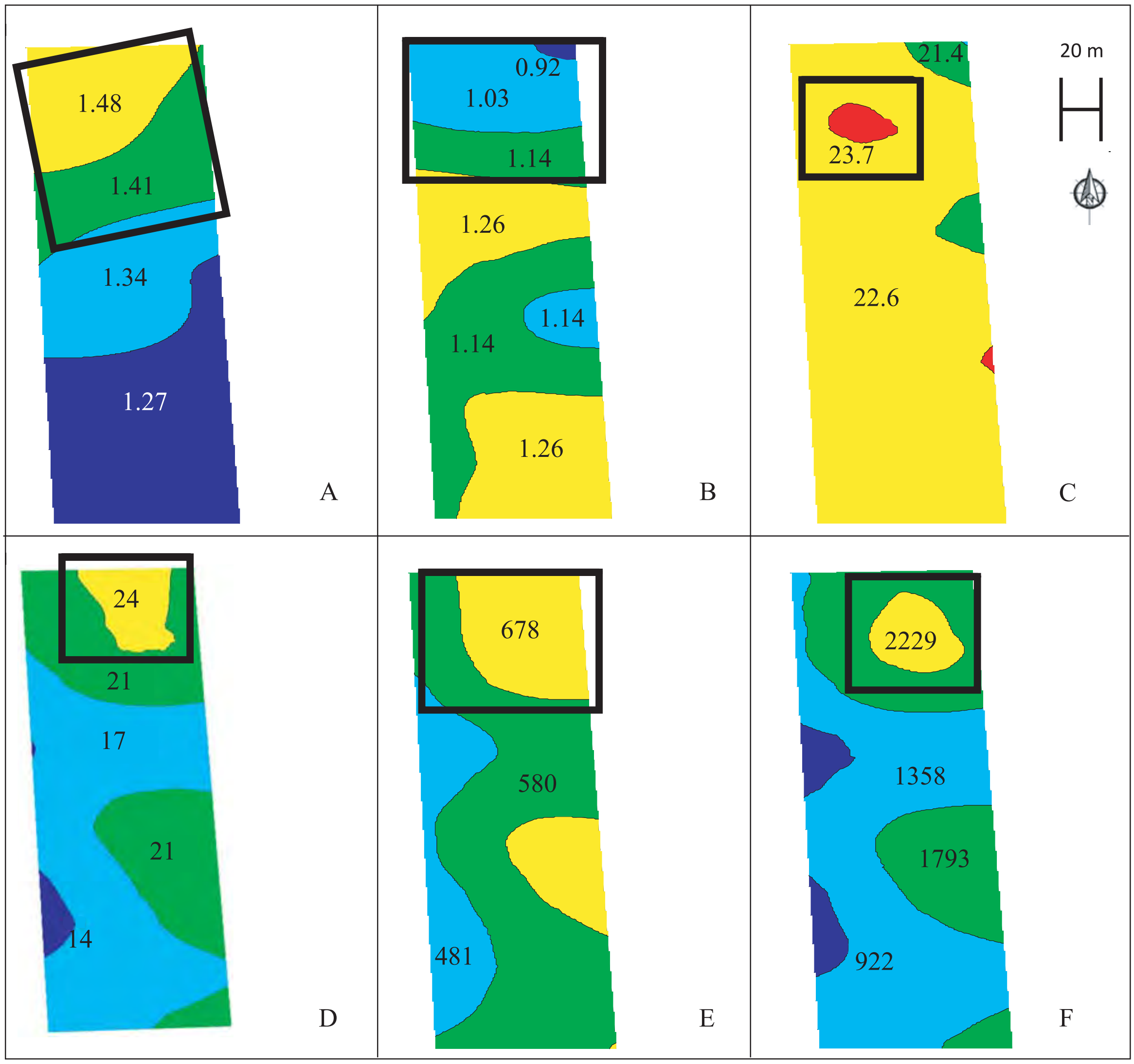

Fig. 4. Spatial variation in; A: Leaf water potential (- bars); B: Berry weight (g): C: Berry Brix; D: Berry color absorbance (A420 + A520): E: Berry total anthocyanins (mg/L): F: Berry total phenols (rng/kg). Chateau des Charmes Vineyard. St. Davids. ON. 2005. Zones marked by black polygons are those with lowest leaf water potential and berry weight, and highest Brix. absorbance. total anthocyanins, and total phenols. Values represent the lower limit within each zone.

Agiorgitiko (Koundouras *et al.*, 1999).

Brix, color intensity, anthocyanins, and phenols were inversely correlated with leaf ψ, particularly in the 2005 season, while TA was directly correlated with leaf ψ in all 3 years (Table 5).

Higher Brix values were observed at seven sites in LWS vines (Table 1). Larger berries normally have lower Brix than smaller berries due to increased water to soluble solids ratio, consistent with these results (Smart and Coombe, 1983; van Leeuwen *et al.*, 2004). However, this is not always the case, since low leaf ψ

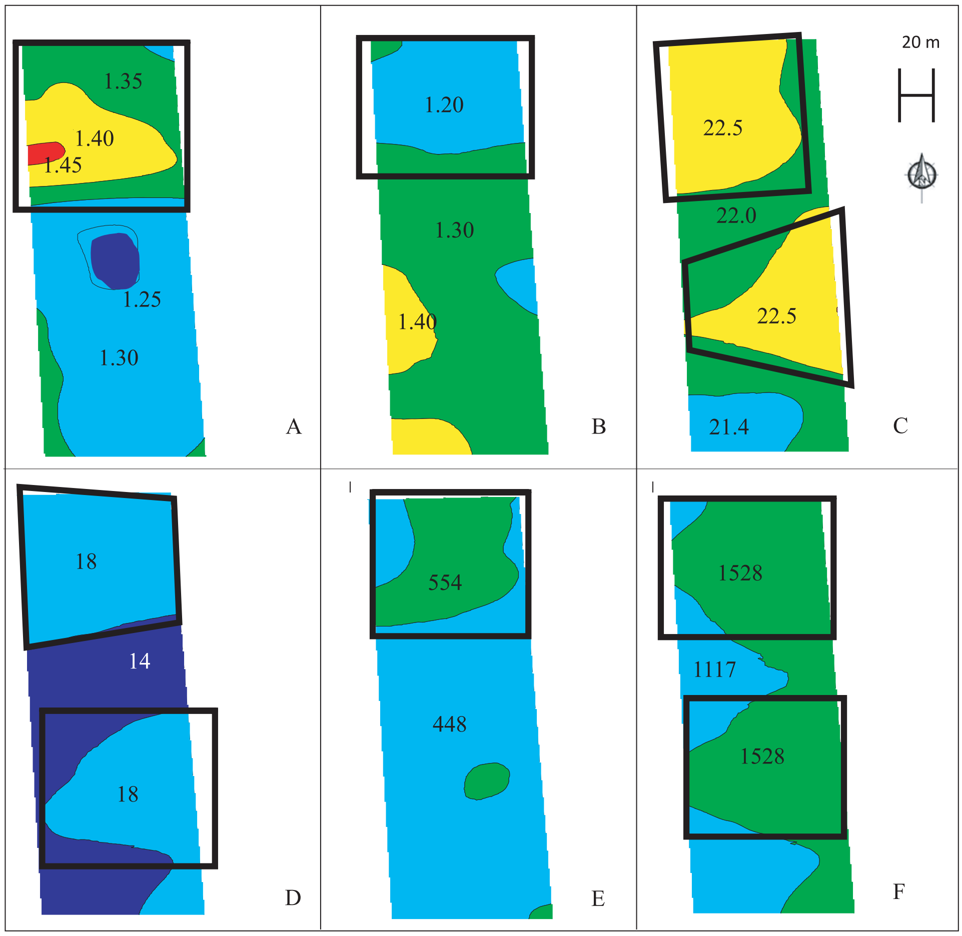

Fig. 5. Spatial variation in; A: Leaf water potential (- bars); B: Berry weight (g): C: Berry Brix; D: Berry color absorbance (A420 + A520): E: Berry total anthocyanins (mg/L): F: Berry total phenols (rng/kg). Chateau des Charmes Vineyard, St. Davids. ON. 2006. Zones marked by black polygons are those with lowest leaf water potential and berry weight, and highest Brix. absorbance. total anthocyanins, and total phenols. Values represent the lower limit within each zone.

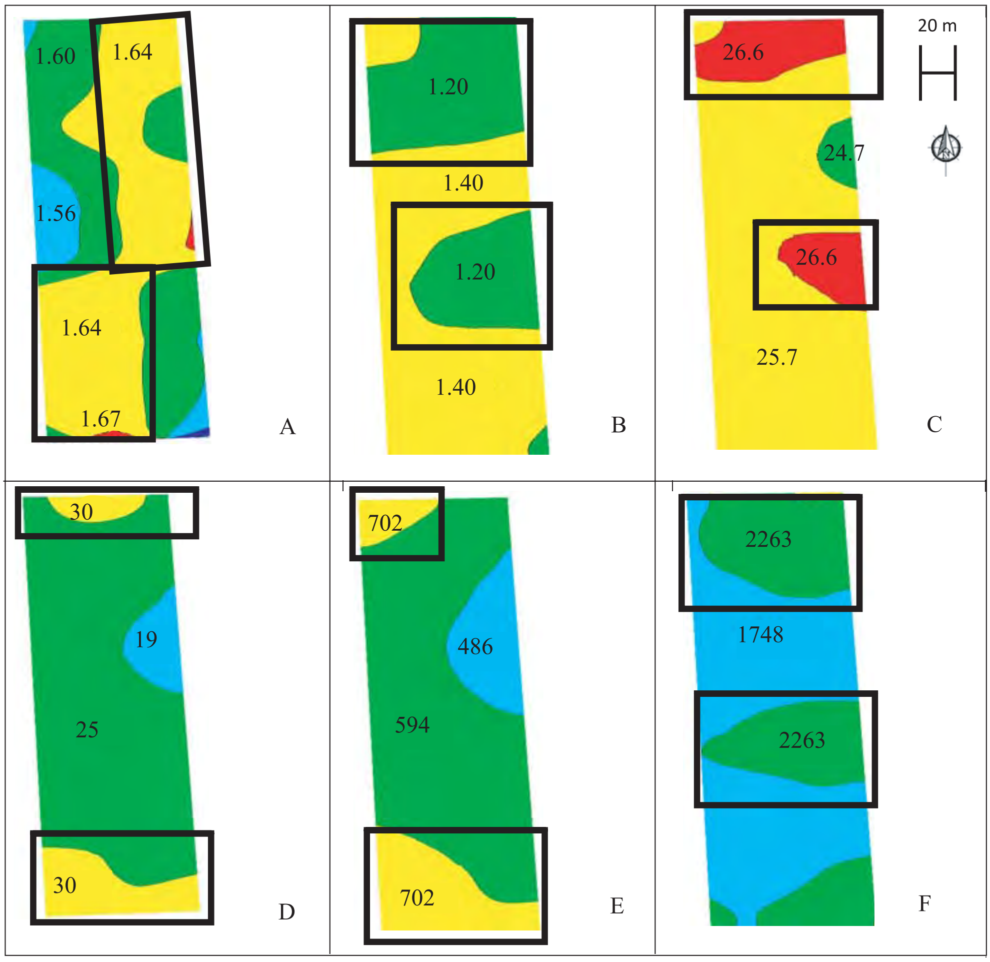

Fig. 6. Spatial variation in; A: Leaf water potential (- bars); B: Berry weight (g): C: Berry Brix; D: Berry color absorbance (A420 + A520): E: Berry total anthocyanins (mg/L): F: Berry total phenols (mg/kg). Chateau des Charmes Vineyard, St. Davids. ON. 2007. Zones marked by black polygons are those with lowest leaf water potential and berry weight, and highest Brix. absorbance. total anthocyanins, and total phenols. Values represent the lower limit within each zone.

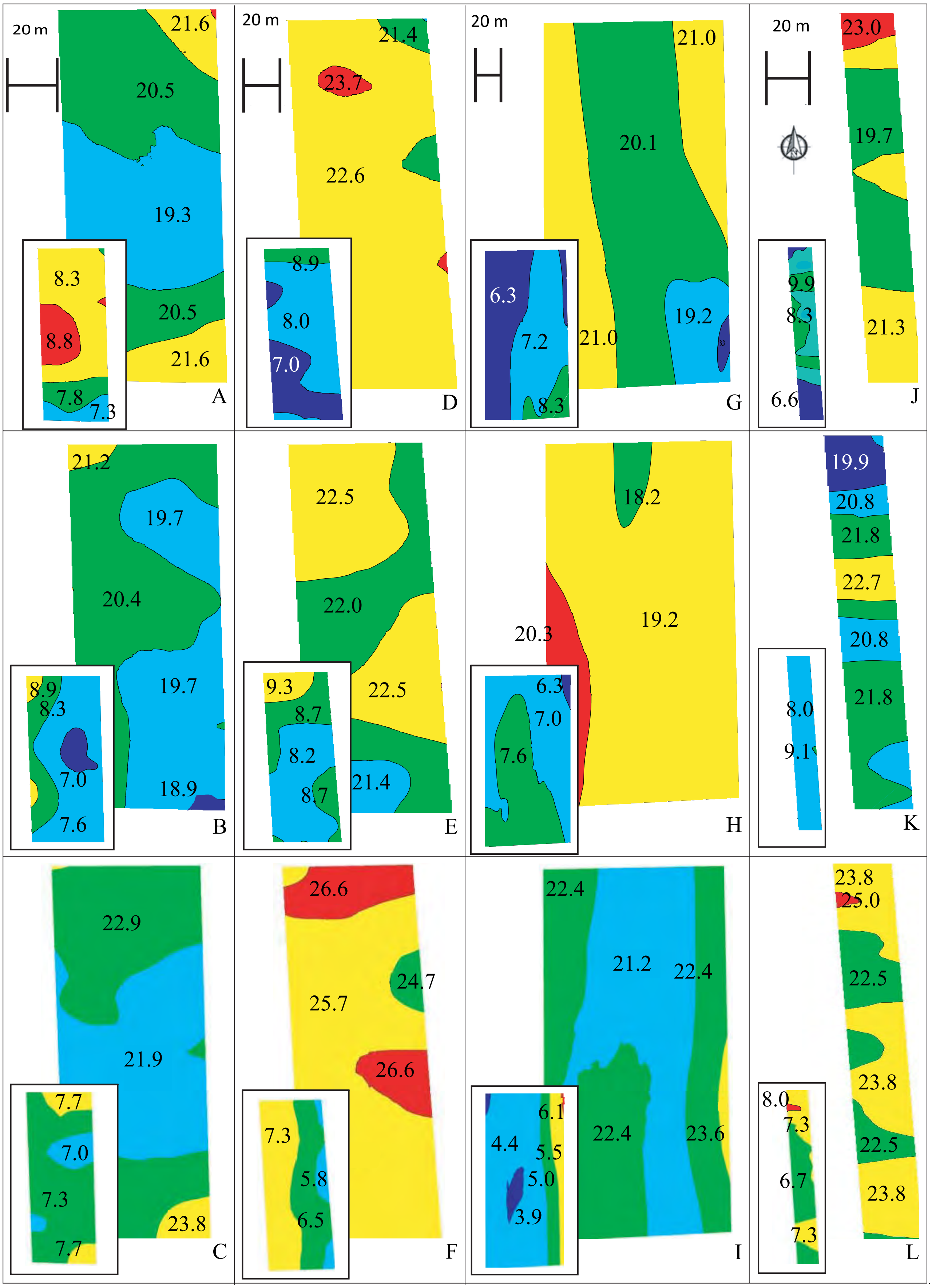

Fig. 7. Spatial distribution of Brix. Cabernet franc. Niagara Peninsula. ON: A to C: Buis: 2005 (A): 2006 (B); 2007 (C) D to F: Chateau des Charmes: 2005 (D); 2006 (E); 2007 (F) G to I: Hemder: 2005 (G); 2006 (H); 2007 (I). J to L: Reif: 2005 (J); 2006 <K); 2007 (L). Insets (not to scale): Spatial distribution of titratable acidity (g/L). Numbers on the maps refer to the minimum value in the range for each zone

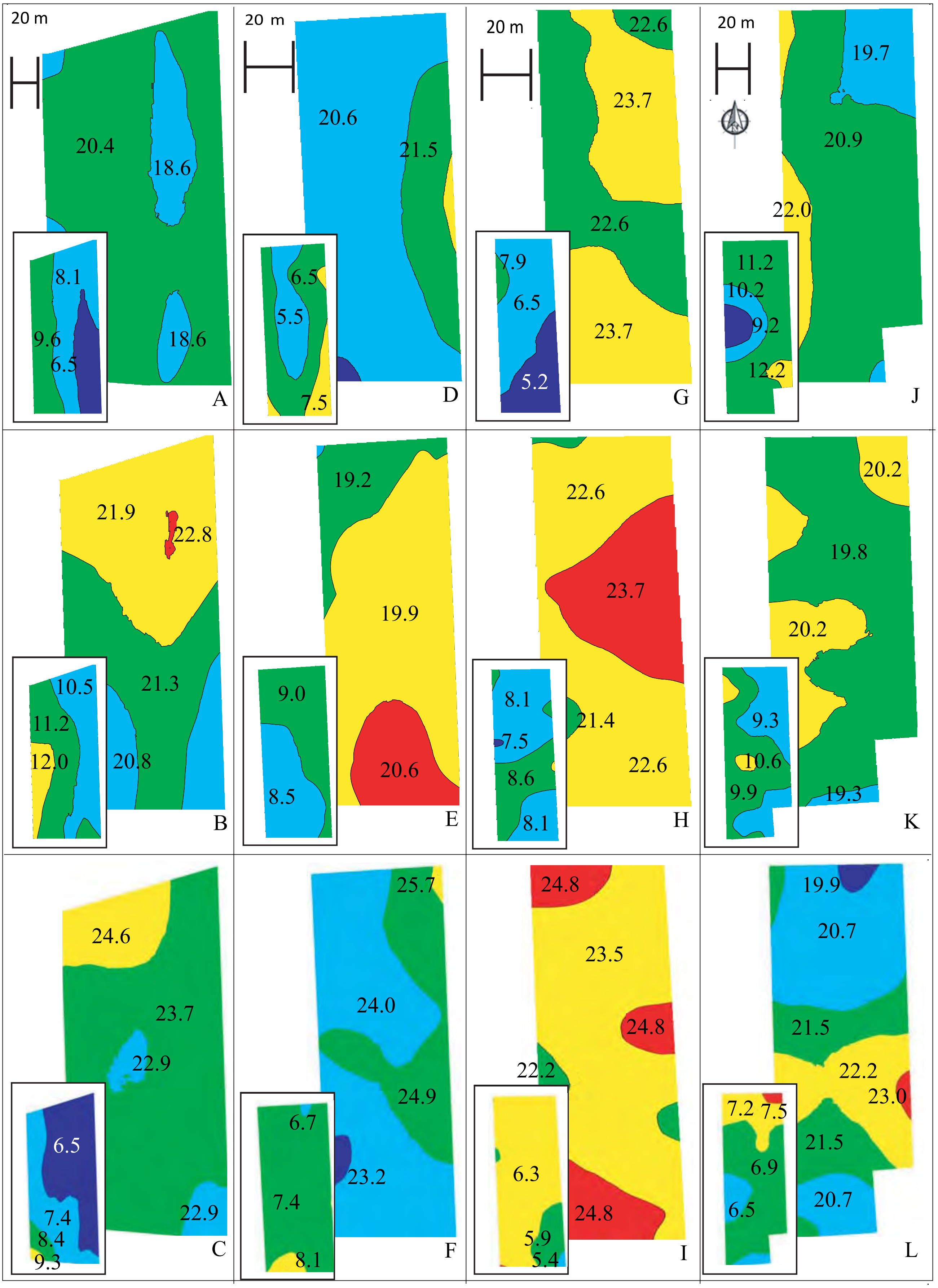

Fig. 8. Spatial distribution of Brix. Cabernet franc. Niagara Peninsula, ON: A to C: Harbour Estate: 2005 (A): 2006 (B); 2007 (C) D to F: George: 2005 (D): 2006 (E); 2007 (F). G to I: Cave Spring: 2005 (G); 2006 (H); 2007 (I). J to L: Henry of Pelham: 2005 (J); 2006 (K); 2007 (L). Insets (not to scale): Spatial distribution of titratable acidity (g/L). Numbers on the maps refer to the minimum value in the range for each zone

reduces photosynthesis, the source of sugar, by closing stomates to reduce transpiration (Smart and Coombe, 1983), and reduced photosynthesis lowers Brix in water-stressed grapevines (Hardie and Considine, 1976). High water availability can increase Brix by enhanced photosynthetic activity or increased leaf area, which is consistent with studies comparing irrigated vs. non-irrigated vines (e.g. Esteban, *et al.*, 1999). On the other hand, although Brix can be increased by mild water stress, sugar content on a whole-

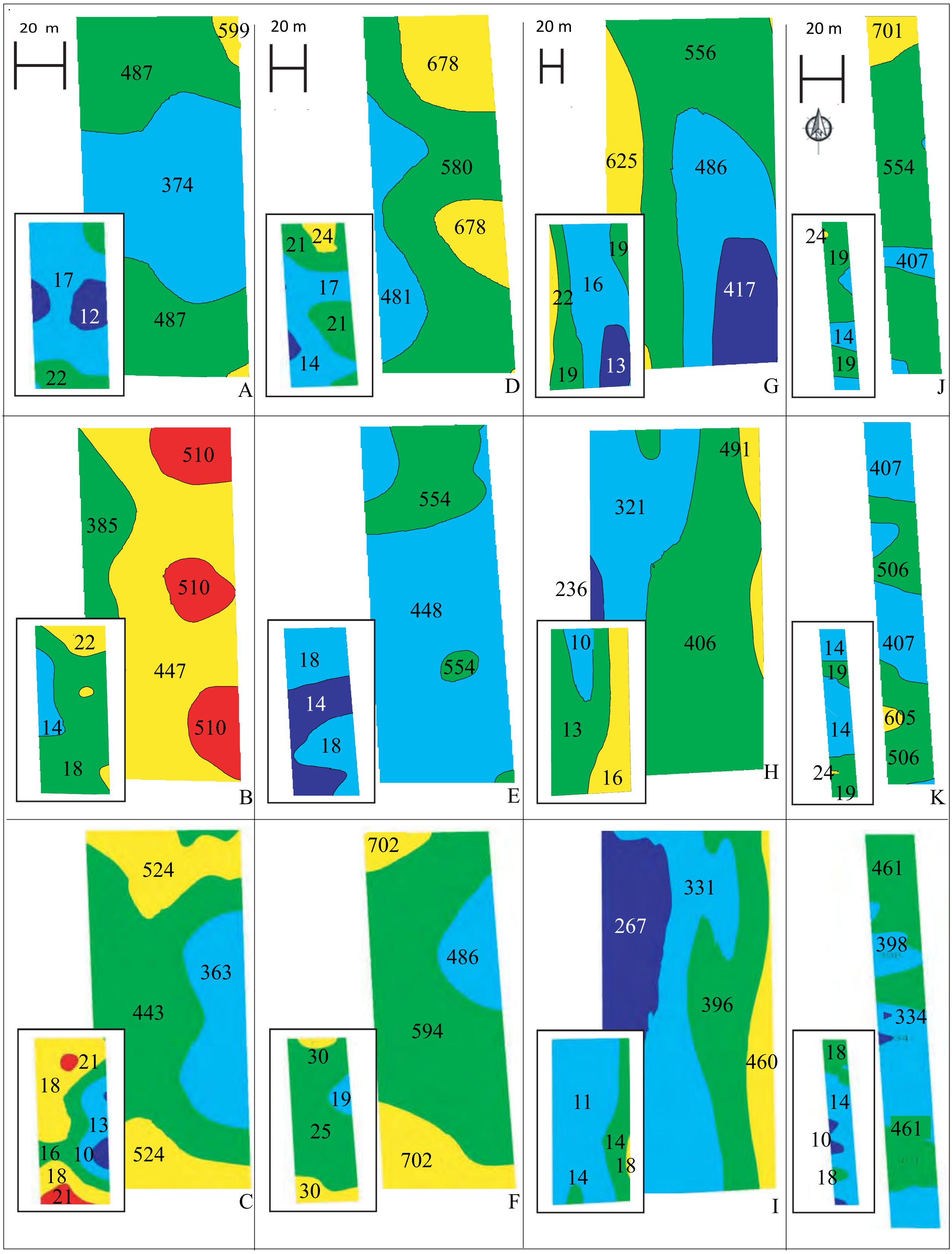

Fig. 9. Spatial distribution of berry total anthocyanins (mg/L), Cabernet franc. Niagara Peninsula. ON; A to C: Buis: 2005 (A); 2006 (B); 2007 (Q D to F: Chateau des Charmes: 2005 (D); 2006 (E); 2007 (F). G to I: Hernder: 2005 (G); 2006 (H); 2007 (I). J to L: Reif: 2005 (J); 2006 (K); 2007 (L). Insets (not to scale): Spatial distribution of berry color intensity. Numbers on the maps refer to the minimum value in the range for each zone.

vine basis is reduced, and advances in fruit ripening induced by water stress may be associated solely with reductions in berry weight (Hardie and Considine, 1976). Therefore, although total sugar production on a per vine basis may decrease, higher Brix in LWS berries was due to the concentrating effect of smaller berries.

TA levels are typically more dependent upon vintage and fruit exposure than on soil and vine water status (Smart, 1985; van

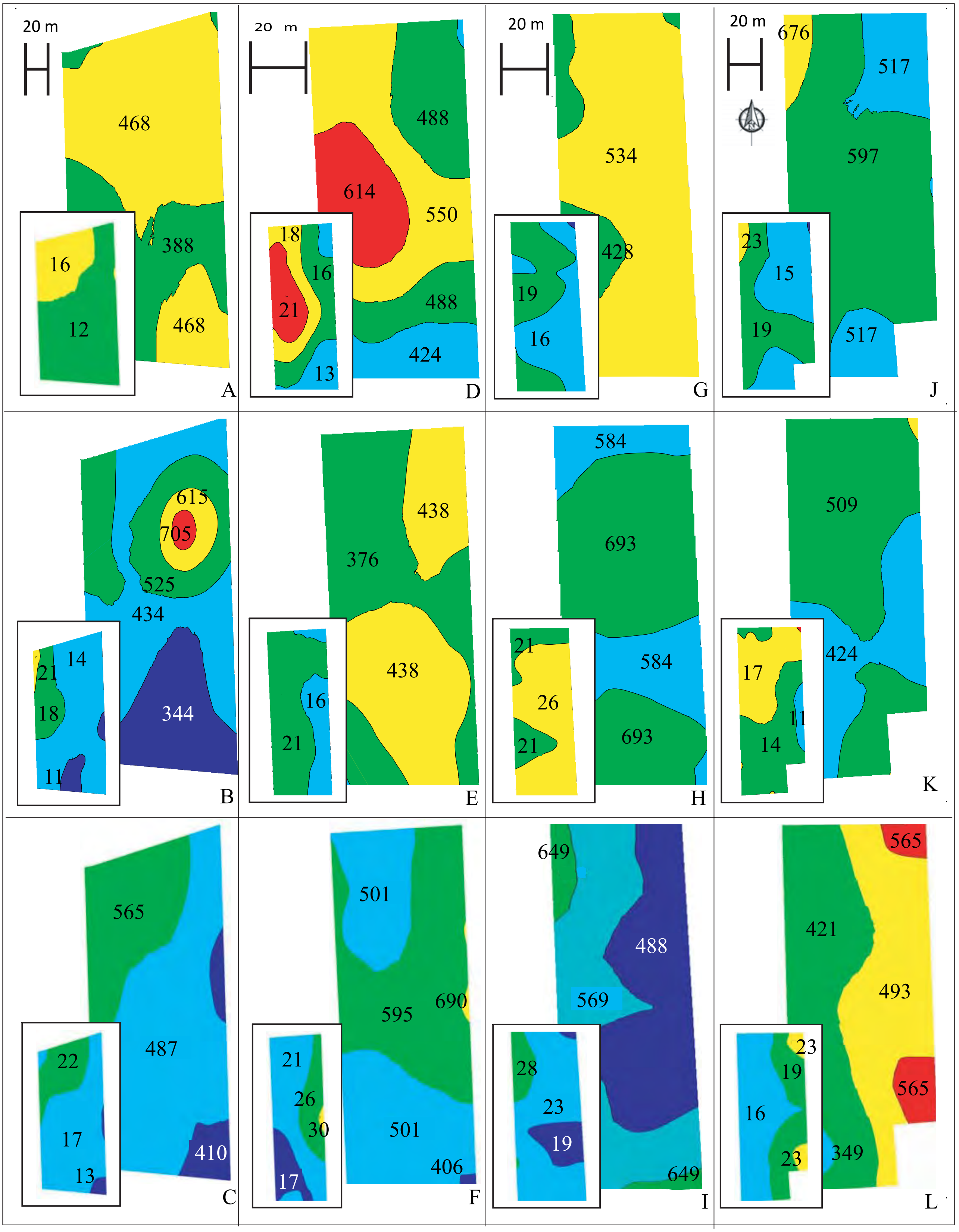

Fig. 10. Spatial distribution of berry total anthocyanms (mg/L). Cabernet franc, Niagara Peninsula, ON; A to C: Harbour Estate: 2005 (A); 2006 (B); 2007 (C). D to F: George: 2005 (D); 2006 (E); 2007 (F). G to I: Cave Spring: 2005 (G); 2006 (H); 2007 (I). J to L: Henry of Pelham: 2005 (J); 2006 (K); 2007 (L). Insets (not to scale): Spatial distribution of berry color intensity. Numbers on the maps refer to the minimum value in the ranee for each zone.

Leeuwen *et al.*, 2004). TA values were highest at nine site X year combinations in HWS vines while only one site in 2006 had lower values in HWS vines (Table 1). TA and leaf ψ (a.v.) were inversely correlated each season (Table 5). This relationship between TA and vine water status could be attributed indirectly to low light levels within the canopies, since high water availability increases vegetative growth and shade inside the canopy (Smart, 1985; Smart, *et al.*, 1985). Berry malic acid is subject to degradation from veraison to maturity and in this case its concentration was decreased less with increased water availability (q.v. Seguin, 1975). Canopy shading decreases the rate of malate degradation (Kliewer and Lider, 1968). It is noteworthy, however, that TA values in HWS vines were lower at Cave Spring (2006), which is at odds with most literature. A possible explanation could be that higher precipitation in 2006 increased vegetative growth at that site, or water might have diluted berry contents including the acids.

Generally vine and soil water status do not play a major role in determination of berry pH (van Leeuwen *et al.*, 2004). However, pH can be increased substantially as a result of either high berry K concentrations or cluster shading (Morrison, 1988; Smart and Coombe, 1983). Highest pH values were observed at seven site X year combinations over the 3-year period in LWS vines, while

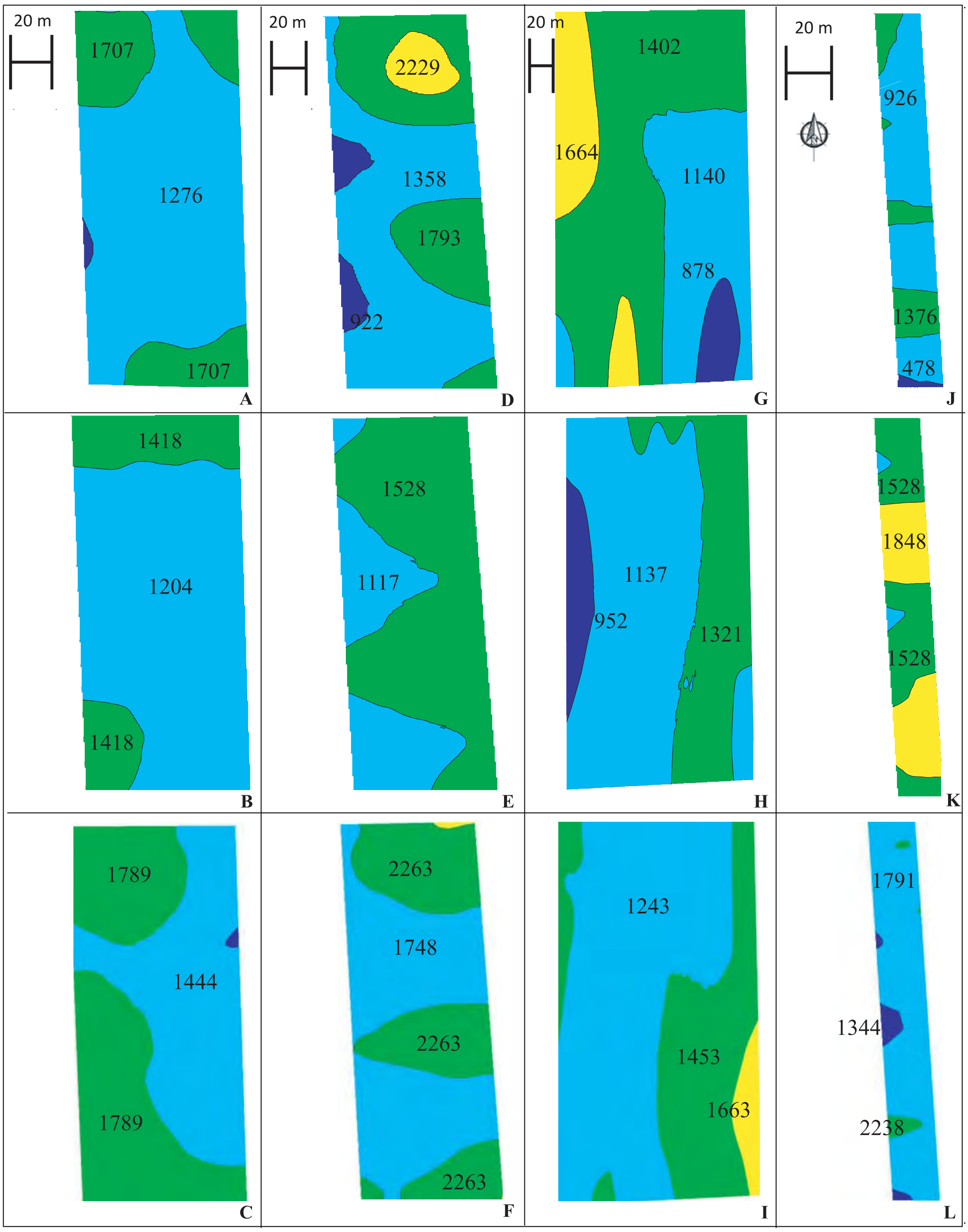

Fig. 11. Spatial distribution of berry total phenols (mg/L). Cabernet franc, Niagara Peninsula. ON: A to C: Buis: 2005 (A); 2006 (B); 2007 (C). D to F: Chateau des Charmes: 2005 (D); 2006 (E): 2007 (F). G to I: Hernder: 2005 (G); 2006 (H); 2007 (I). J to L: Reif: 2005 (J); 2006 (K): 2007 (L). Numbers on the maps refer to the minimum value in the range for each zone.

lower values were observed at one site in LWS vines (Table 1). No correlations were noted between pH and leaf ψ (Table 5). Although speculative, low pH in LWS berries could have been attributed to high temperatures and high light levels in the canopy, lower canopy size, and possibly higher malate degradation in the fruit (Smart and Coombe, 1983). High cluster exposure in non-irrigated vines, due to reduced vigor associated with low water availability, will typically reduce pH (Smart and Coombe, 1983). Shading, on the other hand, normally results in higher berry K concentrations and higher pH than non-shaded vines, thus K levels may play a role in determining juice pH (Morrison, 1988). Correlations between pH and soil K were observed in 2 of

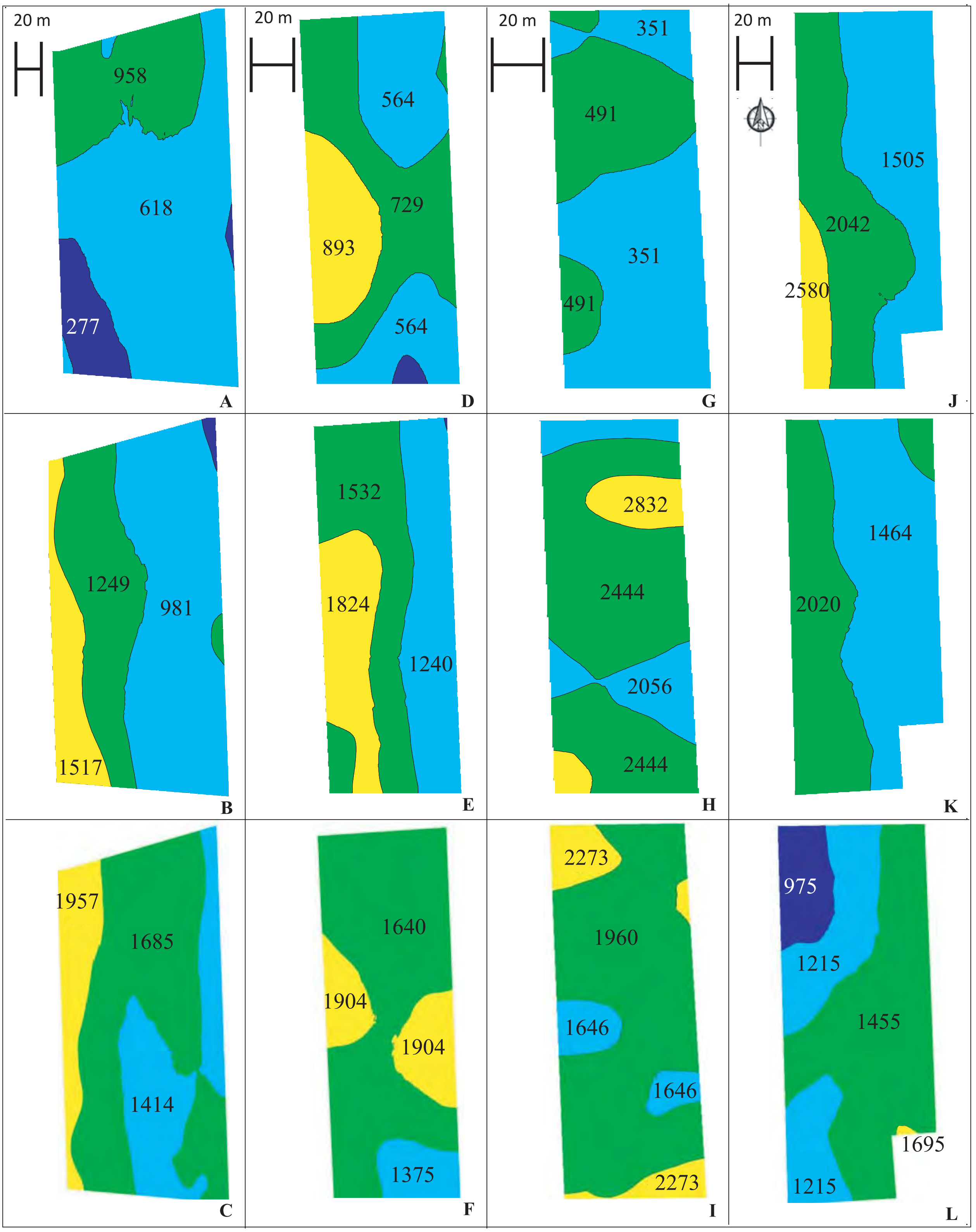

Fig. 12. Spatial distribution of berry total phenols (mg L). Cabernet franc. Niagara Peninsula. ON: A to C: Harbour Estate: 2005 (A); 2006 (B); 2007 (C). D to F: George: 2005 (D); 2006 (E); 2007 (F). G to I: Cave Spring: 2005 (G); 2006 (H); 2007 (I). J to L: Henry of Pelham: 2005 (J); 2006 (K); 2007 (L). Numbers on the maps refer to the minimum value in the range for each zone.

3 seasons (Table 5). Inexplicably, there was higher pH in LWS vines in most cases, likely due to advanced fruit maturity. It is noteworthy that pH differences between HWS and LWS were more obvious in the hot and dry 2005 and 2007 seasons.

Color intensity, anthocyanins, and phenols are very responsive to soil and vine water status (van Leeuwen *et al.*, 2004; 2009). Color intensity, anthocyanins, and phenols were all inversely correlated with leaf ψ, particularly in 2005 (Table 5). Color intensity was highest at five sites in LWS vines, all in 2007; however, lower color intensity was also observed at one site (2005), three sites (2006), and two sites (2007) in LWS vines (Table 2). Albeit speculative, lower color intensity in LWS vines at these sites could have been due to excessive temperatures of sunlight-exposed clusters that led to reduced berry color, particularly in the low vigor sites (e.g. Cave Spring, Hernder, Vieni) during the warm 2005 and 2007 seasons. This is in agreement with Bergqvist *et al.* (2001) that stated that berry temperatures > 35 ^{o}C inhibited color formation. There was an inverse correlation between berry weight and leaf ψ in all three seasons, and therefore the high color intensity at the five sites in LWS vines in 2007 could have been due to smaller berries as the result of less available water to vines. This is in agreement with findings that showed higher color intensity in vines with greater sun exposure in the fruiting zone from deficit irrigation (Mazza *et al.*, 1999).

Free-draining gravelly soils or shallow clay soils have a tendency to lead to low water status, and this has been associated with elevated concentrations of anthocyanins in berries (Koundouras *et al.*, 1999; van Leeuwen, 2010; van Leeuwen and Seguin, 1994; van Leeuwen *et al.*, 2004; 2009). Consequently, highest anthocyanins were observed at five site X year combinations in LWS vines, although lower values were also observed at one site each in 2006 and 2007 in LWS vines (Table 2). The impact of vine water status on color intensity paralleled those of anthocyanins in most sites. The largest differences between water status categories were observed in the hot and dry 2007 year. Water stress may increase or decrease development of anthocyanins in the grape skin depending upon circumstances (Hardie and Considine, 1976; van Leeuwen, 2010; van Leeuwen and Seguin, 1994; van Leeuwen *et al.*, 2004; 2009). This is in agreement with the findings of this study as well as those obtained with Sovereign Coronation table grapes in the Niagara region (Reynolds *et al.*, 2009). Berry skin anthocyanin concentrations from irrigated vines are typically lower than from non-irrigated lower-yielding vines (Esteban *et al.*, 1999). The positive effect of water stress on anthocyanin production is not simply due to decreases in berry size, since the effect is also observed when anthocyanin concentration is expressed on a berry surface area basis (Smart and Coombe, 1983). In fact, irrigation may increase anthocyanin development in red grape cultivars under some circumstances (Bravdo *et al.*, 1985). Therefore, with consistent correlations between berry weight and leaf ψ, the high anthocyanins in LWS were likely due to a concentration effect of smaller berries resulting from low available water, and increased cluster exposure to light due to the smaller canopy size resulting from less available water, which stimulates anthocyanin accumulation in grape berries (Bergqvist *et al.*, 2001; Coipel *et al.*, 2006; van Leeuwen *et al.*, 2004; 2009), or a direct effect of water stress on anthocyanin synthesis. Lower anthocyanin concentration was found in LWS vines at some sites. This could be due to higher temperatures at those specific sites that resulted in decreased anthocyanin concentrations. This is in agreement with Spayd *et al.* (2002), in which high berry temperatures reduced anthocyanin concentration in west-exposed fruit. Sunlight exposed berries increased temperatures from 3 to 13°C compared to non-exposed fruit due to incident radiation (Bergqvist *et al.*, 2001; Spayd *et al.*, 2002).

As with anthocyanins and color intensity, sites or zones with low soil and vine water status typically will have high concentrations of berry phenols relative to high water status sites (Koundouras *et al.*, 1999). Phenols were higher at four site X year combinations in LWS vines; however, lower values in LWS vines were also observed at four other sites (Table 2). Higher phenols in LWS vines are attributable to small canopy size and high cluster exposure to sunlight, resulting from diminished vegetative growth under conditions of low water availability (Coipel *et al.*, 2006; van Leeuwen *et al.*, 2004; 2009). Lower phenol levels were attributed to canopy shading (Smart *et al.*, 1985). Overall shading (leaf and berry) will reduce fruit Brix, tartaric acid, anthocyanins and phenols and increase malic acid and pH (Smart *et al.*, 1985). Temperature may have a direct effect on anthocyanin and phenolic concentration; concentrations of anthocyanins and phenols in Merlot berries at temperature ranges of 30 to 35˚C were highest (Bergqvist *et al.*, 2001; Spayd *et al.*, 2002). Temperatures significantly outside this optimal range may partially explain lower phenols in LWS vines.

Impact of vine water status on must and wine composition: The effects of vine water status on fruit composition in the vineyard were occasionally reflected in the composition of musts and wines. Musts were not widely affected by vine water status. Vine water status impact on must composition was slightly more pronounced in the hot and dry 2005 season, but barely noticeable in the wet 2006 year in which only color intensity was affected at one site. Wine composition tended to be more responsive to vine water status than must composition. Lower TA was found in LWS wines at one site in 2005. This can be explained by lower canopy size, better light exposure and higher rate of malic acid degradation (Smart and Coombe, 1983). This is also consistent with data that showed lower water stress was associated with higher TA (Coombe and Monk, 1979). Lower pH was observed in LWS wines at one site in 2006. This could be explained by high temperatures and high light levels in the canopy, and lower canopy size, and is consistent with a study in which shaded microclimates increased must pH and K content (Smart, 1985). Ethanol was higher in LWS category at two sites in 2005. This was due to higher Brix in LWS vines at both sites due to concentration effect of smaller berry size (Smart and Coombe, 1983). Higher color intensity was found in LWS wines at two sites in 2005 and 2006, while anthocyanins were higher at an additional site in 2005. Higher phenols were also found in LWS wines at one site in 2005. These responses can be attributed to less shade and better light exposure due to smaller canopy size as a consequence of less water availability to the vines (Smart, 1985; Smart *et al.*, 1985). Wines often have greater color and phenols from vines exposed to mild water stress during the growing season (Coipel *et al.*, 2006; Koundouras *et al.*, 1999; van Leeuwen *et al.*, 2004).

Impact of soil type: There is substantial evidence for relationships between soil type and Brix in fruit; generally gravelly or fine-textured soils lead to higher Brix than sandy soils (van Leeuwen *et al.*, 2004: 2009). This relationship is likely a consequence of smaller berry size resulting from mild water stress on well-drained gravelly soils or shallow clay soils. In this study, relationships between soil and fruit composition variables were inconsistent, which generally confirms results of others in continental climates with volatile precipitation patterns (Reynolds and de Savigny, 2001; Reynolds *et al.*, 2010; Reynolds *et al.*, 2007). Brix did not show consistent relationships with soil texture. There were positive correlations between % clay and Brix in 2 of 3 years; however, the negative correlation between % sand and Brix was observed only in 2005. In 2007 there was no relationship between Brix and soil texture. Although there was a positive correlation between Brix and most soil variables in 2005, there was only a single positive correlation between Brix and BS and a negative correlation with P in 2006, and no correlations in 2007; therefore overall there appeared to be inconsistent relationships between Brix and soil variables across the three vintages. TA was negatively correlated with % clay in all 3 years, but only positively correlated with % sand in 2007. TA showed some relationships with soil variables which were inconsistent between years. Berry pH had only a single negative correlation with % sand in 2005. There was positive correlation between berry pH with P and K in 2 years; however, other relationships with soil variables were inconsistent between years.

Color intensity positively correlated with % clay and negatively with % sand (2005, 2007), and there were positive correlations between color intensity and CEC, Ca and Mg, plus a negative correlation with K. There were positive correlations between anthocyanins and clay, CEC, soil pH, BS and Ca in 2 years (2005, 2006); anthocyanins were inversely correlated with P and K in 2 years (2006, 2007). Phenols positively correlated with clay, CEC, soil pH, and BS (2005, 2006) and negatively with sand, P and K (2006 and 2007). Color intensity, anthocyanins and phenols positively correlated with clay in 2 of 3 years. This might have been due to the fact that the vines encountered higher water stress in clay soils, which in turn reduced vegetative growth and berry weight and increased skin to juice ratio, so color, anthocyanins and phenols produced mainly in the skins increased as well (Coipel *et al.*, 2006; van Leeuwen *et al.*, 2004; 2009). Since anthocyanins and phenols are highly concentrated in berry skins, higher color intensity, anthocyanins and phenols are found in wines from clay soils (Koundouras *et al.*, 1999; van Leeuwen *et al.*, 2004; 2009). Heavy clay soils on and at the base of the Niagara Escarpment Bench might therefore positively affect color intensity, anthocyanins and phenols compared to sandy soils.

Correlations among variables including vine water status: In the hot and dry 2005 season, leaf ψ, as an indicator of vine water status, correlated (positively or negatively) with many fruit composition variables and ultimately wine sensory characters, while soil texture variables correlated with far fewer fruit composition or wine sensory attributes (Hakimi Rezaei and Reynolds, 2010a,b). In the wet 2006 season, leaf ψ correlated with TA and % sand correlated with phenols; %clay correlated with Brix, TA, anthocyanins and phenols. In 2007, leaf ψ correlated with TA while % sand and % clay correlated with TA and color. Partial least squares (PLS) analysis of the entire data set in 2005 indicated that leaf ψ correlated with several yield components, fruit composition and wine sensory attributes while % sand and clay correlated with few attributes (Hakimi Rezaei and Reynolds, 2010a,b). In 2006 PLS analysis showed the same correlations for leaf ψ and soil texture variables.

Spatial distribution and correlation of fruit composition, soil moisture and leaf ψ: Zonal approaches to terroir using geomatics (GPS and GIS) are relatively recent and are reviewed in Vaudour (2002). Use of GPS and GIS to map yield components and fruit composition was previously accomplished in the Niagara Region on Chardonnay (Reynolds and de Savigny, 2001) and Riesling (Reynolds *et al.*, 2007; 2010; Willwerth *et al.*, 2010). Perhaps the first published use of geomatic tools to map vine water status and related variables such as yield components and fruit composition showed some clear spatial correlations between berry $δ^{13}C$ and stem ψ (van Leeuwen *et al.*2006; van Leeuwen *et al.*, 2009). This supported data showing relationships between predawn leaf ψ and $δ^{13}C$ (Gaudillère *et al.*, 2002). Spatial relationships between phenolics and vine vigor were likewise found in Pinot noir vineyards in Oregon (Cortell *et al.*, 2006). In this study, spatial distribution of yield was temporally stable, as was vine size. Moreover, spatial distributions of yield and vine size were highly positively correlated at most sites. These conditions are crucial for implementation of precision viticulture. Reynolds *et al.* (2007, 2010) and Willwerth *et al.* (2010) found temporally stable spatial distribution in vine size, which is consistent with our results. For implementation of precision viticulture to be meaningful, variables such as berry weight and composition must also be temporally stable and must additionally be spatially correlated with vine size and yield. Berry weight spatial distribution was temporally stable at several sites. Spatial distribution in Brix and TA were apparent at some sites, as were anthocyanins and phenols, particularly at three sites. Overall, spatial distributions were more stable in yield components than berry composition data.

This investigation was initiated to identify the major factors that contribute to the terroir effect in the vineyards of the Niagara Peninsula in Ontario. The usefulness of these investigations will depend upon the temporal stability of the spatial variability in the most important components, particularly those relating to soil and vine water status. Of equal importance was the stability in the relationships between soil and vine water status and fruit composition. If these relationships are stable, the potential for implementation of precision viticulture is high (Bramley, 2005; Proffitt *et al.*, 2006). Another potential innovative application might be the establishment of temporally-stable zones of different flavor potential (Willwerth *et al.*, 2010). In Cabernet franc, 2-methoxy-3-isobutylpyrazine (IBMP) is ubiquitous worldwide, and is influenced by soil type (less IBMP in gravel soils) (Peyrot des Gachons *et al.*, 2005). The norisoprenoid β-damascenone also impacts wine aroma, by contributing its own odor (apple notes), and by enhancement of odor activity (fruity notes) of other compounds, and suppression of odor activity of IBMP in Cabernet franc; its concentration varied with soil type (Pineau *et al.*, 2007). Cysteine precursors of odor-active thiol compounds were closely linked to N status in Sauvignon blanc, and therefore high N zones within vineyards can potentially increase its varietal typicity (Choné *et al.*, 2006).

Ten Cabernet franc vineyard sites in the Niagara Peninsula were mapped using GPS/GIS with respect to midday leaf ψ and soil moisture. Berry composition variables were likewise mapped and many noteworthy relationships were elucidated between vine water status and these other variables. Soil moisture zones were temporally consistent at nine sites from 2005 to 2006 and at 10 of 10 sites from 2006 to 2007. Vine water status zones (leaf ψ) were temporally consistent, particularly at two sites from 2005 to 2006 and from 2006 to 2007. However, specific areas of the vineyard with high and low vine water status appeared to be transient at some sites and their spatial distribution varied temporally (except Harbour Estate that showed consistent water status zones from 2005 to 2007). Vine size zones were likewise temporally consistent (6-7 sites) but yield zones less so (two sites). Areas of low soil and vine water status were positively correlated with areas of high Brix, color, anthocyanins and phenols and negatively correlated with berry weight and TA. In most vineyards, areas of high and low color intensity were positively correlated with areas of high and low anthocyanins and phenols. These data demonstrate the utility of geomatics in creating management zones within vineyard blocks for small lot winemaking, and for creation of multiple wine products from single vineyards based on segregation according to soil moisture or vine size zones.

Acknowledgements

Authors wish to thank the Natural Sciences and Engineering Research Council of Canada and the Wine Council of Ontario for funding. The participation of all grape growers is hereby acknowledged.

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Received: December, 2013; Revised: January, 2014; Accepted: March, 2014