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Spatial variability in Ontario Cabernet franc vineyards. II. Yield components and their relationship to soil and vine water status

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Abstract

The possible influence of vine water status on grapevine yield components was studied in ten *Vitis vinifera* L. Cabernet franc vineyards in the Niagara Peninsula, Ontario from 2005-2007 using geomatic techniques. Soil texture, soil chemical composition, soil moisture and leaf water potential (ψ; vine water status), were determined on ≈ 80 sentinel vines in each vineyard. Water status zones were identified in GIS-generated maps using leaf ψ and soil moisture measurements. Areas of low soil moisture and low vine water status were negatively correlated linearly and spatially with vine size, yield, and berry weight. The frequency of relationships between variables was vineyard- and vintage-dependent. Spatial variability in soil moisture was temporally-stable in all vineyards across the three vintages (8-10 sites; 2005-06, 2006-07, 2005-07), while vine size (6-7 sites), berry weight (2-7 sites) and yield (2-5 sites) were likewise moderately-stable, but leaf ψ was not (two sites). These data suggest that low soil moisture and low vine water status zones in vineyards are related to corresponding areas of low yield and vine size. These data further suggest that precision viticulture techniques may be utilized in this region to delineate yield-based or vine vigor-based vineyard sub-zones that relate to differing quality levels.

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

Introduction

In the past two decades, geomatic technologies have been used in agriculture for purposes of enhancing the precision of practices such as seeding, fertilization, lime application, spraying, and several others (Robert, 2001). These management practices can be applied with the utilization of yield monitors on harvesting equipment, in combination with global positioning systems (GPS) to continuously monitor position, and geographical information systems (GIS) to create yield maps by interpolation of the data. 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 each year; the costs of variable rate technology may not be justified, and; the spatial variability in yield or other variables may not be temporally stable.

Nonetheless, although the traditional approaches to precision agriculture used for annual crops are unlikely to find application in vineyards, there are many ways whereby geomatic technologies can be utilized. For instance, collection of data, including yield, weight of cane prunings, fruit composition, and vine water status may demonstrate spatial correlations between several 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 several 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 involving remote sensing, yield monitoring, creating yield and berry composition maps, soil sensing and subsequent map creation, and identification of zones for which differential management might be beneficial. Such management might involve selective mechanical harvesting of regions of differing potential quality by controlling the disposition of fruit into two or more containers. The ability for geomatics to demonstrate spatial variability, spatial correlation, and temporal stability in 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 were significant contributors to the terroir effect, insofar as they would be related spatially to a multitude of soil factors, yield, and fruit composition. In the first portion of this study the spatial relationships between soil moisture, vine water status (based on leaf water potential), and soil texture and composition were explored. In this portion of the study, the relationships between soil and vine water status, vine vigor, and yield components are addressed.

Materials and methods

Sites. Ten Cabernet franc vineyards were selected for investigation, one in each of the ten sub-appellations of the Niagara Peninsula (Hakimi Rezaei and Reynolds, 2010a). General 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, parent material, soil drainage, clone, rootstock, year of planting, vine spacing, and floor management were compiled (Hakimi Rezaei and Reynolds, 2010a,b ; Reynolds and Hakimi Rezaei, 2014)). 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 systems included Guyot, pendelbogen, and Scott Henry. Floor management in some sites was clean cultivation and in the others was sod maintained in alternate rows. Rootstocks were 101-14, 3309 or SO 4 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). 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. Since no *p*-values were provided, 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 (% 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). The 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 visible sign 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.

Yield components and vine size: Measurements were made during 2005 to 2007 seasons on 72 to 80 sentinel vines in each vineyard block. Prior to the harvest of each block 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. All sentinel vines were hand-harvested and yield and cluster numbers were determined for each vine as well. In December to March, the vines were pruned based on the corresponding training system. Cane prunings were collected separately from each vine and weighed using a digital scale to determine vine size in kg.

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 yield components and vine size data 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 means of yield components and vine size 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. 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 2005-2007: The three seasons differed substantially with respect to growing degree days (GDD; base 10 °C) and precipitation. The 2005 season was warmer than average with GDD averaging 1582 across the region. Precipitation (426 mm; April to October) was close to average, but the period between May and late July was quite dry. The 2006 season was relatively cool overall (1430 GDD) with mean precipitation of 472 mm that was quite evenly distributed throughout the growing season. It is also noteworthy that mean daily temperatures were lower than average throughout much of July and August. The 2007 season was much drier than the preceding two years, with precipitation averaging 227 mm across the region, and GDD of 1583. Mean daily temperatures remained > 20 °C throughout much of September.

Impact of vine water status on yield and vine size: In 2005, vine water status had an effect on clusters/vine at the Henry of Pelham (HOP) site, in which lower cluster numbers were observed in the LWS category (Table 1). Yield/vine was only affected at the HOP site, where lower yields were produced in the LWS category. Berry weight was affected only at the Vieni site in which lower berry weights were observed in the HWS category. Vine size was affected in both Hernder and Reif sites with higher cane pruning weights in the HWS category. Analysis of variance in 2006 indicated that vine water status had an effect on clusters/vine and yield at the George and Cave Spring sites; at the George site, there were fewer clusters and lower yields in the LWS category, whereas at the Cave Spring site, more clusters and higher yields were observed in LWS vines. Berry weight was much lower in the LWS category at the Buis site, while

Table 1. Impact of vine water status on yield components and vine size of Cabernet franc in the Niagara Peninsula, ON, 2005-2007. LWS, MWS, HWS: low, medium and high water status, respectively

Vineyard	Clusters/ vine				Yield/ vine (kg)				Berry weight (g)				Weight of cane pruning (kg)			
location	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.	LWS	MWS	HWS	Sig.
2005																
Buis	27	22	23 [b]	ns	1.7	1.5	1.6	ns	1.23	1.20	1.27	ns	0.75	0.78	0.89	ns
Ch des Charmes	32	27	31	ns	2.2	1.5	1.8	ns	1.27	1.19	1.21	ns	0.48	0.46	0.47	ns
Hernder	29	20	15	ns	2.2	1.5	1.2	ns	1.12	1.14	1.18	ns	0.44ab	0.33b	0.60a	*
Reif	22	30	22	ns	1.3	1.9	1.3	ns	1.08	1.13	1.12	ns	0.86a	0.57b	0.97a	*
Harbour Estate	46	59	64	ns	3.6	3.8	4.1	ns	1.22	1.23	1.23	ns	1.31	1.61	1.76	ns
George	44	46	47	ns	4.7	5.1	4.1	ns	1.33	1.30	1.26	ns	0.46	0.65	0.43	ns
Cave Spring	41	39	41	ns	2.9	2.9	2.8	ns	1.12	1.19	1.21	ns	0.46	0.50	0.51	ns
H. of Pelham	29b	39a	41a	*	2.0b	3.0a	3.2a	*	1.28	1.37	1.33	ns	0.45	0.55	0.54	ns
Vieni Estate	40	43	40	ns	2.9	3.5	3.1	ns	1.08b	1.12a	1.2a	*	0.24	0.27	0.19	ns
2006																
Buis	67	69	64	ns	5.9	6.0	6.1	ns	1.49b	1.59ab	1.68a	*	0.91	0.94	0.94	ns
Ch des Charmes	39	41	41	ns	2.6	3.4	3.3	ns	1.33	1.36	1.34	ns	0.30	0.49	0.41	ns
Hernder	63	71	62	ns	6.9	7.1	6.3	ns	1.45	1.45	1.47	ns	0.88	0.85	0.89	ns
Reif	45	41	43	ns	5.1	4.5	4.6	ns	1.25	1.26	1.23	ns	0.53	0.44	0.51	ns
Harbour Estate	-	-	-	-	-	-	-	-	1.10	1.08	1.03	ns	1.08	1.21	1.19	ns
George	43b	45ab	49a	*	6.7b	7.3ab	7.7a	*	1.33	1.31	1.35	ns	0.35c	0.47b	0.59a	**
Cave Spring	56a	42b	51ab	*	5.3a	3.8b	4.5ab	*	1.32	1.37	1.34	ns	0.70	0.76	0.67	ns
H. of Pelham	55	52	54	ns	7.0	7.0	6.8	ns	1.39	1.45	1.38	ns	0.41	0.36	0.33	ns
Morrison	62	67	64	ns	3.8	3.9	3.9	ns	1.15	1.14	1.12	ns	0.82	0.94	0.99	ns
2007																
Buis	51	48	45	ns	7.3a	7.1ab	5.7b	*	1.65	1.66	1.62	ns	0.98a	0.96a	0.54b	*
Ch des Charmes	26	29	25	ns	2.6	2.8	2.5	ns	1.37	1.41	1.23	ns	0.42	0.40	0.35	ns
Hernder	53	53	51	ns	4.6	4.2	5.1	ns	1.25	1.23	1.31	ns	0.53	0.45	0.59	ns
Reif	49	43	44	ns	4.1	3.8	3.4	ns	1.35	1.33	1.32	ns	0.57	0.50	0.51	ns
Harbour Estate	53	52	50	ns	5.0	5.8	5.0	ns	1.43	1.51	1.47	ns	1.12	1.32	1.29	ns
George	32	30	32	ns	3.6b	4.0ab	4.5a	*	1.33c	1.42b	1.51a	**	0.28b	0.36b	0.48a	*
Cave Spring	45	41	40	ns	3.7	3.7	3.8	ns	1.05c	1.22b	1.41a	**	0.51	0.56	0.58	ns
H. of Pelham	47	41	39	ns	7.1a	5.5b	5.8b	*	1.45	1.43	1.41	ns	0.3 3	0.36	0.36	ns
Vieni Estate	39	41	40	ns	4.0	4.5	4.1	ns	1.29	1.23	1.26	ns	0.48	0.40	0.32	ns
Morrison	30	39	44	ns	1.9b	2.9a	3.6a	**	1.30	1.25	1.27	ns	0.73	0.64	0.69	ns

[a] *, **, ns: significant at $P \leq 0.05$, 0.01, or not significant, respectively.

in all other sites, berry weights were similar in both LWS and HWS categories. Weight of cane prunings was only affected at the George site, where lower vine size was observed in the LWS category. In 2007, clusters/vine were similar in both LWS and HWS categories. Vine water status had an effect on yield/vine at four sites, in which higher yields were produced at the HOP and Buis sites and lower yields were observed at the George and Morrison sites in the LWS categories. Berry weight was affected at the George and Cave Spring sites with lower berry weights in the LWS categories. Weight of cane prunings was affected by vine water status at two sites; higher values were observed at the Buis site and lower values were observed at the George site in the LWS categories.

Correlation analysis: Correlation analysis of soil factors vs. yield components and vine size for all sites in 2005 revealed that many soil and vine water status as well as soil composition variables were consistently linked. The absolute value (a.v.) of leaf ψ was negatively correlated with yield, berry weight, and vine size (Table 2). Other noteworthy positive correlations included: soil moisture vs. berry weight; % sand vs. vine size; soil OM vs. berry weight; soil P vs. vine size; Soil K vs. vine size. Negative correlations included % clay and soil Mg vs. vine size; CEC vs. vine size; BS and soil Ca vs. yield and vine size; soil K vs. yield. Correlation analysis of soil factors vs. yield components and vine size for all sites in 2006 once again revealed that many soil and vine water status as well as soil composition variables were consistently linked. Leaf ψ (a.v.) was positively correlated with berry weight. Soil moisture was positively correlated with berry weight and negatively correlated with yield. Other positive correlations of note included: % sand and OM vs. yield; BS vs. berry weight; soil P vs. vine size; soil K vs. vine size. Noteworthy negative correlations included: clay vs. yield; CEC, soil pH, and soil Ca vs. yield and vine size; BS vs. yield and vine size; P vs. berry weight; Mg vs. yield and berry weight. In 2007 correlation analysis of soil factors vs. yield components and vine size revealed once again that many soil and vine water status as well as soil composition variables were consistently linked. Leaf ψ (a.v.) was negatively correlated with yield, berry weight, and vine size; soil moisture negatively correlated with vine size; % sand positively correlated with yield, berry weight, and vine size. Negative correlations included: % clay vs. yield, berry weight, and vine size; OM vs. vine size; CEC and soil Ca vs. yield and vine size; soil pH and BS vs. yield and berry weight; soil Mg vs. yield, berry weight, and vine size.

Spatial variability in yield components and vine size- Spatial correlation analysis: Spatial maps of soil moisture and leaf ψ as well as those for soil composition are found in part I of this study. Spatial maps for all other variables (vine size, yield components, berry weight) across all sites and vintages are found in Figs. 1 to 9. Spatial correlation analysis for leaf ψ, soil moisture, vine size, yield, and berry weight are shown in Table 3. Since the specific hypotheses of this study were that soil moisture and vine water status would be the major drivers of the terroir effect,

Table 2. Overall correlations and associated *p* values of soil factors vs. yield components and vine size for Cabernet franc for ten Niagara Peninsula sites in 2005-07. 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						
Yield (kg)	0.0195	-0.1013	0.1429	-0.1364	-0.2139	-0.2880	0.0080	-0.1808	-0.1574	0.1224	-0.1241	-0.2576
	0.8092	0.2083	0.0750	0.0895	0.0073	0.0003	0.9209	0.0239	0.0497	0.1280	0.1227	0.0012
Berry wt (g)	0.0299	-0.1510	0.2571	0.0915	0.0578	0.0171	-0.0070	-0.0580	0.0833	0.0569	0.2841	-0.1713
	0.7066	0.0570	0.0010	0.2497	0.4677	0.8305	0.9258	0.4856	0.2943	0.4745	0.0003	0.0303
Vine size (kg)	0.5476	-0.5752	-0.1613	-0.3850	-0.2786	-0.4384	0.1960	0.2023	-0.3622	-0.4364	-0.0495	-0.6111
	<.0001	<.0001	0.0409	<.0001	0.0003	<.0001	0.0127	0.0101	<.0001	<.0001	0.5330	<.0001
						2006						
Yield (kg)	0.3784	-0.4008	0.2186	-0.3004	-0.2397	-0.1713	-0.1139	-0.0982	-0.2739	-0.2135	-0.2975	-0.0292
	<.0001	<.0001	0.0106	0.0004	0.0049	0.0462	0.1866	0.2551	0.0012	0.0128	0.0004	0.7361
Berry wt (g)	0.0066	0.1164	0.1144	0.1452	0.0631	0.2646	-0.2141	-0.0214	0.1531	-0.1212	0.2379	0.4501
	0.9336	0.1390	0.1460	0.0645	0.4234	0.0006	0.0061	0.7859	0.0511	0.1232	0.0022	<.0001
Vine size (kg)	0.0724	-0.0989	-0.0005	-0.3077	-0.2980	-0.3460	0.4925	0.4145	-0.3407	-0.0581	0.0011	0.0374
	0.3630	0.2134	0.9947	<.0001	0.0001	<.0001	<.0001	<.0001	<.0001	0.4654	0.9890	0.6384
						2007						
Yield (kg)	0.4643	-0.5150	0.0467	-0.2860	-0.3272	-0.2577	-0.1264	-0.1134	-0.2549	-0.4098	-0.0609	-0.3898
	<.0001	<.0001	0.5344	0.0001	<.0001	0.0005	0.0918	0.1306	0.0006	<.0001	0.4174	<.0001
Berry wt (g)	0.3298	-0.3951	-0.0037	-0.1238	-0.1982	-0.1728	-0.0453	0.0366	-0.1074	-0.2881	0.0784	-0.4395
	<.0001	<.0001	0.9606	0.0986	0.0078	0.0207	0.6379	0.6262	0.1523	<.0001	0.2909	<.0001
Vine size (kg)	0.4050	-0.3769	-0.3463	-0.2189	-0.0117	-0.0954	-0.0103	0.1076	-0.1749	-0.3225	-0.2296	-0.4260
	<.0001	<.0001	<.0001	0.0032	0.8766	0.2037	0.8913	0.1516	0.0192	<.0001	0.0020	<.0001

the spatial relationships involving these variables are described. Moreover, a major group of target variables associated with the terroir effect in red winegrape cultivars involve color intensity, anthocyanins, and total phenols, and therefore these variables and their spatial relationships with other metrics were explored. Finally, cluster exposure, canopy microclimate, and other features of vineyards that impact berry composition are linked to vine size, and consequently spatial relationships involving vine size are herein described.

Niagara-on-the-Lake sites: Spatial maps for all variables (vine size and yield components) showed similar relationships across all sites and vintages (Table 3). Niagara-on-the-Lake sites are depicted in Figs. 1 (vine size), 4 (yield), and 7 (berry weight). Those variables with significant positive spatial correlations with soil moisture included vine size (Buis 2005, Fig. 1A; Reif 2005, Fig. 1J) and berry weight (Buis 2005, Fig. 7A; Hernder 2006, Fig. 7H; Reif 2007, Fig. 7L). Inverse spatial correlations with soil moisture included those of vine size (Buis 2006-07, Fig. 1B,C) and yield (Buis 2006-07, Fig. 4B,C; Hernder 2007, Fig. 4I; Reif 2005, Fig. 4J). Leaf ψ was spatially correlated with vine size (Buis 2007, Fig. 1C). Several spatial correlations were apparent amongst vine size, yield, and berry weight; e.g., vine size was positively correlated with yield (Buis 2007, Fig. 4C; Hernder 2007, Fig. 4I) and berry weight (Buis 2005-07, Fig. 7A-C; CDC 2005-07, Fig. 7D-F; Hernder 2005, 2007, Fig. 7G,I), and inversely correlated with yield (Reif 2005, Fig. 4J)

Jordan, Vineland, Beamsville sites: The Jordan, Vineland and Beamsville sites are depicted in Figs. 2, 3 (vine size), Figs. 5,6 (yield), and Figs. 8,9 (berry weight). Soil moisture displayed positive spatial correlations with vine size (Harbour 2007, Fig. 2C; George 2005-06, Fig. 2D,E; Cave Spring 2005-07, Fig. 2G-I), yield (George 2005-07, Fig. 5D-F), and berry weight (George 2005-06, Fig. 8D,E; Cave Spring 2005-07, Fig. 8G-I; Vieni 2007, Fig. 9B). as well as inverse correlations with vine size (HOP 2005, Fig. 2J), yield (Cave Spring 2006, Fig. 5H; Vieni 2005, Fig. 6A; Morrison 2006-07, Fig. 6C,D) and berry weight (Harbour 2007, Fig. 8C). Leaf ψ (a.v.) was negatively correlated with vine size (George 2007, Fig. 2F), yield (George 2007, Fig. 5F; Cave Spring 2007, Fig. 5I; HOP 2005, Fig. 5J; Morrison 2007, Fig. 6D), and berry weight (George 2007, Fig. 8F; Cave Spring 2007, Fig. 8I; HOP 2005, Fig. 8J), and positively correlated with vine size (Vieni 2007, Fig. 3B). Several spatial relationships occurred among vine size, yield, and berry weight; e.g., vine size was correlated to yield (George 2005-07, Fig. 5D-F; HOP 2007, Fig. 5L) and berry weight (Cave Spring 2005; Fig. 8G; HOP 2005-07, Fig. 8J-L; Vieni 2005, Fig. 9A; Morrison 2006-07; Fig. 9C,D),

Temporal stability: Correlation analysis describing temporal stability is depicted in Table 4. Vine size (Figs. 1-3) was highly spatially consistent at six sites across the 2005-2006 vintages particularly Buis, Cave Spring and George, while across 2006-2007, it was highly consistent at seven sites particularly Buis, CDC, George, and Morrison. Yield spatial distribution was consistent at the George and Cave Spring sites in the 2005 and 2006 vintages (Fig. 5D,E George; Fig. 5G,H Cave Spring) but for five sites over the 2006 to 2007 period, particularly CDC. However, although yield spatial distribution at the CDC site was consistent between the 2006 to 2007 vintages (Fig. 3E,F) it was not the case between the 2005 and 2006 vintages (Fig. 3D,E). Berry weight was highly spatially consistent at four locations, particularly the Cave Spring site over the 2005 and 2006 vintages (Fig. 8G,H) as well as in 2006 and 2007 vintages (Fig. 8H,I); in the 2006 to 2007 vintages, berry weight overall was temporally stable across seven sites, particularly at the CDC (Fig. 7E,F) and Harbour locations (Fig. 8B,C).

Table 3. Spatial correlations 2005-2007—Yield, vine size, berry weight, soil moisture. Relationships with WP refer to absolute values

	Berry weight	Soil moisture	Vine size	Leaf ψ
Buis				
SM 05	0.77**			
06	-0.05			
07	-0.20			
Vine size 05	0.51**	0.34**		
06	0.66**	-0.62**		
07	0.26*	-0.54**		
Leaf ψ 05	-0.25	-0.27	-0.29	
06	-0.43	-0.03	-0.15	
07	-0.03	-0.20	0.59*	
Yield 05	0.14	-0.12	-0.28	0.29
06	-0.35**	-0.50**	0.15	0.06
07	0.45**	-0.67**	0.80**	0.36
Chateau des Charmes				
	Berry weight	Soil moisture	Vine size	Leaf ψ
SM 05	-0.34**			
06	-0.22			
07	-0.24			
Vine size 05	0.45**	0.19		
06	0.61**	-0.40**		
07	0.82**	-0.43**		
Leaf ψ 05	-0.27	0.05	0.06	
06	-0.02	-0.10	0.07	
07	0.01	0.53*	0.05	
Yield 05	-0.25	-0.10	-0.17	0.20
06	0.16	0.06	0.57**	0.04
07	0.53**	-0.25	0.64**	-0.20
Hernder				
	Berry weight	Soil moisture	Vine size	Leaf ψ
SM 05	0.12			
06	0.35**			
07	0.14			
Vine size 05	0.54**	0.02		
06	-0.17	-0.25		
07	0.39**	-0.19		
Leaf ψ 05	-0.48	0.18	-0.40	
06	-0.14	0.05	-0.42	
07	-0.23	0.19	-0.02	
Yield 05	0.02	-0.22	0.04	0.13
06	0.49**	-0.09	-0.20	0.30
07	0.36**	-0.49**	0.61**	-0.12
Reif				
	Berry weight	Soil moisture	Vine size	Leaf ψ
SM 05	-0.13			
06	0.02			
07	0.47**			
Vine size 05	-0.01	0.43**		
06	0.01	0.19		
07	0.21	0.21		
Leaf ψ 05	-0.17	0.30	0.25	
06	0.22	0.60**	-0.02	
07	0.38	0.42	-0.17	
Yield 05	0.42**	-0.26*	-0.50**	-0.06
06	-0.01	0.13	0.29*	0.11
07	0.36**	0.25	0.14	0.13

Table 3 contd. Spatial correlations 2005-2007—Yield, vine size, berry weight, soil moisture. Relationships with WP refer to absolute values.

	Berry weight	Soil moisture	Vine size	Leaf ψ
Harbour				
SM 05	0.19			
06	-0.37**			
07	-0.42**			
Vine size 05	0.54**	0.26		
06	0.58**	0.41**		
07	-0.16	0.41**		
Leaf ψ 05	-----	-----	-----	
06	0.52*	0.32	-0.27	
07	-----	-----	-----	
Yield 05	0.38**	-0.30*	0.19	----[a]
06	-----	-----	-----	-----
07	-----	-----	-----	-----
George				
	Berry weight	Soil moisture	Vine size	Leaf ψ
SM 05	0.36**			
06	0.36**			
07	-0.13			
Vine size 05	0.64**	0.72**		
06	0.20	0.50**		
07	0.82**	0.04		
Leaf ψ 05	0.12	-0.05	0.12	
06	0.08	0.01	-0.35	
07	-0.76**	-0.03	-0.77**	
Yield 05	0.55**	0.75**	0.84**	0.06
06	0.46**	0.58**	0.53**	-0.14
07	0.90**	0.31*	0.78**	-0.76**
Cave Spring				
	Berry weight	Soil moisture	Vine size	Leaf ψ
SM 05	0.80**			
06	0.40**			
07	0.47**			
Vine size 05	0.72**	0.68**		
06	0.55**	0.45**		
07	0.65**	0.32*		
Leaf ψ 05	0.01	-0.12	0.03	
06	-0.33	-0.63**	-0.40	
07	-0.76**	-0.59	-0.45	
Yield 05	-0.09	-0.10	0.16	0.11
06	-0.44**	-0.48**	-0.13	0.53*
07	0.45**	0.24	0.50**	-0.40
Henry of Pelham				
	Berry weight	Soil moisture	Vine size	Leaf ψ
SM 05	-0.38**			
06	0.13			
07	0.09			
Vine size 05	0.62**	-0.46**		
06	0.41**	0.02		
07	0.70**	-0.11		
Leaf ψ 05	-0.53*	0.05	-0.20	
06	0.13	-0.21	0.09	
07	-0.10	0.44	0.07	
Yield 05	0.21	-0.12	-0.07	-0.50**
06	-0.12	-0.15	0.24	----[a]
07	0.63**	0.23	0.66**	0.37

Discussion

This investigation was initiated to identify the major factors that contribute to the terroir effect, i.e. the impact of site upon berry composition and wine varietal typicity, in vineyards of the Niagara Peninsula in Ontario. It was hypothesized, consistent with Seguin (1986), that these factors might 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 this terroir effect would be ultimately 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 in most situations.

Table 3 contd. Spatial correlations 2005-2007—Yield, vine size, berry weight, soil moisture. Relationships with WP refer to absolute values

	Berry weight	Soil moisture	Vine size	Leaf ψ
Vieni				
SM 05	0.06			
06	-----			
07	-0.26*			
Vine size 05	0.66**	-0.01		
06	-----	-----		
07	0.51**	0.05		
Leaf ψ 05	0.28	-0.20	0.39	
06	-----	-----	-----	
07	0.24	0.35	0.71**	
Yield 05	0.09	-0.31*	0.28*	-0.14
06	-----	-----	-----	-----
07	0.15	-0.18	0.22	-0.20
Morrison				
	Berry weight	Soil moisture	Vine size	Leaf ψ
SM 05	-----			
06	-0.01			
07	0.16			
Vine size 05	-----	0.09		
06	0.36**	0.13		
07	0.82**	0.07		
Leaf ψ 05	-----	0.70**	-0.13	
06	-0.17	0.19	0.09	
07	0.28	0.40	0.19	
Yield 05	-----	-----	-----	-----
06	0.48**	-0.31*	0.12	0.04
07	-0.04	-0.52**	-0.33*	-0.59*

*, **: Significant at $p \leq 0.05$ or 0.01, respectively. All relationships are based on n=80 except leaf ψ (n = 20).
[a] Correlation coefficients were non-determinable.
[b] Data were missing due to powdery mildew (Harbour, Vieni 2006) and winter injury (Morrison 2005).

Spatial patterns in soil moisture were consistently temporally stable, and those of leaf ψ were occasionally temporally stable. Temporal variations in spatial patterns of these variables were likely influenced by the volatile precipitation patterns that are typical of the region. There were also clear spatial correlations between soil moisture, leaf ψ, soil physical and composition variables, yield components, vine size, and berry composition.

Impact of site climate and vine water status on yield components. It has been long accepted that site climate impacts fruit composition and ultimate wine quality. Mesoclimate effects such as proximity to the Atlantic Ocean in Bordeaux (Bois *et al.*, 2008) and South Africa (Bonnardot *et al.*, 2000) are important in determining vine water status and ultimately fruit composition. Bois et al. (2008) showed spatial and temporal variability in solar radiation throughout the Bordeaux region helped to explain success of Cabernet Sauvignon in the western portions of the region (e.g. Medoc, Bourg, Blaye), and the preponderance of Cabernet franc and Merlot in eastern appellations (e.g. St. Emilion, Pomerol). In the Niagara Region, sites adjacent to the Lake Ontario shore produced wines with most concentrated vegetal and red fruit characteristics (Hakimi Rezaei and Reynolds, 2010a,b; Kontkanen *et al.*, 2005). Site climate played a crucial role in this study as well. The Buis, George, and Vieni sites were characterized by relatively low GDD with 2005-07 means of 1495, 1460, and 1504, respectively, and lowest seasonal values amongst the 10 sites [Buis (1490; 2005), George (1420, 2007), Vieni (1354, 2006)].

Table 4. Temporal correlations 2005-2007 for berry wt., soil moisture, vine size, leaf ψ, and yield for ten Cabernet franc sites in the Niagara Peninsula in Ontario.

Site	Berry weight	Soil moisture	Vine size	Leaf ψ	Yield
2005-2006					
Buis	0.62**	-0.34	0.66**	0.14	-0.25
Cave	0.76**	0.45**	0.73**	0.22	0.65**
CDC	0.31*	0.56**	0.58**	0.40	-0.34
George	0.11	0.50**	0.76**	-0.28	0.69**
Harbour	-0.31	0.50**	0.55**	0.65**	-----[a]
Hernder	-0.08	0.42**	0.16	0.83**	0.07
HOP	0.21	0.53**	0.10	0.03	0.25
Morrison	-----	0.52**	-----	0.24	-----
Reif	0.11	0.84**	0.60**	0.39	-0.38
Vieni	-----	0.59**	-----	0.44	-----
2006-2007					
Buis	-0.03	0.82**	0.86**	-0.40	0.41**
Cave	0.84**	0.68**	0.48**	0.50*	0.27*
CDC	0.78**	0.78**	0.82**	-0.09	0.68**
George	0.43**	0.45**	0.68**	0.45	0.59**
Harbour	0.70**	0.41**	0.36**	0.66**	-----[a]
Hernder	0.39**	0.59**	0.10	0.04	-0.12
HOP	0.21	0.71**	0.36**	0.47	0.58**
Morrison	0.45**	0.71**	0.68**	0.17	0.05
Reif	0.34**	0.87**	-0.03	0.84**	0.56**
Vieni	-----	0.62**	-----	0.19	-----
2005-2007					
Buis	-0.07	-0.14	0.75**	-0.45	-0.26
Cave	0.79**	0.62**	0.44**	-0.12	0.47**
CDC	0.22	0.69**	0.45**	-0.05	-0.13
George	0.67**	0.44**	0.91**	0.08	0.66**
Harbour	-0.03	0.57**	0.42**	0.47	----[b]
Hernder	0.29*	-0.10	0.06	0.11	0.14
HOP	0.64**	0.59**	0.55**	-0.40	0.20
Morrison	-----	0.55**	-----	0.65**	-----
Reif	0.35**	0.67**	-0.15	0.36	-0.19
Vieni	0.57**	0.66**	0.35**	0.66**	0.05

*, **: Significant at $p \leq 0.05$ or 0.01, 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.

The Harbour, George, Reif and Buis sites had relatively high yields, high cluster numbers, high berry weights and vine sizes (Table 1). All of these sites also had highest leaf ψ values, coarse soil textures and cooler temperatures due to close proximity to Lake Ontario (Harbour, George, Buis) or the Niagara River (Reif). In temperate zones with sufficient precipitation, higher vine water availability, lower temperatures and coarse soil textures are typically associated with higher vegetative growth (hence higher vine size), higher yields, and berry weight (Smart and Coombe, 1983; van Leeuwen *et al.*, 2004). Therefore, the assumption is that this phenomenon was also taking place at these sites. The remaining sites including CDC, HOP, Hernder, Cave Spring and Vieni were characterized by high color intensity, anthocyanins, total phenols, Brix, and pH (Hakimi Rezaei, 2009); these sites also had lower leaf ψ values, fine soil texture (clay) that reduced vigor and available water (Coipel et al. 2006), and higher mean air temperatures due to distance from large bodies of water (Bonnardot *et al.*, 2000). The lower leaf ψ values suppressed vegetative growth and caused smaller berry size due to less available water to the vine, while smaller berry size likely led to increased skin to juice ratio (Smart and Coombe, 1983; van Leeuwen *et al.*, 2004). Temperature has a direct effect on

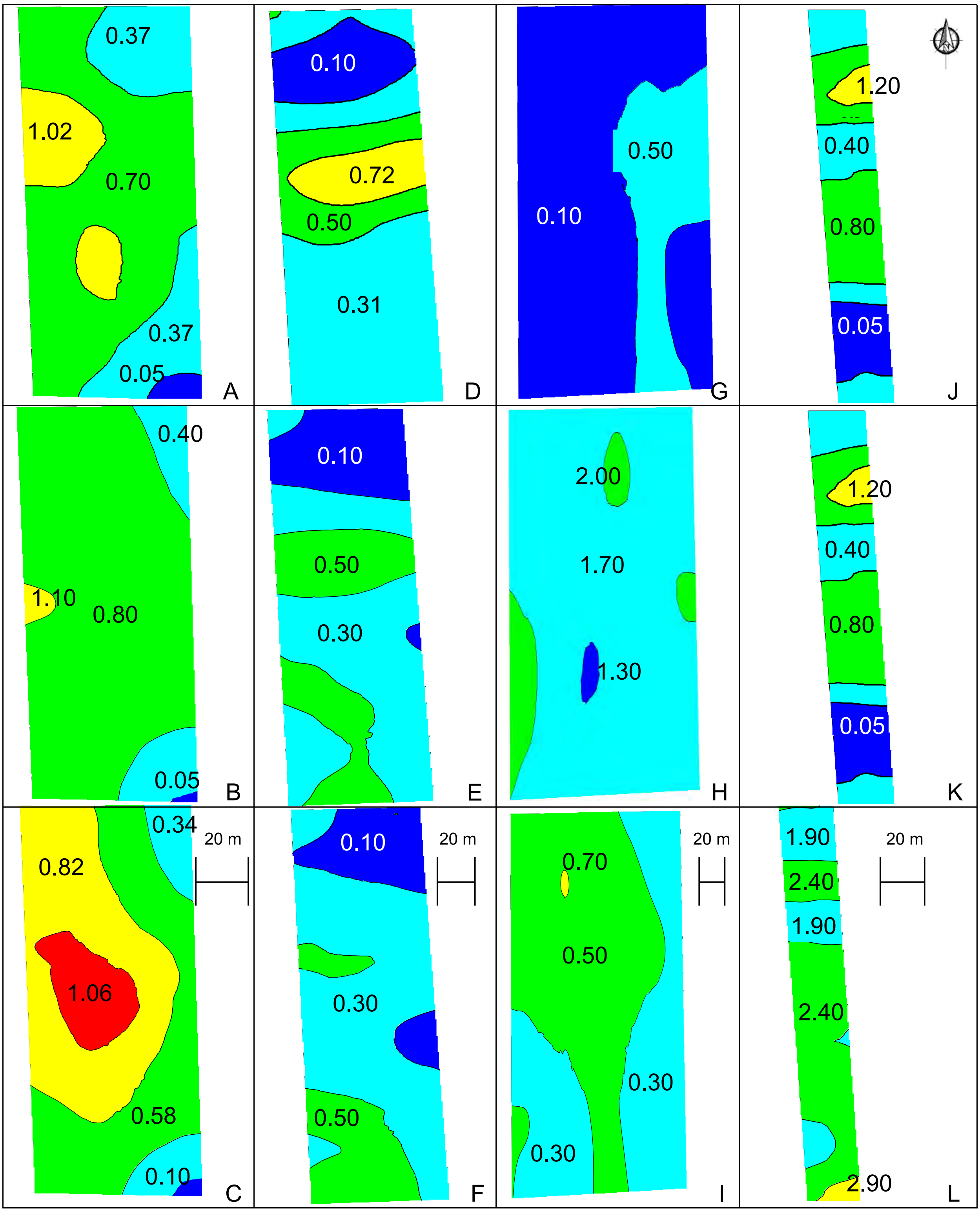

Fig. 1. Spatial distribution of vine size (kg/vine). Cabernet franc, Niagara Peninsula, OX~: A to C: Buis: 2005 (A): 2006 (B): 2007 (C). D to F: Chateau des Chanues: 2005 (D); 2006 (E): 2007 (F). G to I: Hernder: 2005 (G): 2006 (H): 2007 (H). J to L: Reif: 2005 (J): 2006 (K): 2007 (L). Xunibers on the maps refer to the minimum value in the range for each zone.

anthocyanin and phenolic concentration (Morrison, 1988); for example, concentrations of anthocyanins and total phenols were optimized in Merlot berries at a temperature range of 30 to 35 ˚C (Spayd *et al.*, 2002). Temperatures > 35 ˚C are normally inhibitory to anthocyanin synthesis (Bergqvist *et al.*, 2001).

Prior to discussing impacts of vine water status, it is worthy of mention that in some site X year combinations, both LWS and HWS zones were technically water-stressed based upon the commonly-accepted -12 bars (1.2 MPa) metric (Smart and Coombe, 1983). In 2005, seven of 10 vineyards exhibited mean leaf ψ values < -1.2 MPa in their HWS zones; two (Reif, HOP) had mean leaf ψ values < -1.2 MPa in their LWS zones only, while one (Harbour) had mean leaf ψ values that exceeded -1.2 MPa in all water status zones. In the moister 2006 season, two vineyards (CDC, Hernder) contained mean leaf ψ values < -1.2 MPa in their HWS zones, five vineyards had HWS zones whose mean leaf ψ

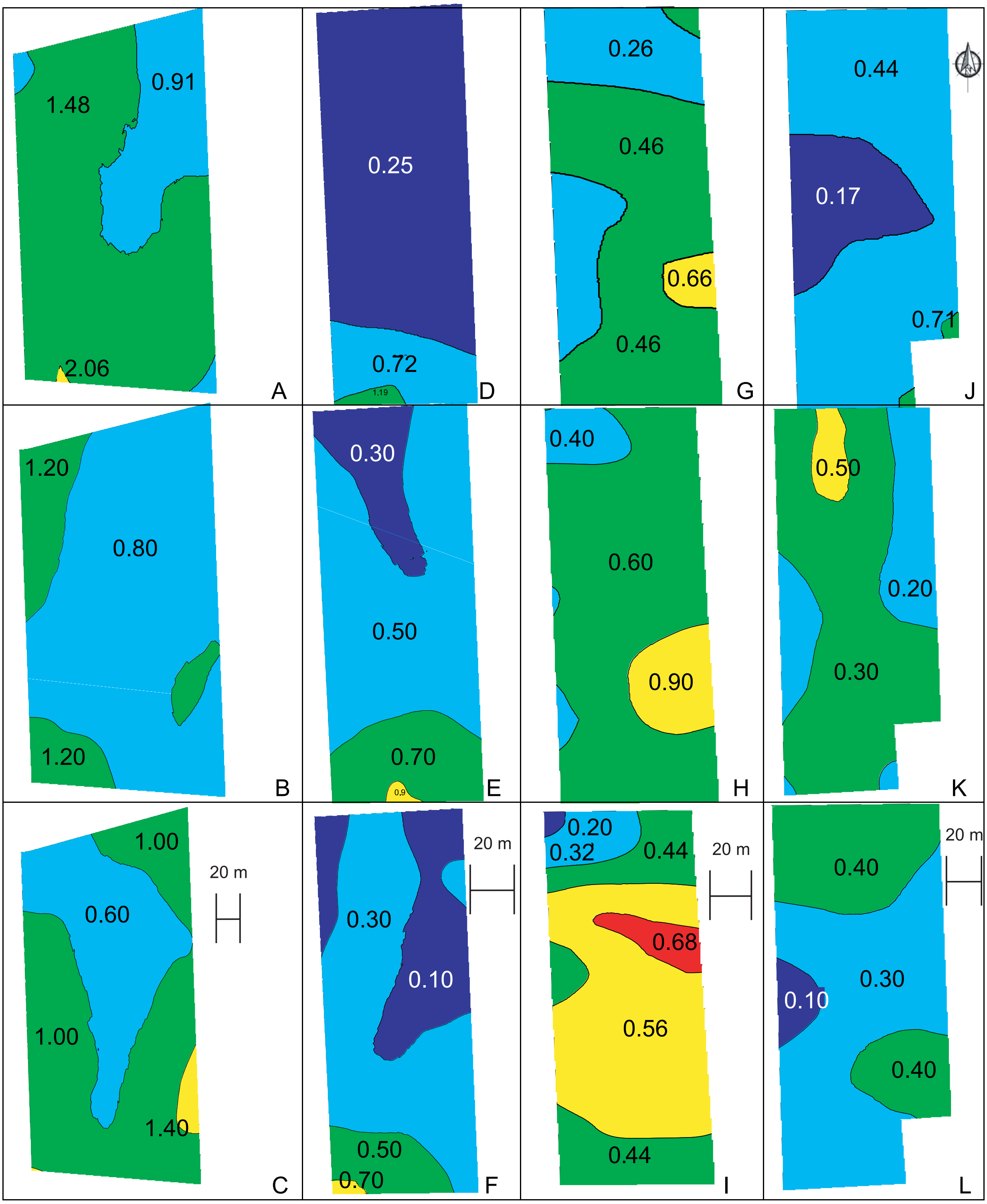

Fig. 2. Spatial distribution of vine size (kg/vine). Cabernet franc, Niagara Peninsula. OX~; A to C: Harbour Estate: 2005 (A): 2006 (B); 2007 (C). D to F: George: 2005 (D): 2006 (E); 2007 (F). G to I: Cave Spring: 2005 (G): 2006 (H): 2007 (I). J to L: Henry of Pelham: 2005 (J); 2006 (K); 2007 (L). Numbers on the maps refer to the minimum value in the range for each zone.

values were not < -1.2 MPa, while three (Harbour, Morrison, Vieni) had mean leaf ψ values that exceeded -1.2 MPa in all water status zones. In the dry 2007 season, six vineyards had mean leaf ψ values < -1.2 MPa in their HWS zones, three vineyards (Buis, Reif, George) had HWS zones with mean leaf ψ values > -1.2 MPa, while one (Harbour) had mean leaf ψ values that exceeded -1.2 MPa in all water status zones. These differences in vine physiology are noteworthy to explain differences (or lack thereof) in vine size, yield components, and berry composition between HWS and LWS zones at some sites.

Vine size was largely unaffected by vine water status when HWS and LWS zones were compared within vineyards (Table 1). However, vine size and leaf ψ were directly correlated, especially in 2005 and 2007 (Table 2). Vine size was higher at Buis (2007) in LWS vines but lower in LWS vines at three other site X year combinations over the three year study period [Hernder (2005); Reif (2005); George (2006, 2007)]. Higher vine size in HWS vines could be due to higher vegetative growth as a result of

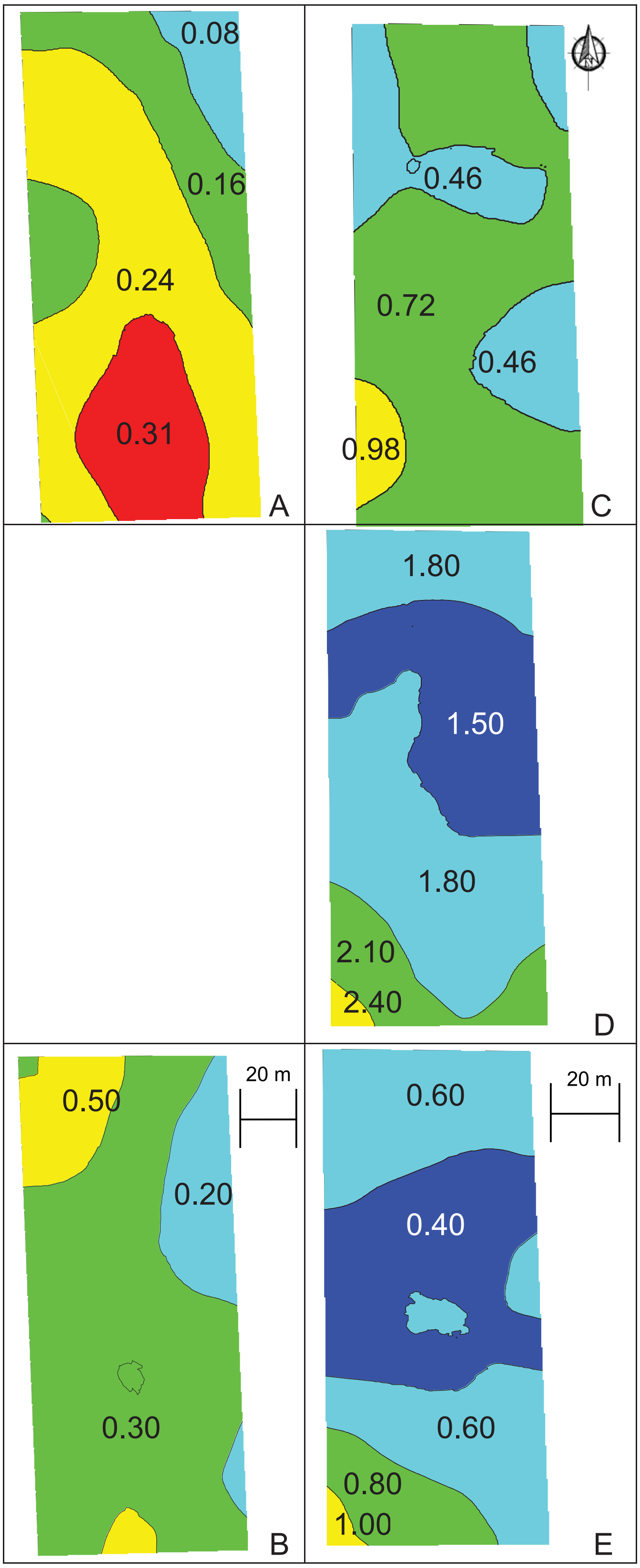

Fig. 3. Spatial distribution of vine size (kg/vine). Cabernet franc, Niagara Peninsula, OX: A to B: Vieni:2005 (A): 2007 (B). C to E: Morrison: 2005 (C): 2006 (D): 2007 (E). Numbers on the maps refer to the minimum value in the range for each zone.

higher water availability to the vines (van Leeuwen et al., 2004). Low water availability decreases vine vegetative growth and size of canopy that allows for more efficient light exposure into canopy and clusters and results in more manageable canopy (Coipel *et al.*, 2006; Koundouras *et al.*, 1999; Smart and Coombe, 1983; van Leeuwen *et al.*, 2004). A benefit of lower vine size in low water status vines might be the reduction in pruning costs as well as the possibility of reduced canopy shade (Smart, 1985; Smart *et al.*, 1985).

Responses of yield components to vine water status were not consistent across all ten sites and are therefore difficult to explain. Clusters per vine, yield, berry weight, and vine size were all directly correlated with leaf ψ, particularly in the 2005 and 2007 seasons (Table 2). However, in most sites, water status did not impact cluster number when HWS and LWS zones were compared within individual vineyards (Table 1). More clusters were observed at Cave Spring (2006) in LWS vines, while two other sites over the three year study period had less clusters in LWS vines [HOP (2005); George (2006)]. Yield was more often unaffected by vine water status than affected; yield was higher in LWS vines at two sites over three years [Buis (2007); HOP (2007)] while lower in LWS vines at four other site X year combinations [HOP (2005); George (2006, 2007); Morrison (2007)]. The phenomenon of increased yield in LWS vines could be explained by the fact that low leaf ψ frequently reduces vegetative growth, induces more floral induction, and increases fruitfulness; as a consequence higher yields are obtained (Smart and Coombe, 1983; van Leeuwen et al., 2004). However, vine size was not reduced under LWS conditions at all sites. Berry weight was lowest at four sites over three years in LWS vines [Vieni (2005); Buis (2006); HOP (2007); Cave Spring (2007)]. Low leaf ψ reduces photosynthesis in leaves, and therefore, less water and photosynthate are translocated to berries (Smart and Coombe, 1983). This is in agreement with numerous other studies that have shown increased water applied as irrigation results in higher berry weights (Bravdo *et al.*, 1985; Hardie and Considine, 1976; Reynolds *et al.*, 2009; Smart, 1985). In non-irrigated vineyards, soil texture and composition is not crucial to the terroir effect but soil depth was critical in terms of how it impacted vine water, N status, and berry size (Coipel *et al.*, 2006). Shallow soils led to vines with low water status and low N, which also produced small berries that were ultimately higher in Brix and anthocyanins than those produced on deeper soils. Results from this study confirmed that the deeper, coarse-textured soils typically had high leaf ψ values whereas the shallow, fine-textured clay and clay loam soils had low leaf ψ values. These soils at some sites also tended to have small berries and concomitantly higher Brix, color intensity, anthocyanins, and phenols (Hakimi Rezaei, 2009).

Impact of soil type: The relatively safe assumption was made at the beginning that various soil variables would not change drastically during the course of this study. Vine size was positively correlated with sand and negatively with clay in two years (2005, 2007). Clay may limit root growth and penetration due to poor drainage or soil compaction while sandy soils facilitate grapevine growth (Coipel *et al.*, 2006; Seguin, 1986); in fact the highest growth and vine size was at Harbour site that had a sandy loam soil and the lowest vine size was observed at CDC, Cave Spring and Vieni with clay loam soil textures. Interestingly the impact of soil texture on vine size was not substantial in 2006, which was a wet year that showed high water availability, and consequently there was no difference between sand and clay in terms of limiting root and canopy growth. Vine size was also positively

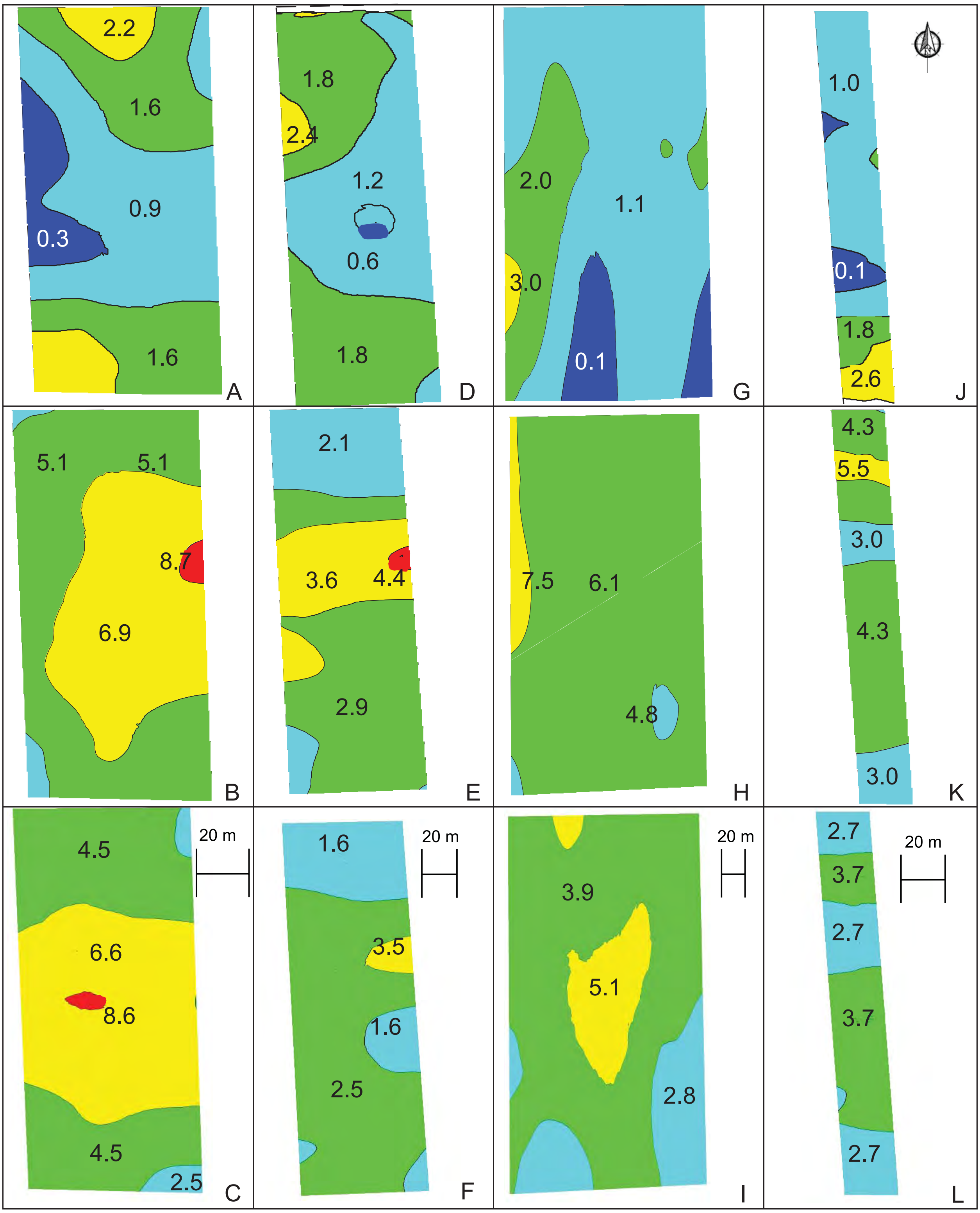

Fig. 4. Spatial distribution of yield (kg/vine). Cabernet franc, Niagara Peninsula, ON: A to C: Buis: 2005 (A): 2006 (B); 2007 (C). D to F: Chateau des Charmes: 2005 (D); 2006 (E): 2007 (F). G to I: Hernder: 2005 (G): 2006 (H): 2007 (H). J to L: Reif: 2005 (J); 2006 (K); 2007 (L). Numbers on the maps refer to the minimum value in the range for each zone.

correlated with P and K in two years (2005, 2006). Vine size was negatively correlated with CEC and Ca in all three years. In terms of relationships between soil texture and yield components, pooled data showed that yield was positively correlated with sand and negatively with clay in two of three years. This could be due to more vegetative growth in sandy soils and as a result higher yields. Similarly, fine-textured soils can suppress vegetative growth and yield (Coipel *et al.*, 2006; van Leeuwen, 2004; 2009).

Yield was negatively correlated with % clay, pH, BS and Ca in all three years. Clay provides less water availability or higher water stress to grapevines due to root restriction; also clay has more colloids that contribute to higher soil pH, BS and Ca (Coipel *et al.*, 2006). Berry weight had no consistent relationships with soil texture or soil variables during the study, which is not consistent with other data from Europe (Coipel *et al.*, 2006; van Leeuwen, 2004; 2009).

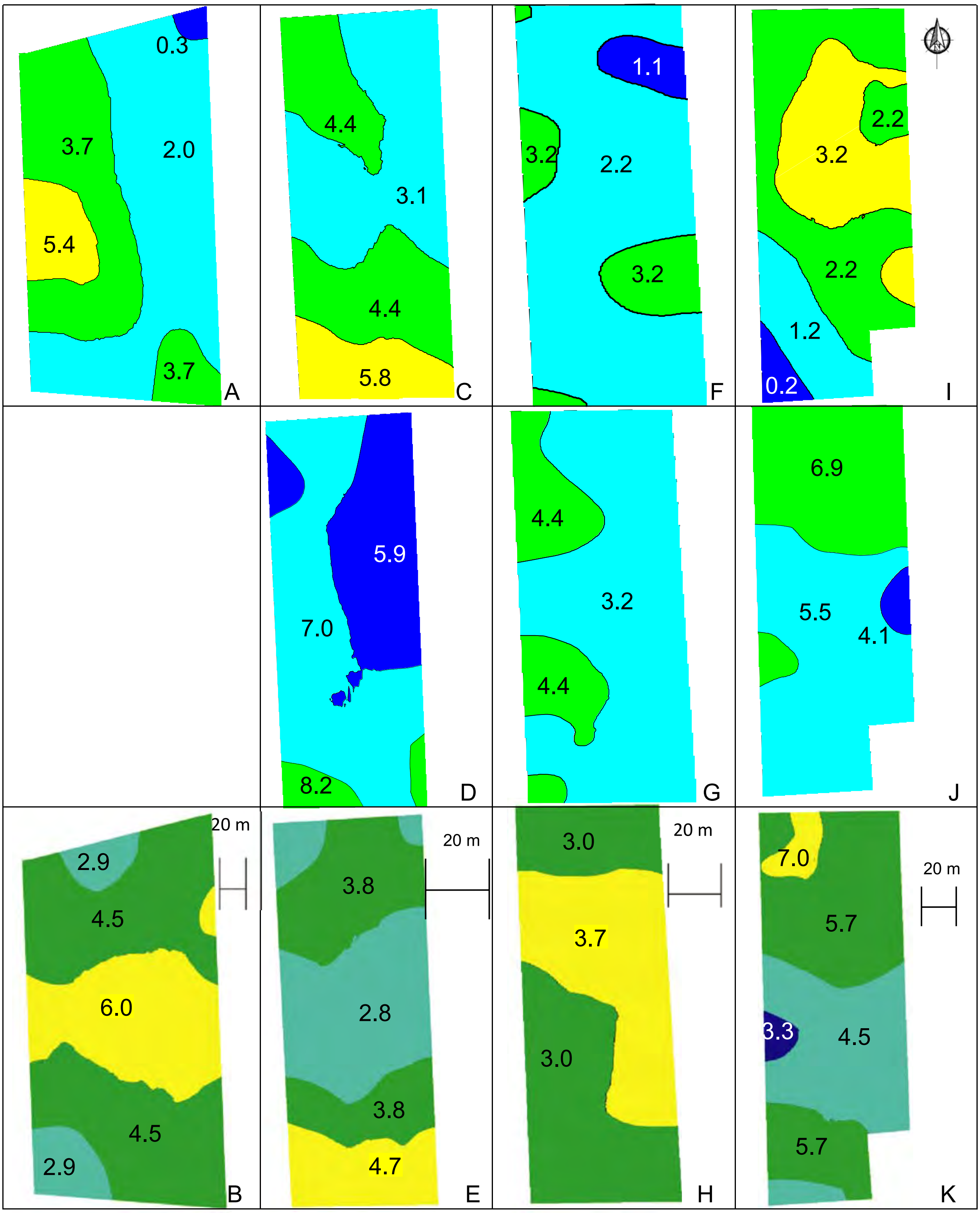

Fig. 5. Spatial distribution of yield (kg/vine). Cabernet franc, Niagara Peninsula, ON: A to B: Harbour Estate: 2005 (A): 2007 (B). C to E: George: 2005 (C): 2006 (D): 2007 (E). F to H: Cave Spring: 2005 (F);

Correlations among variables including vine water status. In the hot and dry year of 2005, leaf ψ, as an indicator of vine water status, correlated (either in positive or negative direction) with many yield components, fruit composition, and wine sensory characters, while soil texture variables were correlated with only four yield components, fruit composition or wine sensory characters (Hakimi Rezaei and Reynolds 2010a,b). In the wet year of 2006, leaf ψ was correlated with berry weight and TA and % sand correlated with yield and phenols; %clay correlated with yield, Brix, TA, anthocyanins and phenols. In 2007, leaf ψ correlated with yield, berry weight, vine size and TA while % sand and % clay correlated with yield, berry weight, vine size, TA and color. Partial least squares (PLS) analysis of the entire data set in 2005 indicated that leaf ψ correlated with numerous yield components, fruit composition and wine sensory characters while % sand and % clay correlated with few attributes (Hakimi Rezaei

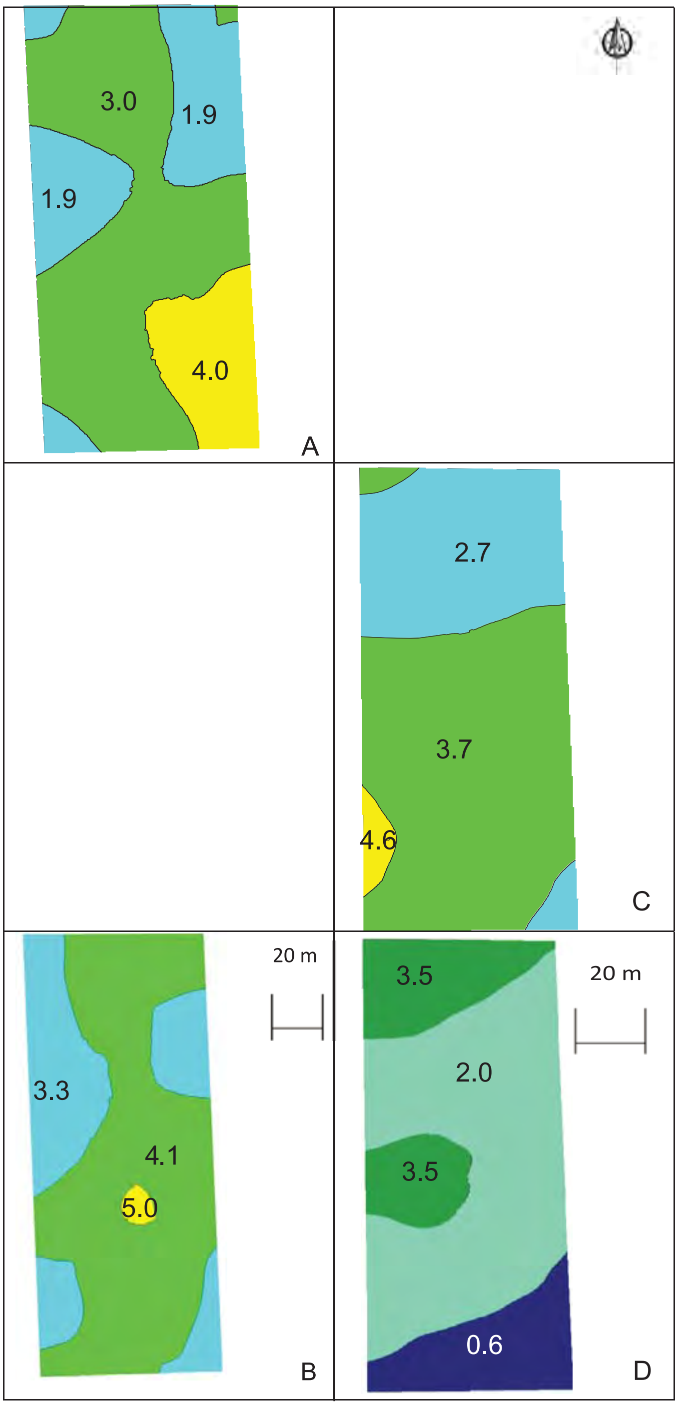

Fig. 6. Spatial distribution of yield (kg/vine). Cabernet franc, Niagara Peninsula, ON: A to B: Vieni: 2005 (A): 2007 (B). C to D: Morrison: 2006 (C): 2007 (D). Xunibers on trie maps refer to the minimum value in the range for each zone.

and Reynolds, 2010a,b). In 2006 PLS analysis showed the same correlations for leaf ψ and soil texture variables.

Spatial distribution and correlation of yield components, vine size, 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.*, 2010; Reynolds *et al.*, 2007; 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 $\delta^{13}C$ and stem ψ (van Leeuwen, *et al.*, 2006; van Leeuwen *et al.*, 2009). This supported data showing relationships between predawn leaf ψ and $\delta^{13}C$ (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 the present study, spatial distribution of yield was temporally stable, particularly at Cave Spring and George (2005-2006) and at CDC (2006-2007); overall only two sites showed temporal stability in 2005-2006 and 2005-2007, but five sites showed temporal stability in yield in 2006-2007. Vine size spatial distribution was likewise relatively stable in 2005-2006, in which areas of the same vine size were observed at six sites; in 2006-2007 the same trend was observed at seven sites, and temporal stability between the 2005 and 2007 seasons was likewise observed for seven sites. Interestingly, spatial distribution of yield and vine size were highly correlated at Cave Spring (2005-2006), George (2005-2006) and CDC (2006-2007) that shows areas of higher yield had also higher vine size. Reynolds *et al*. (2007, 2010) and Willwerth *et al.* (2010) found relatively stable spatial distribution in vine size, which is consistent with our results. Berry weight spatial distribution was temporally stable, particularly at Cave Spring in 2005-2007, as well as at CDC and Harbour in 2006-2007; overall berry weight was temporally stable for only two sites (2005-2006), but was stable at seven sites (2006-2007). It is interesting to note that at Cave Spring, areas of high yield were also areas of high berry weight in 2005-2006, but this was not the case in 2006-2007. Overall, spatial distributions were more stable in soil moisture and yield components than leaf ψ data.

This investigation was initiated to identify 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 temporal stability of the spatial variability in the most important components, particularly soil and vine water status. Of equal importance was stability in the relationships between soil and vine water status and yield components, and the temporal stability of vine size and yield. If these relationships are stable, then the potential for implementation of precision viticulture is high (Bramley, 2005; Proffitt *et al*., 2006). Another application might be 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 soil type exerts an influence (less IBMP in gravel soils) (Peyrot des Gachons *et al.*, 2005). The norisoprenoid β-damascenone also has a substantial impact upon wine aroma, and although it has odor impact by itself, it also enhances fruity notes of some compounds and suppresses the odor activity of IBMP in Cabernet franc; its concentration varied according to soil type (Pineau *et al.*, 2007). Cysteine precursors of odor-active thiol compounds were closely linked to N status in Sauvignon blanc, and zones within vineyards with high N supply 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. Vine size, yield components, and berry composition variables were likewise mapped and many

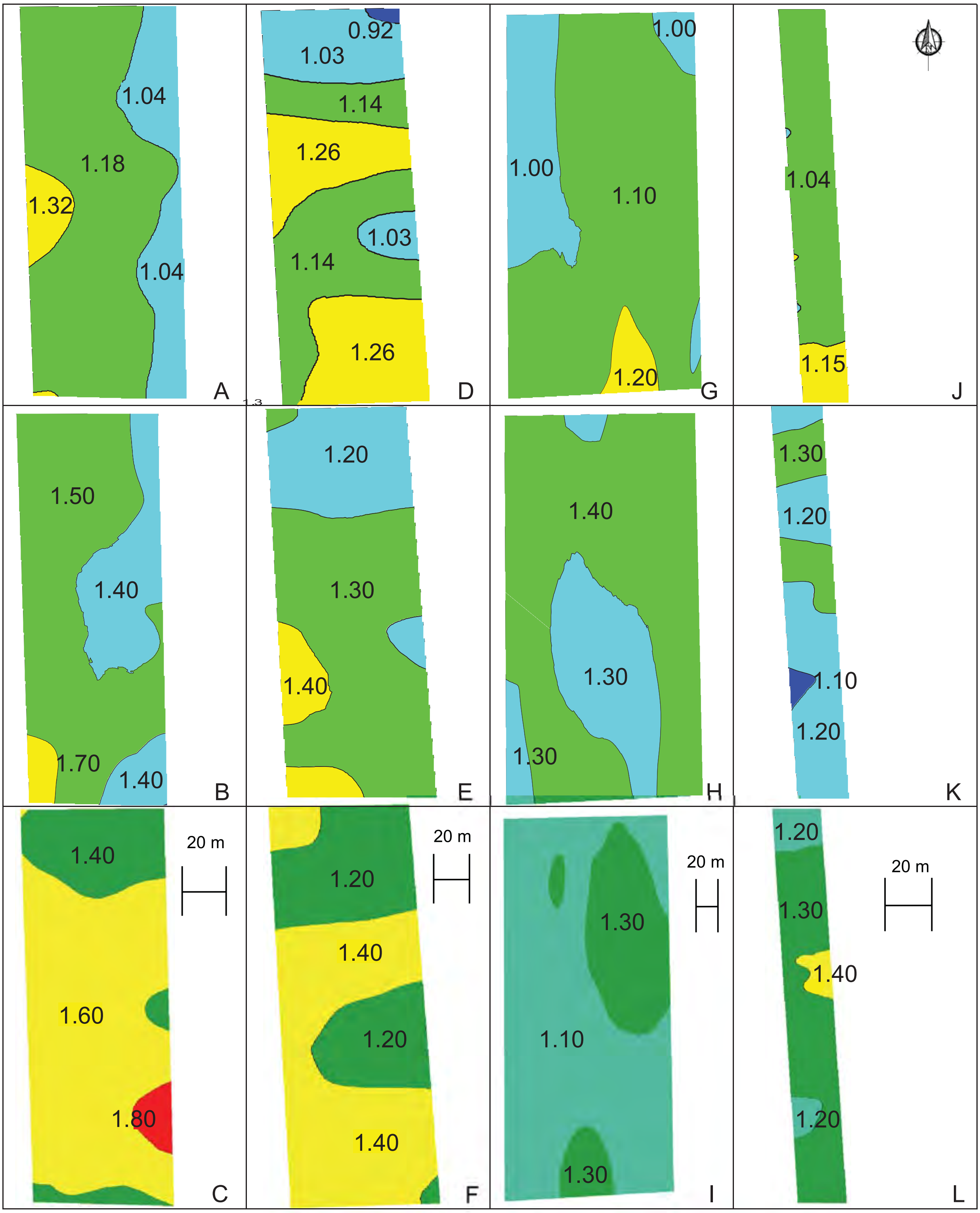

Fig. 7. Spatial distribution of berry weight (g). Cabernet franc, X'iagara Peninsula, ON; A to C: Buis: 2005 (A): 2006 (B); 2007 (C). D to F: Chateau des Charmes: 2005 (D); 2006 (E): 2007 (F). G to I: Hernder: 2005 (G): 2006 (H): 2007 (H). J to L: Reif: 2005 (J); 2006 (K); 2007 (L). Numbers on the maps refer to the minimum value in the range for each zone.

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 at two sites from 2006 to 2007. However, specific areas of the vineyard with high and low 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). Relationships between yield components and vine water status were not consistent across all ten sites. Clusters per vine, yield, berry weight, and vine size were all directly correlated with leaf ψ, particularly in the 2005 and 2007 seasons. However, in most sites, water status did not impact yield components and vine size when HWS and LWS zones were compared within individual vineyards. Areas of low

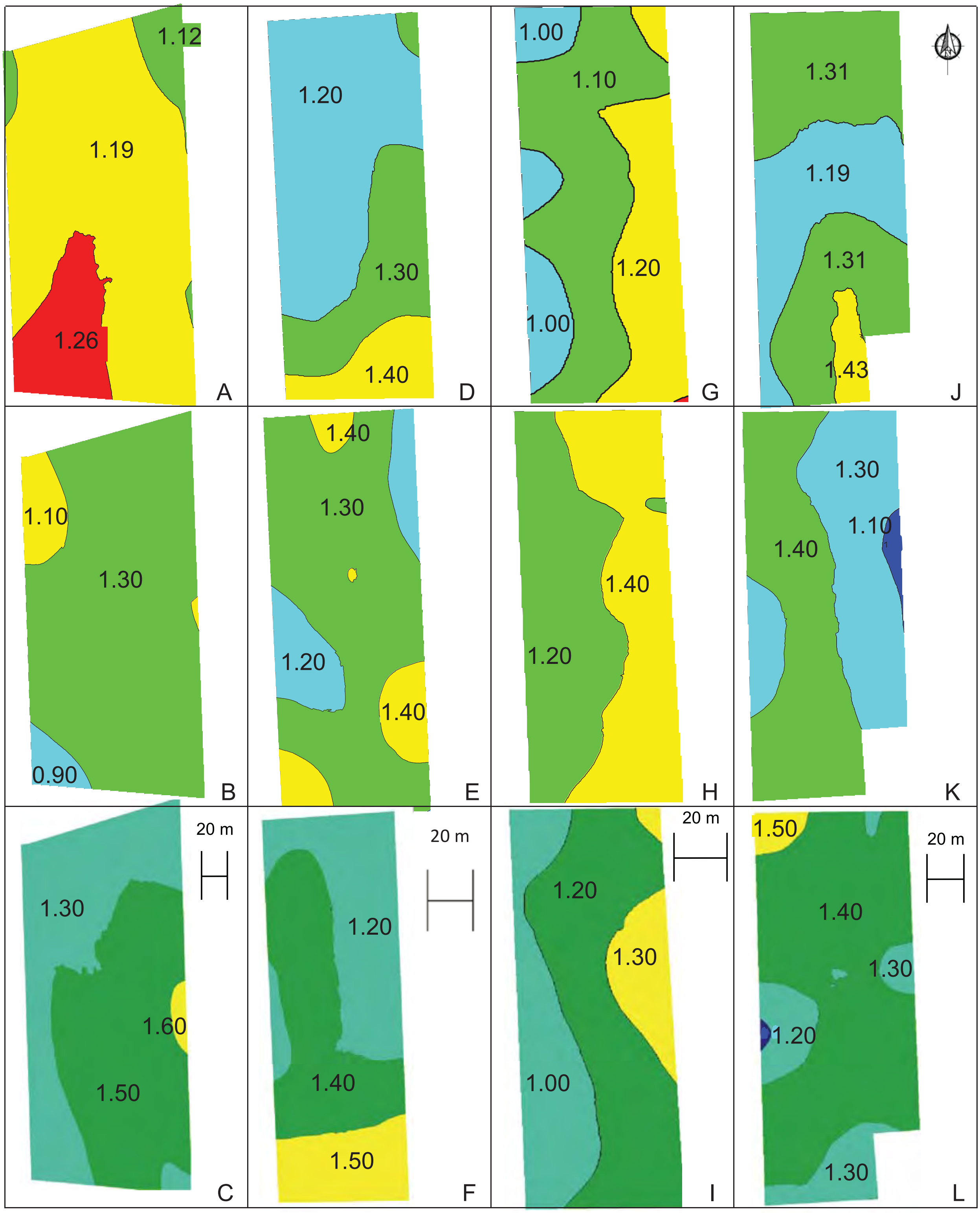

Fig. 8. Spatial distribution of berry weight (g). Cabernet franc, X’iagara Peninsula, ON: A to C: Harbour Estate: 2005 (A): 2006 (B); 2007 (C). D to F: George: 2005 (D): 2006 (E); 2007 (F). G to I: Cave Spring: 2005 (G): 2006 (H): 2007 (I). J to L: Henry of Pelham: 2005 (J); 2006 (K); 2007 (L). Numbers on the maps refer to the minimum value in the range for each zone.

water status were negatively correlated with berry weight. Vine size, yield, and berry weight spatial variation was temporally stable at several sites throughout the three year study. These data suggest that low soil moisture and low vine water status zones in vineyards are related to corresponding areas of low yield and vine size. These data further suggest that precision viticulture techniques may be utilized in this region to delineate yield-based or vine vigor-based vineyard sub-zones that further relate to differing quality levels.

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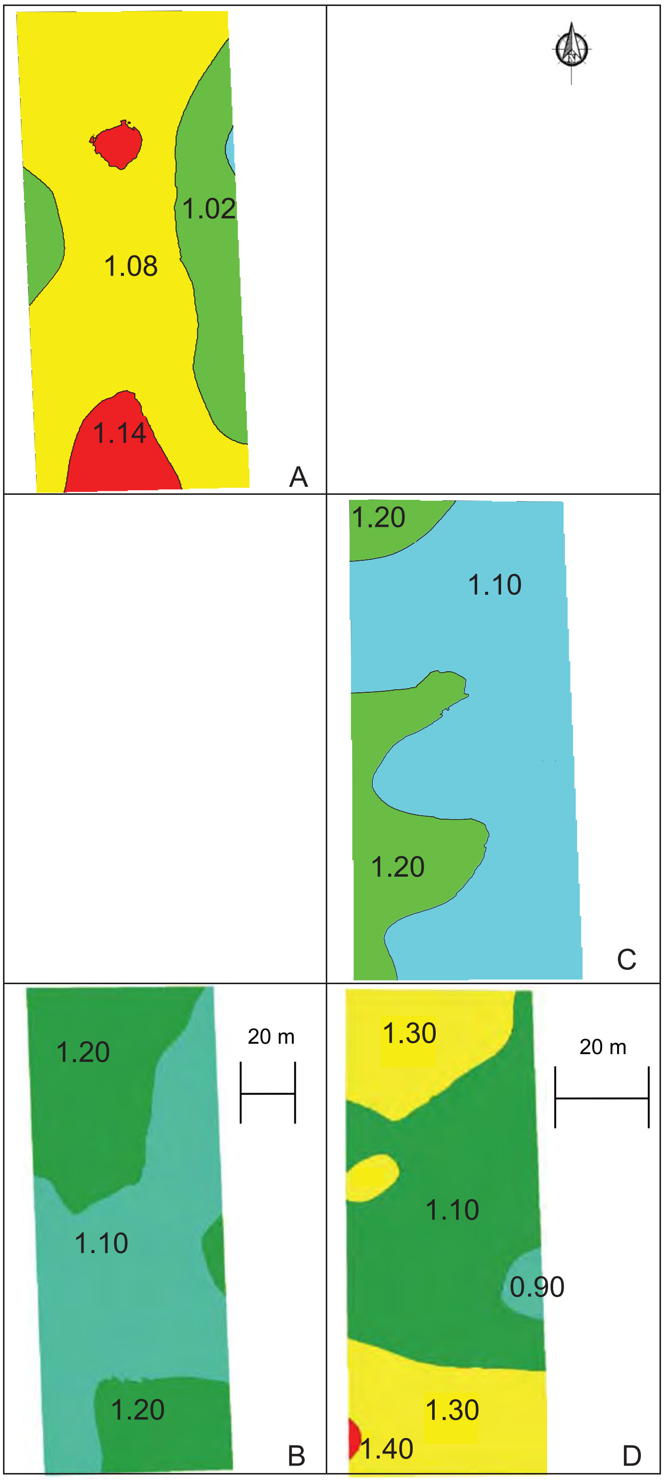

Fig. 9. Spatial distribution of berry weight (g). Cabernet franc, X'iagara Peninsula, ON: A to B: Vieni: 2005 (A): 2007 (B). C to D: Morrison: 2006 (C); 2007 (D). Numbers on the maps refer to the minimum value

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