

Use of geomatic technologies to determine the basis for Terroir. Spatial variation in five Ontario Chardonnay vineyards

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Abstract

The aim of this study was to test the hypothesis that soil texture would play a minor role in the determination of yield components, fruit composition, and wine sensory attributes of Chardonnay (*i.e.* the terroir effect), and that vine size, crop size and associated fruit environment would play the major roles. Five Chardonnay vineyards in the Niagara Peninsula of Ontario, Canada were chosen for study. These vineyards were located on sites with heterogeneous soil types to allow study of the impact upon yield, fruit composition and wine sensory attributes of: 1. Soil texture with mesoclimate kept constant; 2. The comparative magnitude of effects of soil texture and vine vigor. Vineyard blocks were delineated using global positioning systems (GPS), and a series of 72 to 162 data vines per site were geo-located within a sampling grid imposed on each vineyard block. Data were collected on soil texture, soil composition, tissue elemental composition, vine performance (yield components and weight of cane prunings), and fruit composition. These variables were mapped using geographical information systems (GIS) software and relationships between them were elucidated. Soil texture and composition were occasionally correlated to yield components and fruit composition but often these relationships were site-specific. Spatial relationships were common between % sand and clay, vine size, yield, berry weight, soluble solids (Brix), and titratable acidity (TA); however, relationships were both vineyard and vintage dependent. Several spatial relationships were apparent as well between vine size, yield, Brix, TA, and various soil/petiole composition variables, including organic matter, soil pH, cation exchange capacity, and soil/petiole N, P, K, Ca, Mg, and B. Spatial relationships between yield, berry weight, berry composition, vine size, and several soil physical variables suggest a likely soil basis to the so-called “terroir effect”. Vine size, yield, and berry weight were stable temporally within individual vineyards despite differences in annual climatic conditions. Soil texture (% sand) was frequently associated with high vine size, yield, and berry weight. Vine size directly correlated with berry weight. TA was often correlated with vine size. Soil composition had little relationship to petiole composition, fruit composition or yield except in a few specific cases, *e.g.*, between pH and soil K.

Key words: Fruit composition, soil texture, GPS, GIS, precision viticulture

Introduction

Terroir can be defined as the effects of vineyard location, including geology, soil, and climate, on wine composition and quality. In many terroir models, soil classification often plays a primary role, and consequently has been the most widely-addressed factor in research (Seguin 1986; van Leeuwen, 2010; van Leeuwen *et al.*, 2004). Examination of soil's influence on wine composition and quality, however, has been difficult to study objectively due to confounding influences of site climate, season, and within-vineyard variability.

Early attempts to define terroir showed that soil had no influence on wine quality of Australian Riesling and Clare Riesling, but greatest effects were attributable to climate, season, and cultivar (Rankine *et al.*, 1971). Soil had some influence during one vintage on sensory attributes of Chenin blanc and Cinsault in the Stellenbosch region of South Africa (Saayman, 1977), but these effects were reversed the following season, suggesting that climate and vintage had a greater impact than soil. No differences were found between Chardonnay wines produced from fruit obtained from Monterey (Region I), Oakville (Napa Co.; Region III), and Livermore (Alameda Co.; Region III) vineyards, despite large differences in soil types and heat unit accumulation (Noble, 1979).

The terroir concept as it pertains to wine quality first appeared in the literature > 25 years ago (Seguin, 1986). The definition was refined to include, in descending order of significance, physical and chemical aspects of soil, configuration of the terrain, mesoclimate, rootstock, cultivar, vine age, cultural practices, grape berry microflora (yeasts and malolactic bacteria), vinification practices, and transport of the fruit and finished wines (Mesnier, 1984). The definition of terroir was further refined by the integration of mesoclimate characteristics (heat accumulation, precipitation) with soil classification (Jourjon *et al.*, 1991). Other terroir models have closely paralleled the “New World” concept of wine quality insofar that soil is recognized as a factor that influences root growth, photosynthesis, and vegetative growth (Riou *et al.*, 1995).

Despite evidence to the contrary, many demonstrated putative relationships between soil and wine sensory characteristics. Sensory descriptive analysis objectively related wine sensory attributes to soil type for Cabernet franc wines produced from several sites in the Loire Valley (Asselin *et al.*, 1983). Brown calcareous soils with appreciable chalk content produced wines with greatest aroma and flavor intensity. However, sensory differences between the wines were greater between sites within appellations than between appellations, and relationships between

soil type and sensory variables were not attributable to specific site features. The terroir concept has been re-defined to embrace soil water content and its availability to vines during various parts of the growing season (Van Leeuwen *et al.*, 2004). Loire Valley soils that previously had been associated with intense wine varietal character were free-draining sandstones that provided mild water stress to the vines during fruit maturation (Penavayre *et al.*, 1991). Sandy soils overlying clays allowed for unlimited water supply during the growing season, more vigorous vines, and less intense varietal character. Among the many soil types within the Loire Valley, the well-drained tuffeau chalk was identified as conferring the greatest varietal typicity on Cabernet franc wines (Morlat and Asselin, 1992). The various soil types were acknowledged as having an association with specific vigor levels in the vines, and it was suggested that soil played an indirect role in determining varietal typicity and intensity (Asselin *et al.*, 1992).

An outgrowth of the terroir concept has involved use of multivariate statistics to delineate unique winegrowing regions based on soil, climate, and fruit composition data. Cluster analysis and other statistical tools were useful in defining adjacent viticultural zones in Spain based upon wine chemical composition (Latorre *et al.*, 1992) and helped in the separation of Italian Chardonnay wines from various vineyards and vintages (Seeber *et al.*, 1991). Although effects of soil and mesoclimate have been investigated widely in Europe, little has taken place in North America. Pinot noir wines produced from the Carneros, Napa, and Sonoma regions were discriminated through the use of principal components analysis (PCA) applied to sensory descriptive data (Guinard and Cliff, 1987), as were commercial Pinot noir and Chardonnay wines produced throughout the Okanagan Valley in British Columbia (Cliff and Dever, 1996). In Ontario, sub-appellations were proposed based upon sensory descriptive analysis of both commercial (Douglas *et al.*, 2001) and experimental (Willwerth *et al.*, 2015) Riesling wines, Chardonnay (Schlosser *et al.*, 2005), and Bordeaux red winegrape cultivars (Kontkanen *et al.*, 2005).

Use of remote sensing techniques and geographic information systems (GIS) for the study of vineyards is a relatively recent development that has yet seen few applications. GIS was used to map 2000 ha of the Loire Valley in terms of soil type and rootstock, but authors did not use the information to elucidate relationships between soil and wine varietal typicity (Morlat and Asselin, 1992). In California, GIS was used to map viticultural regions in terms of phylloxera damage based on leaf reflectance (Baldy *et al.*, 1996), and to distinguish between high and low vigor management zones in Zinfandel vineyards (Greenspan and O'Donnell, 2001). In the past decade, there has been a substantial increase in the application of geomatic techniques for purposes of implementing precision viticulture. Although less laborious than manual data collection and the subsequent production of a multitude of maps, use of aircraft is costly and remote sensing in agricultural systems is in many ways imprecise (Stamatiadis *et al.* 2006). The data that is collected must be converted to variables such as normalized difference vegetative index (NDVI) through computer software such as ENVI (Marciniak *et al.* 2015). Moreover, validation of data acquired by remote sensing is still necessary to determine whether ostensibly-unique zones are relevant from a standpoint of physiology, productivity, and

berry composition. One particular challenge involved masking of cover crop NDVI from all images to assess the vine canopy-specific NDVI (Marciniak *et al.*, 2015). In southern France, spatial variability in vine water status, vine trunk circumference, yield, and soil moisture were spatially correlated with NDVI, but berry composition was unrelated to NDVI (Acevedo-Opazo *et al.*, 2008a,b). In Marlborough, New Zealand, variability in soil texture in Sauvignon blanc vineyards was linked to variability in yield, vine vigor, and berry composition (Bramley *et al.*, 2011c, Trought and Bramley, 2011; Trought *et al.*, 2008). Remote sensing and GIS techniques have been utilized widely and for several purposes in many vineyards in Australia (Bramley, 2005; Bramley and Hamilton, 2004; Bramley *et al.*, 2010, 2011a,b). These applications included use of remote sensing to map phenolics and color (Lamb *et al.*, 2004), assessment of yield temporal stability (Bramley and Hamilton, 2004), assessment of spatial correlations among soil components, vine vigor, yield, berry composition, and wine sensory attributes (Bramley *et al.*, 2011a), and application of these techniques in large, highly variable vineyards (Bramley *et al.*, 2011b).

Wine quality is determined primarily by vineyard factors such as site, soil, and canopy management. The impact of traditional terroir-related factors such as geology and soil were given equal weighting with training systems, vine spacing, and canopy management in terms of impacts upon wine quality (Smart, 1985). Relationships exist between canopy management, aroma compounds in the grape berries, and intensity of wine varietal character, as well as between mesoclimate, flavor compounds, and wine sensory attributes with soil type held constant (Reynolds *et al.*, 1995). However, despite the volume of research on this subject, it is not clear if soil is a primary determinant of wine quality, or whether soil is simply a medium that impacts vine growth and vigor, and that the skill by which this vigor is accommodated ultimately determines wine quality. This study was intended to address this controversy through the use of geomatic tools such as global positioning systems (GPS) and GIS.

Ontario vineyards are often located on sites containing heterogeneous soil types. It was hypothesized that soil texture would play a minor role in determining yield components, fruit composition, and wine sensory attributes, and that vine vigor, crop size and fruit environment would play the major roles. This hypothesis was also tested in a related study with Riesling (Reynolds *et al.*, 2007). This study attempted to resolve this question of direct soil effects by testing the independent effects of soil texture and vine vigor on yield components and berry composition of Chardonnay, as well as on must and wine composition, and wine sensory attributes (Reynolds *et al.*, 2013). Geomatic technologies were likewise used to identify zones of different water status in Cabernet franc (Reynolds and Hakimi Rezaei, 2014a,b,c) and Riesling (Willwerth *et al.*, 2010). Zones of lowest water status were associated with highest monoterpenes in Riesling berries (Willwerth *et al.*, 2010), and highest anthocyanins and phenols in Cabernet franc (Reynolds and Hakimi Rezaei, 2014c). An improved understanding of the impact of soil texture/composition and vine vigor on wine quality could have substantial consequences for choice of future vineyard sites, cultural practices, grape cultivars and rootstocks. Elucidation of unique flavor profiles from specific vineyard blocks could lead to unique cultural practices for each of them. There might also be

implications from this type of study for precision viticulture, if spatial variability in vine vigor and yield were highly correlated, and if spatial variation in yield was temporally consistent within individual vineyard blocks.

Materials and methods

Site selection: A series of sites were selected in the spring of 1998 throughout the Niagara Peninsula on the basis of their diverse soil types (Table 1). Five co-operators were selected; two in the Lakeshore region of Niagara-on-the-Lake (Buis; Falk); two in the Lakeshore Plain region [Château des Charmes (CDC); Lambert], and one on the Niagara Escarpment near Vineland (Wismer). All vineyard blocks had heterogeneous soil types, particularly with respect to soil texture (Kingston and Presant, 1989) and hence it was assumed that they would be quite variable in yield and vine size. Clay loam till soils such as Jeddo (JDD) had solum depths of 44 cm with 2-3% gravel content, while Chinguacousy (CGU) soils had 9% gravel content in their A-horizons and 52 cm solum depths. Lacustrine soils such as Vineland and Tavistock had low gravel values (0-1%) but high solum depths (83 and 64 cm, respectively), that had potential for greater rooting depth than clay loam till-based soils (Kingston and Presant, 1989). Cultural practices within each vineyard were consistent throughout the 5 yr of data collection and none of the vineyards were irrigated during this period. In each vineyard, a grid-style sampling pattern was established with a “sentinel vine” at each grid intersection point. These sampling sites (“sentinel vines”; 72 to 162 per vineyard block) were conspicuously marked. A global positioning system (GPS) at < 1 m accuracy was used in May 1998 to delineate shape and size of the vineyard blocks and to geo-locate each sentinel vine used for data collection. A GBX-12R GPS unit (CSI-Wireless, Calgary, AB) was used in conjunction with an MGL-3 antenna, receiving beacon differential on frequency 322 from Youngstown, NY. Details of vines sampled, soil types, and vineyard management are in Table 1.

GIS mapping; soil and petiole analysis: Soil mapping was carried out on a site-by-site basis. Soil samples (\approx 200 g) were collected using a 3 cm X 75 cm (diameter X length) soil probe near each sentinel vine in September 1998. Soil analyses including elemental concentration, cation exchange capacity (CEC), base saturation (BS; as %Ca, Mg, and K), pH, and organic matter (OM) concentration were performed on each soil sample. Proportions of sand, silt, and clay (mechanical analysis by hydrometer) were determined on sub-samples, and soil texture and composition maps of each vineyard block were constructed from this information (q.v. sand maps; Fig. 1A to E) using GIS programs MapInfo and Vertical Mapper (Northwood GeoScience, Ottawa, ON). The inverse distance weighting (IDW) interpolation algorithm (default setting, $W=2$) was used to construct the grid files. IDW was chosen rather than the more popular kriging technique based on the assumption that data would be highly variable and unpredictable over short distances, as a consequence of the glaciated soils—for some sites at least three soil series were listed (Kingston and Presant, 1989). In all cases, six categories with equal ranges were specified where possible for all maps. Soil samples were air-dried, pulverized and sieved to remove particles > 2 mm in diameter. Sub-samples were retained for elemental analysis (P, K, Ca, Mg, Mn, Fe, Cu, Zn, B) using Perkin-Elmer Optima 3000 inductively-coupled plasma emission spectroscopy

(ICP). OM analysis was performed using standard colorimetric methods (CSSS, 1993). Soil pH, CEC and BS-Ca/Mg/K were measured by standard methods (CSSS, 1993). Petiole sampling (\approx 30 g per sentinel vine) occurred in July/August 1998, and elemental composition was thereafter determined. Petiole samples were dry-ashed at 550°C and extracted with hydrochloric and nitric acids. Samples were analyzed for N, P, K, Ca, Mg, Mn, Fe, Cu, Zn, and B using ICP as previously described. All soil/petiole analyses were carried out at Agri-Food Laboratories, Guelph, ON.

Viticultural data collection: For each sentinel vine, data were collected annually at pruning time for weight of cane prunings (vine size) as an estimate of vine vigor. Yield components (yield per vine; clusters per vine; cluster weight; berries per cluster; berry weight; crop load) were either measured directly or calculated annually from measured variables. Samples of 100 berries were taken from each sentinel vine for determination of berry weight and standard fruit composition indices [soluble solids (Brix); titratable acidity (TA); pH]; these were stored at -25°C until analysis. Thawed samples were heated to 80 °C for 1 hour using a Fisher Scientific Isotemp 228 water bath (Fisher Scientific, Ottawa, ON) to dissolve precipitated tartaric acid, cooled, homogenized in a fruit and vegetable juicer (Omega Products Inc., Harrisburg, PA, model 500), and clarified using a IEC Centra CL2 centrifuge (Int. Equipment Co., Needham Heights, MA). Brix were measured using a temperature-compensated Abbé bench refractometer (American Optical Corp., Buffalo, NY, model 10450), and pH was measured using an Accumet pH/ion meter (Fisher Scientific, Ottawa, ON, model 25). TA was measured on 5-mL samples titrated to a pH 8.2 endpoint with 0.1 N NaOH using a Man-Tech PC-Titrate autotitrator (Man-Tech Associates Inc., Guelph, ON, model PC-1300-475). A database was compiled annually on all sentinel vines for yield and berry composition variables.

Statistical analysis. The SAS statistical package (SAS Institute, Cary, NC) was used for analysis of the results of all portions of the experiment. Correlations were determined (PROC CORR) between soil composition, soil texture, yield components and berry composition for all vintages, and PCA was conducted on the 1998 data set to elucidate possible relationships among soil, petiole, yield, and berry compositional variables. MapInfo and Vertical Mapper (Northwood GeoScience, Ottawa, ON) were used to construct maps of soil texture and composition, petiole composition, yield components, vine size, and berry composition. These maps were used to examine spatial variation for selected variables in each season, and to compare spatial relationships between correlated variables. Spatial correlations between variables or temporally stable relationships within variables were considered evident only upon compelling visual evidence among maps and confirmation by linear correlations between variables.

Results and discussion

Climatic data. Growing degree day (GDD; base 10°C) and rainfall data for 1998-2002 for the five sites are in Table 2. Data were obtained from Weather Innovations Network (<http://www.weatherinnovations.com>) weather stations, situated as close to the study sites as possible throughout the Niagara Peninsula. The Falk and Buis sites were adjacent to each other and representative data are those from the Falk site. Highest rainfall occurred at CDC (1999, 2000), Wismer (1998, 2001), and Buis/Falk (2002). Lowest

Table 1. General features of five Niagara Peninsula Chardonnay vineyards used for elucidation of terroir studies, 1998-2002.

Variable	Buis	Château des Charmes	Falk	Lambert	Wismer
Location	Niagara-on-the-Lake	St. Davids	Niagara-on-the-Lake	Niagara-on-the-Lake	Vineland
Sub-appellation	Lakeshore	Lake Plain	Lakeshore	Lake Plain	Escarpment Bench
Area of vineyard block (ha)	3.36	Two blocks of 1.38 and 1.34 ha, separated by 120 m	1.09	1.81	1.12
Number of sentinel vines	162	135	72	88	107
Soil series (Kingston and Present, 1989)	Jeddo (JDD) 8 Vineland (VLD) 1	JDD21 Tavistock (TVK) 11 Chinguacousy (CGU) 16	VLD1 VLD4 JDD8	JDD2 JDD3 CGU19	CGU1 CGU3 JDD1
Parent materials (Kingston and Present, 1989)	JDD8: Reddish-hued clay loam till VLD1: Reddish-hued lacustrine fine and very fine sandy loam	JDD21: Clay loam till TVK11: 40-100 cm reddish-hued loamy textures over clay loam till CGU16: Reddish-hued clay loam till	VLD1: q.v. Buis VLD4: Brownish-hued lacustrine fine and very fine sandy loam JDD8: q.v. Buis	JDD2: Reddish-hued clay loam till JDD3: 15-40 cm loamy textures over reddish-hued clay loam till CGU19: Reddish-hued clay loam till	CGU1: Clay loam till CGU3: 15-40 cm loamy textures over clay loam till JDD1: Clay loam till
Soil drainage (Kingston and Present, 1989)	JDD8: Imperfect to poor VLD1: Imperfect	JDD21: Poor TVK11: Imperfect CGU16: Imperfect	VLD1: Imperfect VLD4: Imperfect to poor JDD8: Imperfect to poor	JDD2: Poor JDD3: Poor CGU19: Imperfect to poor	CGU1: Imperfect CGU3: Imperfect JDD1: Poor
Available moisture—A, B horizon (%; Kingston and Present, 1989)	JDD8: 20.0 (A); 18.6 (B) VLD1: 23.3 (A); 18.4-25.7 (B)	JDD21: 20.0 (A); 18.6 (B) TVK11: 21.0 (A); 13.4-21.7 (B) CGU16: 14.0 (A); 12.0 (B)	VLD1, VLD4: 23.3 (A); 18.4-25.7 (B) JDD8: 20.0 (A); 18.6 (B)	JDD2, JDD3: 20.0 (A); 18.6 (B) CGU19: 14.0 (A); 12.0 (B)	CGU1, CGU3: 14.0 (A); 12.0 (B) JDD1: 20.0 (A); 18.6 (B)
Depth of solum (cm, base of B horizon; Kingston and Present, 1989)	JDD8: 44 VLD1: 84	JDD21: 44 TVK11: 65-70 CGU16: 52	VLD1, VLD4: 84 JDD8: 44	JDD2, JDD3: 44 CGU19: 52	CGU1, CGU3: 52 JDD1: 44
% gravel and stones (A and B horizons; Kingston and Present, 1989)	JDD8: 2 (A); 2-3 (B) VLD1: 1 (A); 1 (B)	JDD21: 2 (A); 2-3 (B) TVK11: 1 (A); 0 (B) CGU16: 9 (A); 3-4 (B)	VLD1, VLD4: 1 (A); 1 (B) JDD8: 2 (A); 2-3 (B)	JDD2, JDD3: 2 (A); 2-3 (B) CGU19: 9 (A); 3-4 (B)	CGU1, CGU3: 9 (A); 3-4 (B) JDD1: 2 (A); 2-3 (B)
Clone	ENTAV 96	ENTAV 75, 76, 77, 78, 95, 96	Not specified at time of planting	ENTAV 96	ENTAV 96
Rootstock	SO 4	SO 4	SO 4	SO 4	3309
Vine age at initiation of trial (yr. planted)	1986	1996	1996	1991	1993
Vine spacing (m; row X vine)	2.4 X 1.2	2.5 X 1.2	2.4 X 1.2	2.7 X 1.2	2.4 X 1.5
Training system	Scott Henry	Guyot double	Scott Henry	Scott Henry	Scott Henry

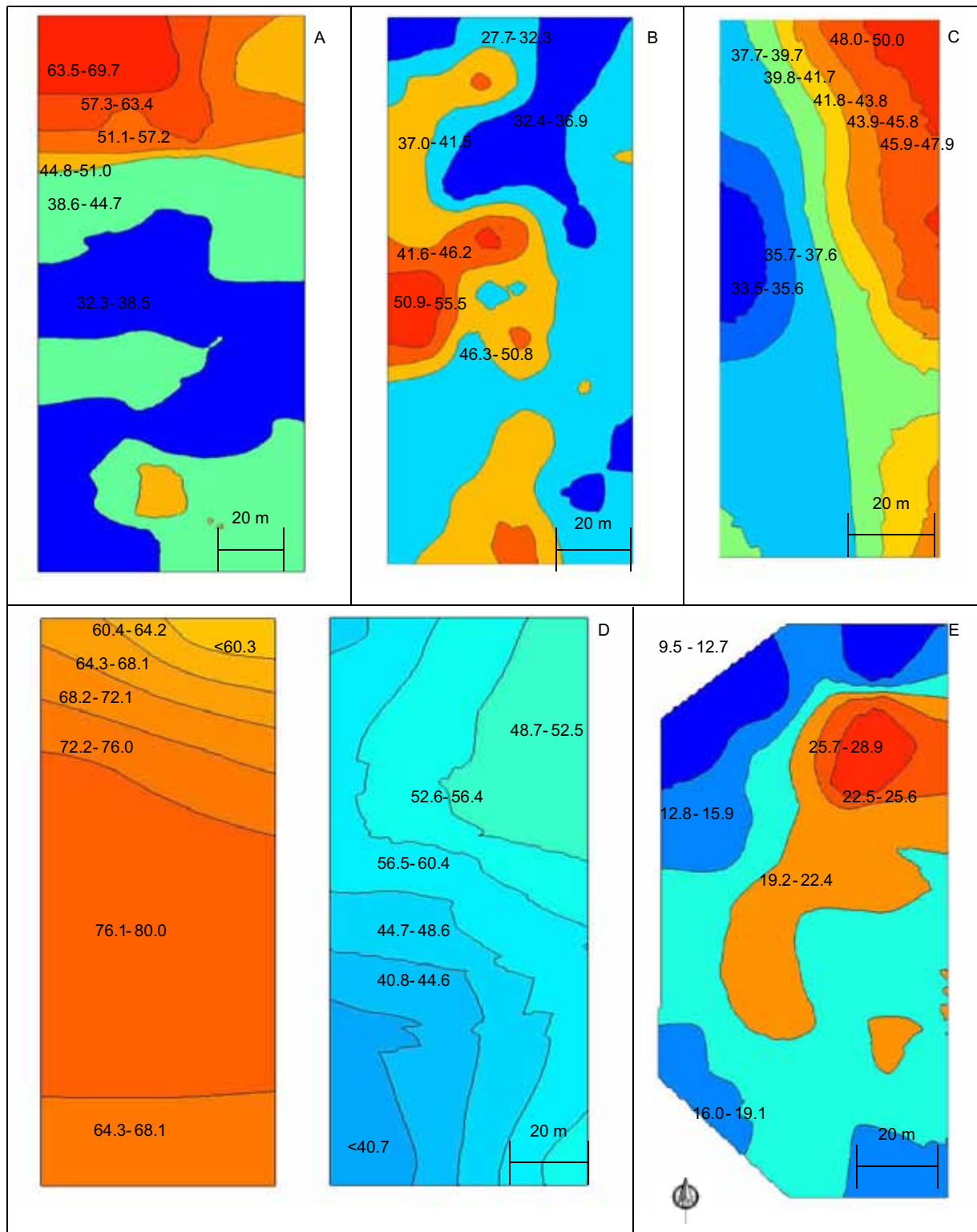


Fig. 1. Distribution of sand within Chardonnay blocks in five Niagara Peninsula vineyards. Legend: A= Buis; B= Lambert; C= Falk; D= Château des Charmes (space between the two blocks 120 m); E= Wismer.

rainfall occurred at Buis/Falk (1998, 2000, 2001), and Wismer (1999, 2002). The long term regional precipitation average was 499 mm, suggesting that vintages in the study period experienced below average rainfall except 2000, which was 128% of average. CDC had the highest GDD accumulation in all five vintages, while lowest GDD was at the Wismer (1998-2001) and Buis/Falk sites (2002). The long term regional heat unit average was 1516 GDD, suggesting that vintages in the study period experienced above average GDD except 2000, which was 95% of average.

Spatial variability in soil/petiole variables

Soil physical properties: Ranges in soil/petiole composition are in Table 3. Spatial maps for % sand are in Fig. 1, while Supplementary Figs. S1 to S8 depict spatial distribution of soil OM/pH (Fig. S1), CEC/BS-Ca (Fig. S2), petiole N (Fig. S3), and soil/petiole P, K, Ca, Mg, and B (Figs. S4-S8). The sites differed greatly in their variability in soil/petiole composition variables. There was wide variability in soil texture (Table 3; Fig. 1). The CDC site contained a section that was 60 to 80% sand, while

Table 2. Climatic data for five sites from four weather stations between April 1 and October 31, 1998 and 2002 in the Niagara Peninsula, ON (Niagara Agricultural Weather Network). Long term mean for precipitation was 499 mm and long term GDD was 1516

Site	Rainfall (mm)					Growing degree days (base 10 °C)				
	1998	1999	2000	2001	2002	1998	1999	2000	2001	2002
Falk, Buis	336	476	619	410	531	1583	1525	1345	1501	1570
Lambert	354	461	669	449	512	1604	1554	1360	1550	1584
Château des Charmes	387	497	688	427	477	1629	1625	1411	1583	1618
Wismer	393	446	668	454	447	1535	1489	1303	1496	1573
Mean (four weather stations)	368	470	661	435	492	1588	1548	1355	1533	1586
Mean (entire region; 12 stations)	352	451	637	416	456	1612	1572	1422	1566	1566

the Wismer site had a narrower range. Spatial variability in OM was common, particularly the elevated OM values in the eastern block of CDC and the northern end of the Wismer site. An inverse relationship (based on careful visual inspection and qualitative observation of maps) was clear between sand and both OM and pH at the CDC site, confirmed by *r* values of -0.62 and -0.74, respectively ($P < 0.0001$; data not shown). Ranges in pH values were narrow, with substantial spatial variation at the CDC and Wismer sites. Apparent spatial relationships occurred between OM and pH, particularly at the Lambert, Falk, CDC, and Wismer sites; *r* values were 0.06 to 0.28 for the first three sites but 0.63 ($P < 0.0001$) for the Wismer site (data not shown). CEC and BS-Ca had narrow ranges, but were spatially variable at the Buis, CDC and Wismer sites. Spatial relationships, as expected, were apparent between CEC and BS-Ca at the Buis and CDC sites ($r =$

Table 3. Soil and tissue composition for five Ontario Chardonnay vineyards, 1998. Petiole samples were taken postbloom; soil samples were taken in August

Variable	Buis		Château des Charmes		Falk		Lambert		Wismer	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Soil										
Sand (%)	27-72	43.5	37-80	61.1	32-51	40.7	25-56	36.1	4-36	18.3
Silt (%)	14-51	37.9	9-30	19.7	35-50	42.3	26-56	46.7	36-62	52.8
Clay (%)	11-25	18.5	9-33	19.3	14-21	17.0	12-23	17.2	20-43	28.6
pH	5.6-7.2	6.47	5.2-7.7	6.77	6.7-7.4	7.13	5.8-7.5	6.71	6.3-7.4	6.97
OM (%)	2.0-4.2	3.32	1.4-4.0	2.66	1.7-3.5	2.77	2.1-3.8	2.71	2.2-6.0	3.32
P (mg/kg soil)	9.0-62	30.7	17-105	47.5	28-79	48.1	17-62	34.8	20-78	38.0
K (mg/kg soil)	172-690	369 ^y	159-780	322 ^y	190-355	282 ^y	112-580	226 ^y	97-333	171 ^y
Ca (mg/kg soil)	1600-3321	2343	689-3408	2304	1916-2828	2427	1712-2911	2379	1928-3854	2828
Mg (mg/kg soil)	112-262	181	76-413	199	92-172	127	97-308	180	186-817	345
B (mg/kg soil)	0.32-1.07	0.68 ^z	0.25-1.67	0.87	0.47-0.97	0.75	0.34-2.16	1.16	0.53-1.59	0.92
Cu (mg/kg soil)	2.4-13.1	6.44	7.8-35.6	18.3 ^y	2.3-7.0	4.09	1.6-6.4	2.52	3.4-9.2	5.91 ^y
Fe (mg/kg soil)	26-150	54.0	15-73	31.0	26-53	38.0	17-63	33.3	26-56	37.7
Mn (mg/kg soil)	8.8-46	27.1	8.3-38	26.0	19-39	29.2	10-53	29.5	13-44	29.5
Zn (mg/kg soil)	1.9-6.2	3.86	1.6-9.5	3.47	1.1-3.9	2.40	1.0-9.3	2.07	0-7.2	3.19
CEC	11-21	15.5	7.0-21	15.9	12-17	15.1	13-19	15.4	13-27	18.7
BS/K (%)	2.9-11.2	6.1	2.1-16.4	5.8	3.2-6.1	4.8	1.9-7.9	3.8	1.4-3.8	2.3
BS/Mg (%)	7-14	9.8	5-18	10.6	5-9	7.0	6-14	9.6	9-25	14.9
BS/Ca (%)	57-81	75.5	34-90	70.2	77-83	80.2	58-84	77.6	68-82	76.1
Petioles										
N (%)	0.37-0.84	0.59 ^z	0.54-1.02	0.70 ^z	0.44-1.59	0.59 ^z	0.62-0.95	0.79 ^z	0.39-0.62	0.49 ^z
P (%)	0.07-0.43	0.15 ^z	0.01-0.89	0.10 ^z	0.15-0.70	0.33 ^y	0.09-0.36	0.67 ^y	0.20-0.80	0.49 ^y
K (%)	0.94-4.39	2.66 ^y	0.22-3.26	1.40 ^y	2.85-5.14	4.16 ^y	0.53-4.13	1.86 ^y	0.24-2.3	1.19 ^z
Ca (%)	1.78-3.15	2.36	0.82-3.23	2.36	1.15-1.97	1.47	1.25-2.31	1.74	1.77-3.25	2.34 ^y
Mg (%)	0.34-1.57	0.77	0.27-1.93	0.98 ^z	0.23-0.45	0.31 ^z	0.33-0.82	0.60 ^z	0.80-1.94	1.37 ^y
B (mg/kg)	27-39	33.1	25-44	34.8	27-40	34.4	27-41	34.5	26-37	30.4 ^z
Cu (mg/kg)	2.67-13.3	4.93	3.60-27.75	6.42	3.69-18.78	6.44	5.00-11.20	7.83	156-413	256
Fe (mg/kg)	27-208	64.5 ^y	56-271	97.2 ^y	21-130	49.7	28-172	47.9	35-784	100.9 ^y
Mn (mg/kg)	44-845	121.8 ^y	1.79-209	33.3 ^z	41-145	76.3	24-276	121.3 ^y	21-417	227.2 ^y
Zn (mg/kg)	50-173	92.3 ^y	4.5-300	50.2	10-210	106 ^y	33-648	61.5	77-181	109.3 ^y

^z Soil or petiole deficiency according to local guidelines.

^y Soil or petiole excess according to local guidelines.

(Brady and Weil, 2002), and consequently these differential rates of movement within soil and plant present the likelihood of a lack of putative relationships between many elements.

Correlations between soil variables and petiole elements are in Table 4. Substantial spatial variability occurred in all sites for petiole N. There were no spatial relationships between petiole N and soil physical properties such as OM, pH, CEC, and BS-Ca. Soil/petiole P was spatially variable in most blocks, and in the case of CDC and Wismer, spatial relationships were apparent between soil and petiolar P. Soil/petiole K varied spatially at all sites and showed apparent spatial relationships between soil and petiolar K

at all sites; linear correlations were observed for Lambert (0.53; $P < 0.0001$) and Wismer sites (0.65; $P < 0.0001$). Soil/petiole Ca showed spatial variability in each block and spatial relationships were apparent between soil/petiole Ca concentrations at the CDC and Wismer sites; a correlation was observed at the Wismer site ($r = 0.79$; $P < 0.0001$). The same was apparent for soil/petiole Mg, particularly for the Falk and CDC sites. Soil/petiole B varied spatially but no obvious relationships were apparent between soil/petiole B except a putative inverse relationship at the CDC site that was not supported by linear correlation.

Vine size. Spatial variability in vine size was apparent at all sites

Table 4. Significant correlations between soil/petiole composition variables for five Niagara Peninsula Chardonnay vineyards, 1998. Boldfaced coefficients are those between soil/petioles for like elements

Petiole variable	Soil variable									
	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	
N			-0.26*W			0.30*W				
P			0.36**W	0.31*F 0.57****W	0.30*W		0.26*W	-0.31*F 0.29*W	0.26*W	
K	0.51****L 0.53****W	0.53****L 0.65****W	0.46****W	0.57****W	0.24*L 0.68****W		0.33**L 0.41***W	0.46****W	-0.23*B 0.65****W	
Ca	0.33**L 0.50****W	0.38***L 0.59****W	0.79****W	0.23*L 0.81****W	0.23*L 0.66****W		0.47***W		0.66****W	
Mg	-0.38***L -0.53****W	-0.43***L -0.59****W	-0.47****W	-0.30*F -0.51****W	-0.26**L -0.65****W		-0.36**W	-0.61****W	-0.50****W	
Zn			-0.35*F		-0.34*F	0.23*B		0.30*W		
Mn	-0.43***W	-0.60****W	-0.27**B -0.64****W	-0.23*B -0.60****W	-0.26**L -0.42***W	0.37**W	-0.37**F		0.22*L -0.58****W	
Cu	-0.31**L -0.30*W	0.37***B -0.31**L	-0.41***W		-0.23*L	0.23*B	0.30**B	0.31**C		
Fe		0.35**C	0.30*F				0.31**C 0.29**L			
B	-0.28**L		-0.23*B -0.38**F 0.41***W	-0.39**F 0.36**W				0.30**B		

Petiole variable	Soil variable									
	Sand	Silt	Clay	OM	pH	CEC	Base saturation			
							K	Mg	Ca	
N	0.31*F	0.25*W	-0.37**W			0.26*W				
P	-0.52***F	0.60****F -0.38**W	0.30*W	0.39**W		0.44***W		0.62****W	-0.59****W	
K	0.26**B -0.35**W	-0.28**B -0.26**L	0.50****W	0.72****W	0.39**W	0.55****W	0.60****L 0.44***W	0.55****W	-0.24*L -0.52****W	
Ca		-0.49****W	0.56****W	-0.48***F 0.75****W	0.60****W	0.82***W	0.34**L	0.73****W	0.23*B -0.56****W	
Mg	-0.25**L 0.35***W	0.23*B 0.30**L	-0.55****W	-0.38**F -0.63****W		-0.53****W -0.30*F	-0.50****L -0.38**W	-0.42***W	0.37**W	
Zn	0.31*F	0.22*B		-0.41**F	-0.38**F	-0.34*F				
Mn	-0.38**F	0.39**F 0.40**W	-0.42***W	-0.54****W	-0.62****W	-0.65****W	0.27**B	-0.24*B -0.54***W	-0.41***B 0.38**W	
Cu						-0.32**W	0.39***B -0.37**F -0.36***L			
Fe		-0.27*W					0.34*C -0.35*F		0.31*F	
B				0.27**B 0.33**W		0.41***W -0.31*F	-0.25**L	0.36**W	-0.24*B	

B,C,F,L,W: Buis, Chateau des Charmes, Falk, Lambert, and Wismer Vineyards, respectively.

*, **, ***, ****: Significant r values at $P < 0.05$, 0.01, 0.001, or 0.0001, respectively.

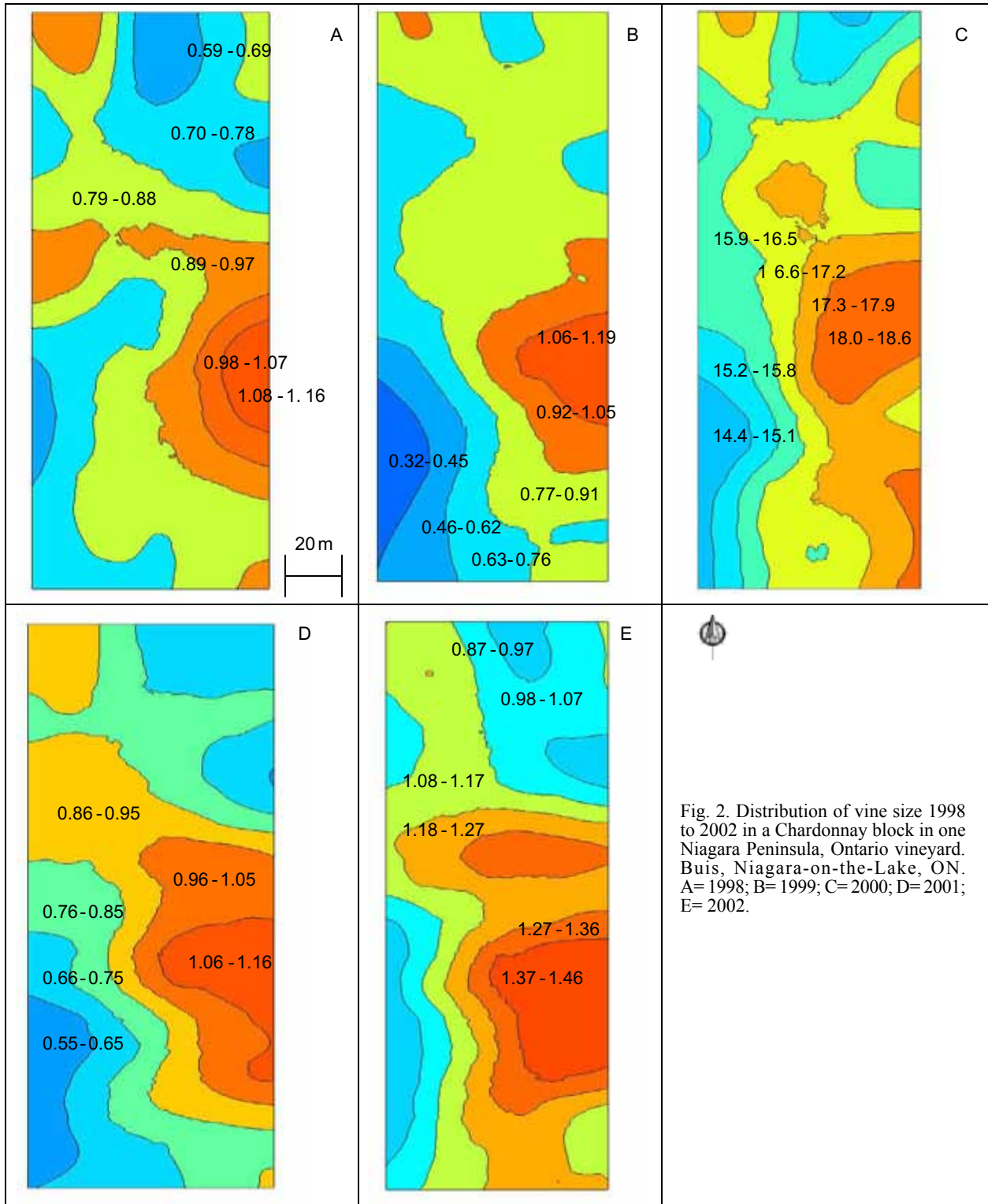


Fig. 2. Distribution of vine size 1998 to 2002 in a Chardonnay block in one Niagara Peninsula, Ontario vineyard. Buis, Niagara-on-the-Lake, ON. A= 1998; B= 1999; C= 2000; D= 2001; E= 2002.

(Figs. 2-6). Temporal stability in vine size was noticeable across the five study years. At the Buis site, the spatial pattern of trunk circumference (used as a substitute for weight of cane prunings in the 2000 winter) was similar to vine size in the two previous and succeeding years (Fig. 2). Temporal stability in vine size was consistent at the Lambert (Fig. 3), Falk (Fig. 4), CDC (Fig. 5), and Wismer locations (Fig. 6). This strongly suggests that despite seasonal differences, spatial patterns in vine size were consistent within these vineyards. Since vine size spatial variability was consistent within sites, and the patterns were not strongly

influenced by climatic variables, it is likely a major component of the terroir effect. This is consistent with Bramley (2010), Bramley *et al.* (2011c) and many others, who have demonstrated temporal stability in mean block vine size across several vintages.

Yield components: Spatial variability in yield was noticeable across all vineyard blocks. As with vine size, temporal stability in yield and berry weight was apparent. Yield maps from one site (Buis) are shown (Fig. 7); others are shown in Figs. S9 (Lambert), S10 (Falk), S11 (CDC), and S12 (Wismer). Yield patterns were stable at the Buis site (1998-2001) but not in 2002, as were

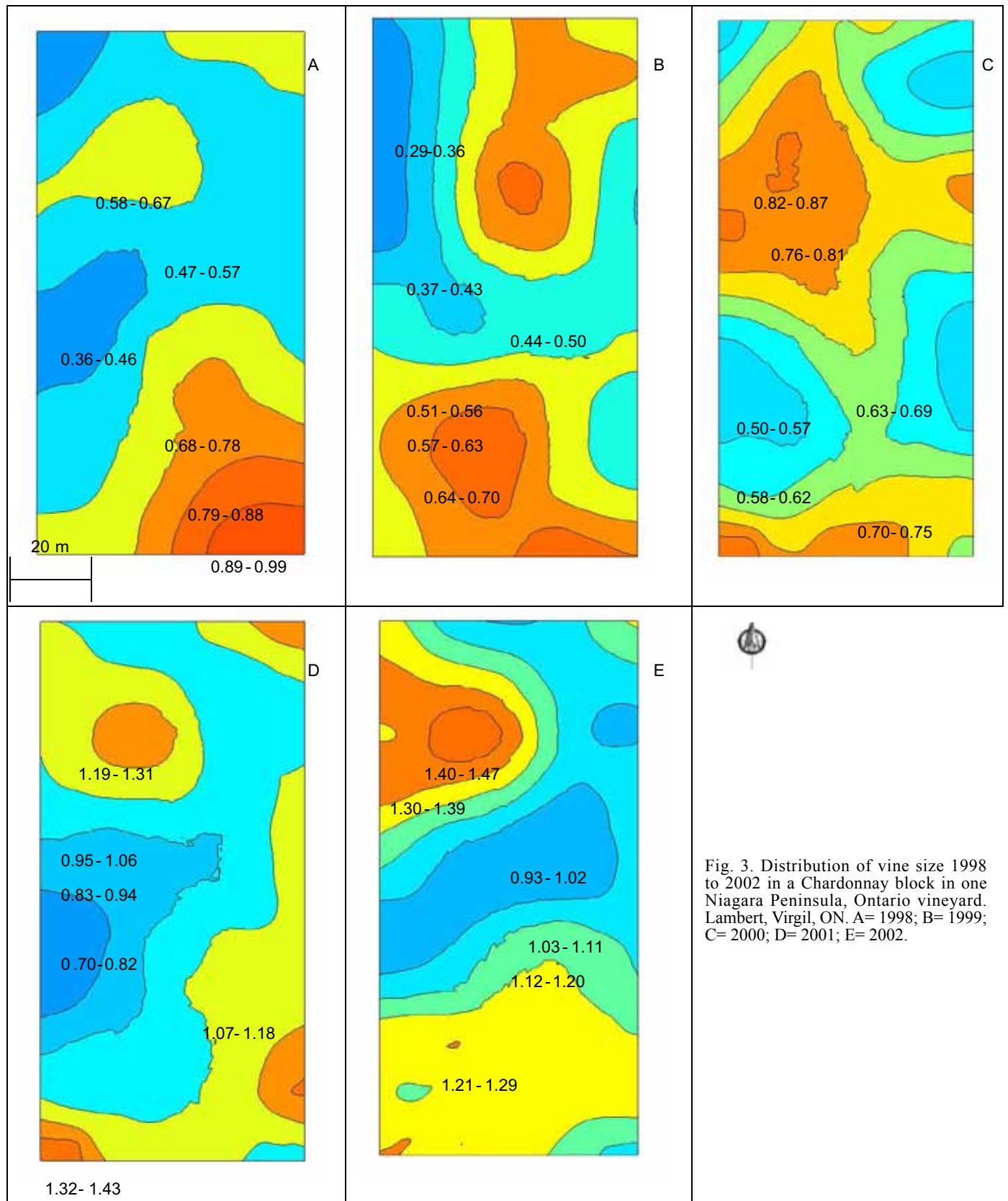


Fig. 3. Distribution of vine size 1998 to 2002 in a Chardonnay block in one Niagara Peninsula, Ontario vineyard, Lambert, Virgil, ON. A= 1998; B= 1999; C= 2000; D= 2001; E= 2002.

berry weight patterns (1999-2001; Fig. 7, insets). The Lambert site showed temporal stability in yield (1998, 1999, 2002), and berry weight (1998, 1999, 2001). The Falk site displayed temporal stability in yield (1998-2002) and in berry weight (2001 excepted). CDC yield was unstable temporally (1998-2001), but larger berries were consistently produced in the western, sandier portion of the

block. The Wismer site showed consistent temporal stability in yield and berry weight. Consistencies in yield and berry weight patterns for most sites are noteworthy, as they indicate that seasonal climatic variability was insufficient to modify spatial patterns. As with vine size, this is consistent with many others (Bramley, 2010; Bramley and Hamilton, 2004; Bramley *et al.*, 2011a,b).

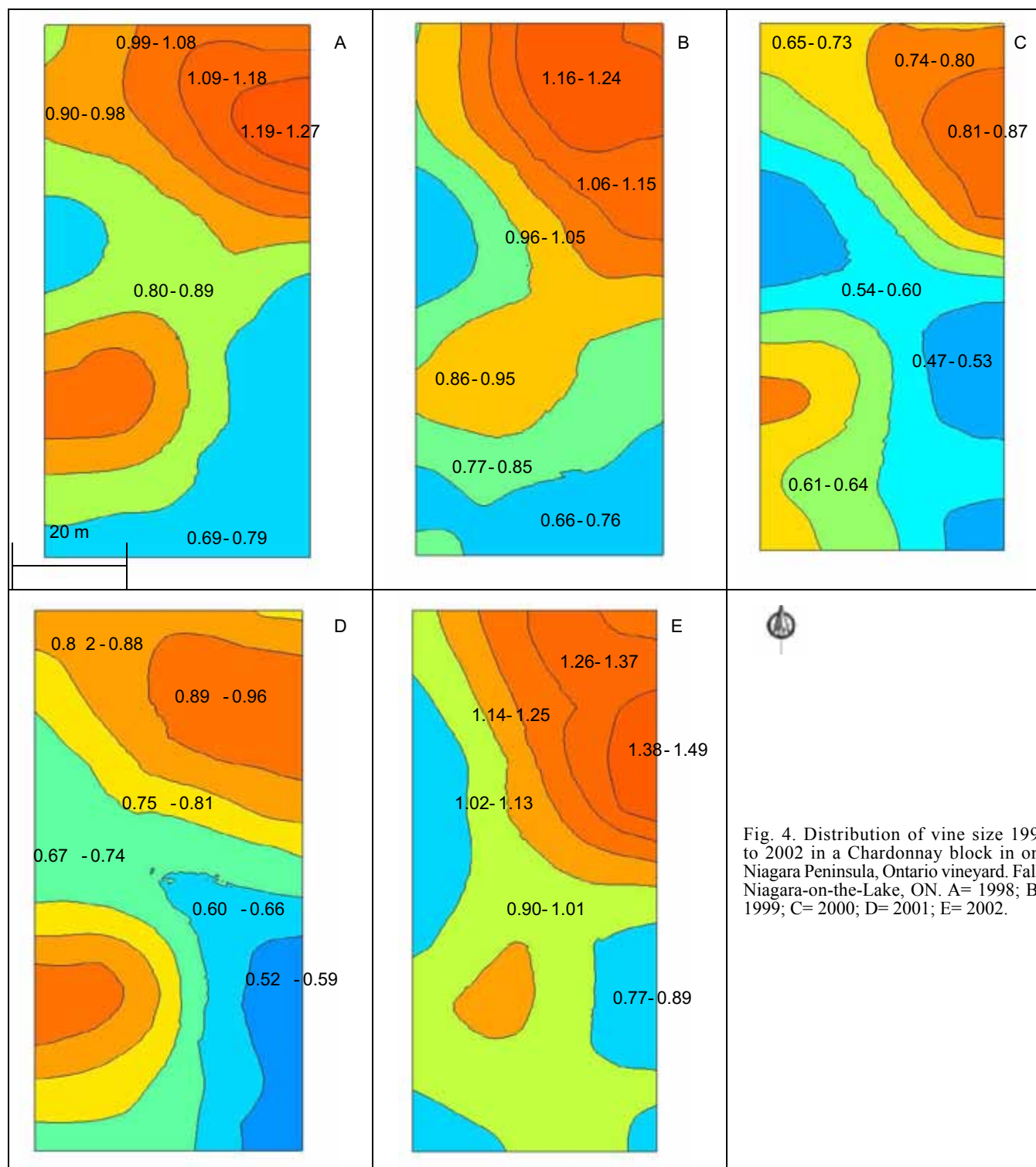


Fig. 4. Distribution of vine size 1998 to 2002 in a Chardonnay block in one Niagara Peninsula, Ontario vineyard, Falk, Niagara-on-the-Lake, ON. A= 1998; B= 1999; C= 2000; D= 2001; E= 2002.

Fruit composition. Brix and TA varied spatially each year at each site. Brix and TA maps from one site (Buis) are shown (Fig. 8), while others are seen in Figs. S13 (Lambert), S14 (Falk), S15 (CDC) and S16 (Wismer). Temporal stability in Brix at the Buis site was evident (1998, 1999, 2001), and patterns were similar throughout the five years. Spatial patterns in TA were also temporally stable (Fig. 8, inset). Similar trends were noticeable for Brix and TA spatial variability at the Lambert site (1998, 1999, 2001). Brix was temporally stable at the Falk site in all seasons except 2000, and TA showed temporal stability in all seasons except 1998. CDC did not display temporally stable Brix, but TA

was temporally stable across four years of data collection. The Wismer site showed temporally stable Brix (1999, 2001, 2002), but the other two years were anomalous; TA patterns, however, were stable across the five years. As with vine size and yield, the frequent temporal consistency suggests that Brix, TA, and perhaps other metrics of fruit composition are stable spatially within vineyards despite climatic variability (Santesteban *et al.*, 2013).

Spatial relationships: soil physical properties and soil/petiole composition vs. yield components and berry composition. Spatial relationships between variables were based on visual inspection and qualitative observation of maps. High % sand

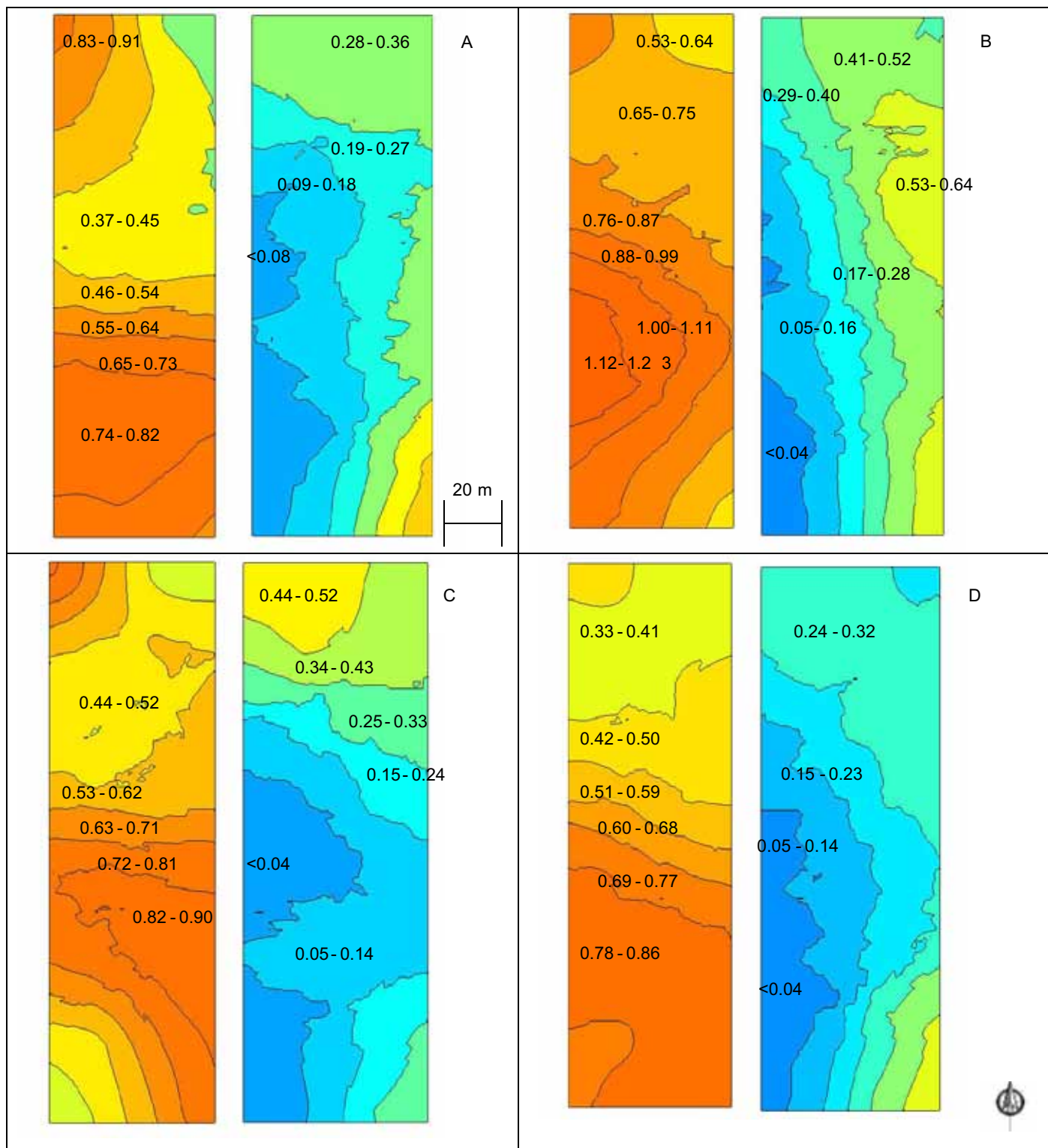


Fig. 5. Distribution of vine size 1998 to 2001 in a Chardonnay block in one Niagara Peninsula, Ontario vineyard. Château des Charmes, St. Davids, ON. The space between the two blocks was 120 m. A= 1998; B= 1999; C= 2000; D= 2001.

zones (Fig. 1) related spatially with high vine size (Falk, CDC; Fig. 4, 5) and high yields (CDC), and linear correlation data verified this (Table 5). Zones of high vine size also related spatially with high yields, berry weights, Brix, and TA, and in most cases were consistent with linear correlation data (Table 6). These relationships were vineyard- and vintage-dependent. The Buis site displayed vine size vs. yield relationships (1998, 2001, 2002; Figs. 2, 7), and low vine size vs. high Brix relationships in the other two years (1998, 2001; Fig. 2, 8). The Lambert site

indicated relationships between vine size (Fig. 3) and yield, between these and berry weight (2002 excepted), and between vine size and both lower Brix and higher TA. Vine size at the Falk site (Fig. 4) was spatially correlated with yield in one season (lower yield in 2000). A relationship was apparent between vine size and berry weight (1998-2000), and between vine size and Brix (2000 excepted). The CDC site was anomalous; as expected vine size (Fig. 5) correlated spatially with yield (1999-2000 only), but berry weights were highest in the high vine size regions every

Table 5. Significant correlations between soil and yield component variables for five Niagara Peninsula Chardonnay vineyards, 1998-2001

Yield Variable	Soil variable								
	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B
1998			0.22*C	0.31*F					0.30**B
Yield/ vine			0.34*F						
Clusters			0.39**F						
Berry wt.	-0.35**C 0.30*W	0.44***W	-0.60****C 0.24*L 0.42***W	-0.44****C 0.22*L 0.51****W	0.31**C 0.46***W	-0.30**B -0.58****C	0.33**W	0.24*C -0.22*L	-0.39***C 0.41***W
Vine size	-0.37***C		-0.38***C 0.29**L	0.20**B -0.38***C		-0.41***C		-0.22*L	-0.39***C 0.26**L
1999		-0.32*B	-0.29**C	0.33*B -0.23*C 0.30*F		-0.36**B -0.26*C		*0.27C	
Yield/ vine									
Clusters		0.31**C	-0.39***C		0.30**C	-0.30*B -0.30**C		0.34**C -0.28*W	
Berry wt.	-0.26*C	0.25*C 0.32**W	-0.40**F -0.59****C	0.23*L -0.42***C	0.35**C 0.42***W	-0.55****C		*0.23C 0.40**W	-0.37***C
Vine size	-0.41***C		-0.49****C -0.37*F 0.35**W	-0.35**C 0.37**W	0.26*W	-0.50****C			-0.39***C 0.28*L 0.32**W
2000			-0.29**C	-0.40***C 0.35**W	0.28*W	-0.31**C	0.30**B	-0.35**B	0.97****B -0.27**C 0.47***W
Yield/ vine									
Clusters	-0.33**C		-0.56****C	-0.48****C	0.25*C	-0.49****C			-0.35**B -0.45****C 0.33**W
Berry wt.		0.25**C		-0.23*C			0.47****B	-0.26**B -0.38**W	0.87****B
Vine size			-0.34***C	-0.39***C		-0.30**C	-0.22*B	0.26*B	-0.61****B -0.31**C 0.28*W
Yield Variable	Soil variable								
	Sand	Silt	Clay	OM	pH	CEC	Base saturation		
							K	Mg	Ca
1998	-0.24*B	*0.25B			0.35**W	0.24*C		-0.32**C	
Yield/ vine	-0.26**L				0.24*C	0.40**F			
Clusters	0.36**W		-0.31*W			0.37**F			0.24*B
Berry wt.	0.60****C	-0.58****C -0.37**W	-0.56****C	-0.32**C 0.50****W	-0.51****C 0.25*L	-0.57****C 0.26**L	0.40***C	0.47***W	-0.54****C -0.31*F
Vine size	0.40***C 0.31*F	-0.35**C	-0.41***C	-0.31**C 0.33**L	-0.27*C	-0.34**C			-0.43***W -0.35**C
1999	0.24*C	.30**L	0.40**B		-0.44***C	-0.27*C	-0.37**B	0.31*B	-0.26*C
Yield/ vine	-0.30**L		-0.24*C				0.23*C		
Clusters	0.32**C	-0.29**C	-0.32**C		-0.36***C	-0.35**C	-0.36**B		-0.39***C
Berry wt.	-0.23**L 0.38**W	0.24**L	-0.29*W				0.39***C		
Berry wt.	0.62****C 0.53****F	-0.62****C -0.48***F	-0.57****C -0.37**F	-0.38***C 0.35**W	-0.37***C	-0.32*F 0.26*W	0.47****C 0.36*F	0.22*L	-0.51****C -0.32*F
Vine size	0.51****C 0.49***F	-0.49****C -0.45**F	-0.50****C -0.34*F -0.27*L	-0.25*C 0.43***W	-0.27*C	-0.46****C -0.34*F 0.38**W	0.28*C	0.34**W	-0.46****C -0.27*W

B,C,F,L,W: Buis, Château des Charmes, Falk, Lambert, and Wismer Vineyards, respectively.

*, **, ***, ****: Significant r values at $P < 0.05$, 0.01, 0.001, or 0.0001, respectively.

Table 5 contd. Significant correlations between soil and yield component variables for five Niagara Peninsula Chardonnay vineyards, 1998-2001.

Yield Variable	Soil variable								
	Sand	Silt	Clay	OM	pH	CEC	Base saturation		
							K	Mg	Ca
<u>2000</u>	0.44****B	-0.33**C	0.68****B	-0.39***C	0.45***W	-0.81****B	0.68****B	-0.45****B	-0.91****B
Yield/ vine	0.36**C		-0.28**C	0.38**W		-0.32**C		0.40**W	-0.39**W
						0.29*W			
Clusters	0.58****C	-0.55****C	-0.27**B	-0.54****C	-0.29**C	0.25*B	-0.26**B	0.22*B	0.30**B
			-0.50****C	0.27*W	0.28*W	-0.59****C	0.45**C	0.26*W	-0.43****C
Berry wt.	0.33***B	-0.27**C	0.54***B		0.33**W	-0.63***B	0.56****B	-0.39***B	-0.75****B
	0.24*C	-0.33*F							-0.24*C
	0.36**F								
Vine size	-0.30**B	-0.29**C	-0.40***B	0.25*B	0.29*W	0.47***B	-0.31***B	0.31**B	0.60****B
	0.37***C	-0.42**F	-0.37***C	-0.30**C		-0.29**C		-0.26*C	-0.36**C
	0.41**F			0.29*W					
	0.27*W								
<u>2001</u>				0.44**F			0.36**F		
Yield/ vine							-0.26*L		
Clusters				0.44**F			0.23*B		-0.23*B
							-0.34**L		
Berry wt.									0.27*L
Vine size	-0.33**C		0.37***C			0.25*C	0.26**B		
							-0.34**C		

B,C,F,L,W: Buis, Château des Charmes, Falk, Lambert, and Wismer Vineyards, respectively.

*, **, ***, ****: Significant r values at $P < 0.05, 0.01, 0.001, \text{ or } 0.0001$, respectively.

Table 6. Significant correlations between vine size, yield, and berry composition variables for five Niagara Peninsula Chardonnay vineyards, 1998-2001

	Yield	Berry weight	Brix	TA	pH
<u>1998</u>	0.26***B	0.50****C	0.50****C	0.19*C	0.35****C
Vine size	0.23**C	0.49****L			
Yield		0.19**B	-0.34****C	-0.21*L	-0.17*B
			-0.25**F		-0.23**C
			-0.46****W		
Berry weight			0.19**B	0.18**B	-0.21**B
			0.24**C	0.49****C	0.65****C
			-0.22*W	0.40****W	
Brix				-0.24**W	0.23**C
					0.25*F
					0.38***L
TA					0.50****C
<u>1999</u>	0.23*B	0.56****C	0.48****F	0.23*B	0.50****C
Vine size	-0.26*F	0.27*F		0.47****C	0.38***F
	0.26**W	0.32***W		-0.21*L	0.24**W
Yield		0.21**C	-0.40****B	0.36***C	-0.25**B
		0.22*L	-0.35***C	-0.23*L	-0.32**L
			-0.41***F		
			-0.48****		
			-0.39****W		
Berry weight			0.33**L	0.45****C	0.50****C
				0.28**F	0.32***W
				0.58****W	
Brix				-0.23*B	0.51****B
				-0.20**C	0.35****C
				-0.41***F	0.44****F
				-0.29**W	0.57****L
					0.49****W
TA					-0.51****B
					0.20**C
					-0.45****F
					-0.28**W

Table 6 contd. Significant correlations between vine size, yield, and berry composition variables for five Niagara Peninsula Chardonnay vineyards, 1998-2001

	Yield	Berry weight	Brix	TA	pH
<u>2000</u>					
Vine size	-0.44****B 0.42****C -0.27*F 0.33***W	-0.32****B 0.35****C	0.41****B 0.29**F	0.67****B 0.30***C 0.24**W	-0.47****B 0.35****C 0.25*F
Yield		0.77****B 0.30***W	-0.93****B -0.41****C	-0.73****B -0.45****F	0.96****B -0.23*W
Berry weight			-0.77****B	-0.57****B 0.31***C	0.79****B 0.25**C -0.34**F
Brix				0.66****B -0.25*F -0.46****W	-0.96****B 0.37***F
TA					-0.73****B 0.37****C -0.37**F
<u>2001</u>					
Vine size	0.16*B 0.29***C	0.31****B 0.56****C 0.46****L 0.35***W	0.38****C 0.58****L 0.35***W	0.37****B 0.57****C 0.25**W	0.51****C 0.46****L 0.30***W
Yield		-0.28**L	-0.45****B -0.22**C -0.22*F -0.44****L -0.56****W	-0.17*B -0.30**W	-0.19*C -0.44****L -0.26**W
Berry weight			0.17*B 0.28***C 0.47****L	0.18**B 0.55****C 0.31**L 0.35***W	0.58****C 0.36***L
Brix				-0.35**F 0.35**L 0.25**W	0.57****C 0.35**F 0.57****L 0.52****W
TA					-0.24**B -0.56****C -0.44****F

B,C,F,L,W: Buis, Château des Charmes, Falk, Lambert, and Wismer Vineyards, respectively.

*, **, ***, ****: Significant r values at $P < 0.05$, 0.01, 0.001, or 0.0001, respectively.

Table 7. Significant correlations between soil and berry composition variables for five Niagara Peninsula Chardonnay vineyards, 1998-2001

Berry Variable	Soil variable								
	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B
<u>1998</u>									
Brix	-0.34**C 0.33*F	-0.29*W	-0.31**W	-0.32**W	0.30*F -0.29*W		0.32*F -0.21*L	-0.24*B	-0.31**C -0.27*W
TA	0.42****L 0.46****W	0.46****L 0.58****W	0.25*C 0.52****W	0.25*C 0.50****W	-0.24*B 0.37****L 0.56****W	0.24*C	-0.23*B 0.27*C 0.43***W	0.22*B 0.43***W	0.25*B 0.46****W
pH	-0.25*B	-0.29**B -0.25*C 0.29*W	0.27*C		-0.28**C	-0.24*B	-0.25*L 0.27*W	-0.26*C	-0.25*B 0.21*L 0.27*W
<u>1999</u>									
Brix			0.42***C		-0.29**C	0.31**C -0.22*L		-0.51****C	
TA	-0.30**C -0.32*F 0.31**W	0.33**C 0.35***L 0.37**W	-0.53****C 0.29*W	-0.34*B -0.40***C 0.21*L 0.28**W	0.38**C 0.42***W	-0.44****C -0.37**F	0.30*W	0.45****C -0.28**L 0.39**W	-0.35**C
pH		0.28**C 0.36*F 0.23*L	-0.27**C	-0.37***C					

Table 7 contd. Significant correlations between soil and berry composition variables for five Niagara Peninsula Chardonnay vineyards, 1998-2001.

Berry Variable	Soil variable								
	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B
<u>2000</u> Brix		-0.23*C	0.37***C	0.31**C	-0.41***C	0.24*C	-0.35***B	0.34**B -0.42**C 0.44**F -0.32**W	-0.97***B
TA		0.31**W	-0.34**C 0.30*W	-0.41***C 0.40**W	0.38**W	-0.34**C	-0.29**B -0.24*C	0.54****W	-0.80***B 0.32**W
pH	-0.25*C	0.27*C	-0.56****C 0.26*W	-0.40***C 0.42**F	0.38***C	-0.53****C	0.34**B	-0.36***B 0.35**C	0.99***B -0.25*C
<u>2001</u> Brix			0.26*W	-0.24*B	0.25*L				-0.23*B 0.26*L
TA	0.37***L	-0.29**C -0.32*F 0.38***L	0.23*C		-0.25*C 0.36***L			-0.24*C	
pH		-0.31**C						-0.32**C	
Berry Variable	Soil variable								
	Sand	Silt	Clay	OM	pH	CEC	Base saturation		
							K	Mg	Ca
<u>1998</u> Brix				-0.33**W		-0.33**W		-0.27*W	0.32**B 0.22*L
TA	-0.31**C 0.21*L -0.33**W	0.28**C -0.26*W	0.31**C 0.54****W	0.36***B 0.57****W	-0.21*L	0.53****W	-0.26*C 0.52****L 0.36**W	0.21*L 0.44***W	0.24*C -0.38***W
pH	-0.35**C	0.25**C	0.39***C	0.29*W	0.26*C		-0.26*B -0.28**C -0.27**L 0.29*W		0.26*C 0.32**L
<u>1999</u> Brix	-0.29**C 0.32*F 0.21*L	0.25*C -0.24*L -0.31**W	-0.38**B 0.30**C		0.51****C	0.37***C	-0.31**C	-0.23*C 0.27*W	0.42***C
TA	0.55****C -0.27*W	-0.48****C	-0.57****C 0.32**W	-0.27**C 0.32**W	-0.40***C 0.21*L	-0.41***C -0.32*F 0.22*L 0.30*W	0.37***C 0.32**L 0.26*W	-0.34*B	-0.61****C
pH	0.44****C 0.37**F 0.28**L 0.27*W	-0.40***C -0.38**F -0.32**L	-0.44****C	-0.28**C		-0.31**C	0.35**C 0.39**F 0.31**L		
<u>2000</u> Brix	-0.38***B -0.44****C	0.37***C	-0.71****B 0.42***C	0.26*C -0.31**W	0.33**C -0.35*F	0.77****B 0.34**C -0.25*W	-0.71****B -0.29**C	0.43****B	0.91****B 0.31**C
TA	-0.43****B 0.40***C 0.37**F -0.27*W	-0.38***C -0.44**F -0.26*W	-0.53****B -0.39***C 0.48****W	0.40***W		0.67****B -0.32**C 0.36**W	-0.46****B 0.34**C	0.32**B -0.22*C 0.37**W	0.78****B -0.32**C 0.34**W
pH	0.44****B 0.56****C	-0.50****C	0.69****B -0.59****C			-0.81****B -0.54****C	0.69****B 0.52****C -0.43***W	-0.47****B 0.36**F	-0.93****B -0.46****C
<u>2001</u> Brix	0.39**F	-0.38**F				0.26*W			
TA				-0.32*F			0.22*B -0.28**C 0.41***L		
pH	-0.28**C		0.30**				-0.34**C		0.23*C

B,C,F,L,W: Buis, Château des Charmes, Falk, Lambert, and Wismer Vineyards, respectively.

*, **, ***, ****: Significant r values at $P < 0.05, 0.01, 0.001, \text{ or } 0.0001$, respectively.

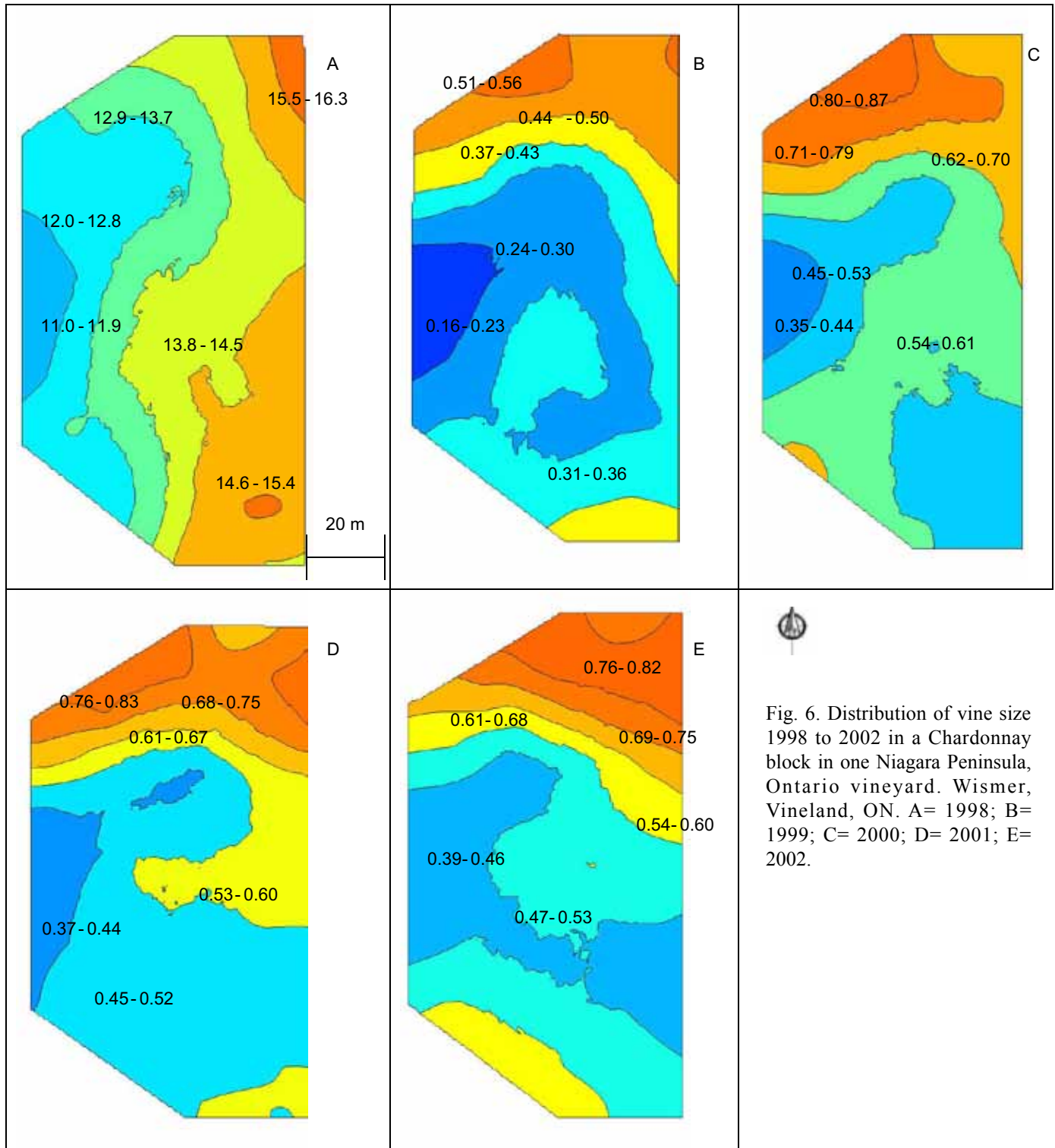


Fig. 6. Distribution of vine size 1998 to 2002 in a Chardonnay block in one Niagara Peninsula, Ontario vineyard. Wismer, Vineland, ON. A= 1998; B= 1999; C= 2000; D= 2001; E= 2002.

year. Highest Brix was associated with highest yields and vine size in two seasons (1998, 2001), but produced opposite results in 1999-2000. High TA consistently aligned with high vine size. Wismer vine size (Fig. 6) showed spatial relationships with yield (1998-2002). A similar relationship existed between these variables and berry weight (1998-2000 only). High vine size and yield zones aligned with high Brix (1999, 2001) and high TA zones (1998-2002).

Many soil physical variables displayed spatial relationships with vine size, yield components, and berry composition, although not

always supported by significant linear correlations (Tables 5, 6). High OM zones and high soil pH zones aligned spatially with high yield regions (e.g. Lambert). However, low OM/ low pH zones also corresponded to high yield areas (e.g. Falk), and also high vine size (e.g. CDC; Fig. 5). High OM/ soil pH was also related to high Brix (e.g. Wismer). In most cases, CEC spatial variability was similar to that of OM, while spatial patterns in BS-Ca matched those of OM and CEC for the CDC site only.

Some soil/ petiole elemental composition variables displayed spatial relationships with vine size, yield components, and berry

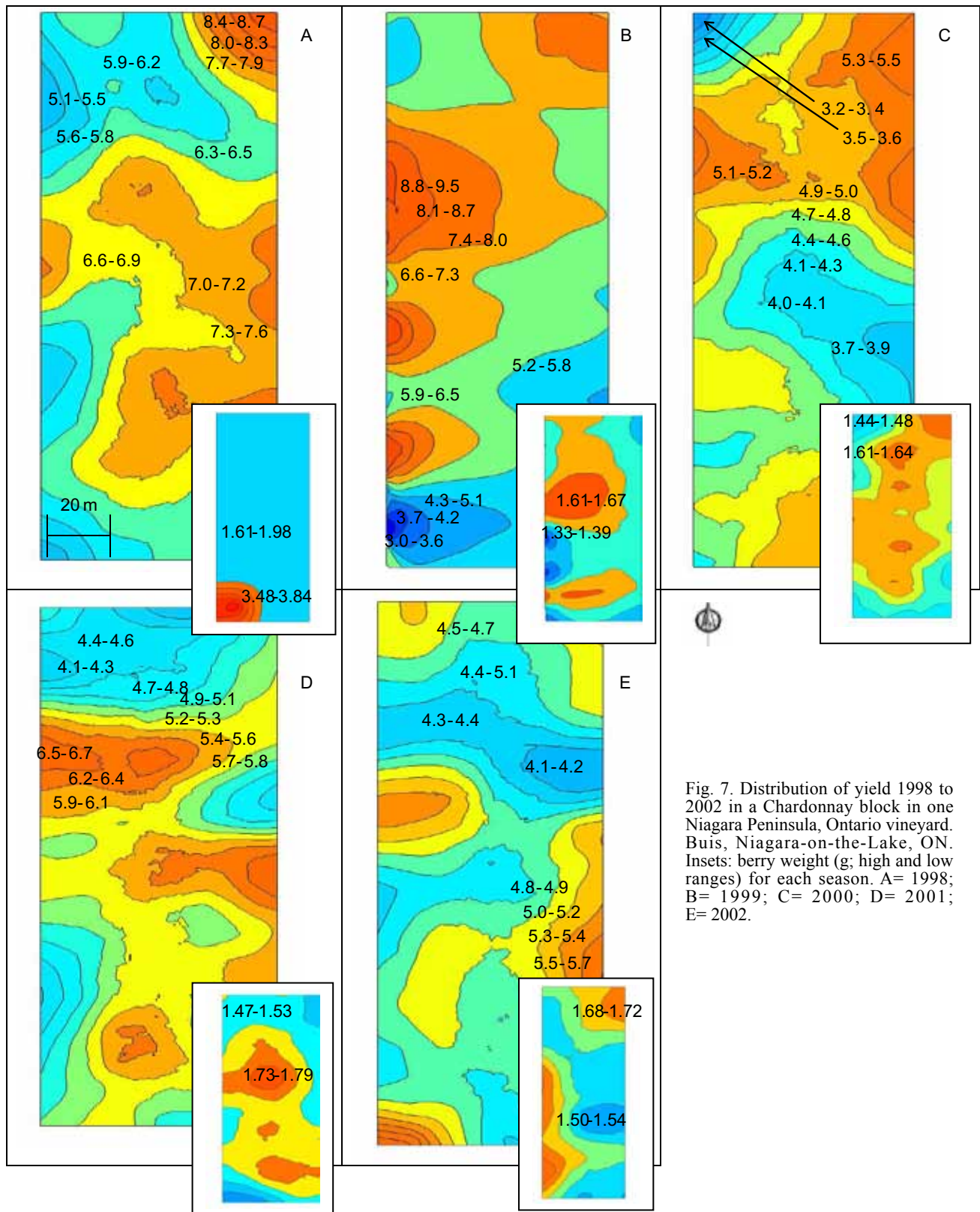


Fig. 7. Distribution of yield 1998 to 2002 in a Chardonnay block in one Niagara Peninsula, Ontario vineyard. Buis, Niagara-on-the-Lake, ON. Insets: berry weight (g; high and low ranges) for each season. A= 1998; B= 1999; C= 2000; D= 2001; E= 2002.

composition although not always supported by significant linear correlations (Tables 5, 7). Petiole N was associated with high vine size zones at one site only (Falk; Fig. 4). Soil and/or petiole P were associated with soil texture, vine size, or yield: high soil P was associated with high vine size (Falk, Wismer; Figs. 4, 6), and at Wismer, petiole P was related. At one site, lowest soil/petiole P were found in the high vine size zone (CDC; Fig. 5), while at another site low soil but high petiole P were found in

the low vine size regions (Buis; Fig. 2). Soil/petiole K displayed similar anomalies: high soil K was associated with high vine size in all sites, but spatial relationships between soil/petiole K were apparent at two sites only (CDC, Wismer), although relationships were discernible elsewhere (Lambert, Falk). Soil/petiole Ca displayed similar patterns; high soil Ca was aligned with high vine size zones (Buis, Lambert, Wismer; Figs. 2, 3, 6) but associated with low vine size areas in two other sites (Falk, CDC). Spatial

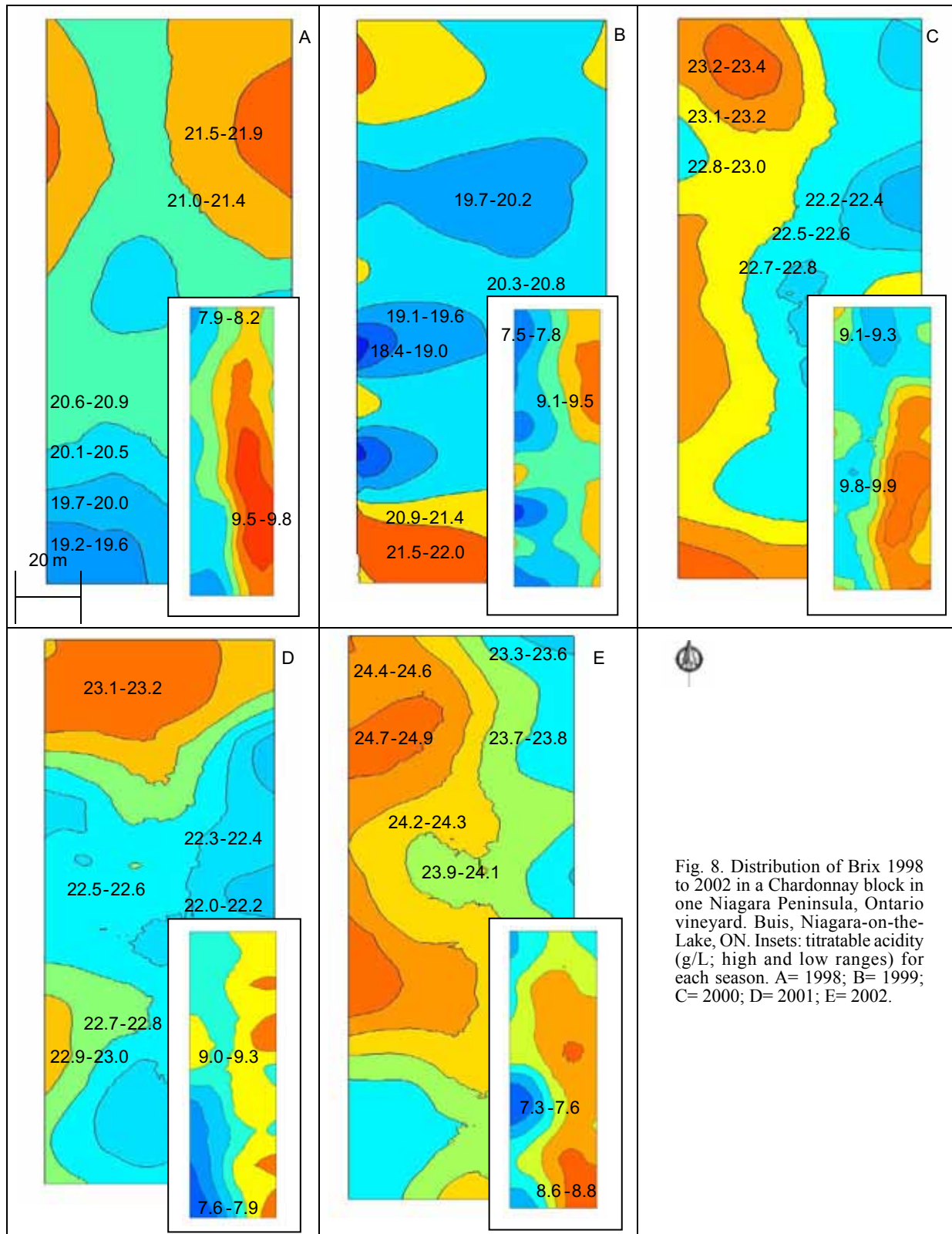


Fig. 8. Distribution of Brix 1998 to 2002 in a Chardonnay block in one Niagara Peninsula, Ontario vineyard. Buis, Niagara-on-the-Lake, ON. Insets: titratable acidity (g/L; high and low ranges) for each season. A= 1998; B= 1999; C= 2000; D= 2001; E= 2002.

relationships between soil/petiole Ca were observed (CDC, Wismer). Soil Mg was associated with high vine size at three sites (Buis, Lambert, Wismer), but associated with low vine size areas elsewhere (Falk, CDC). Apparent spatial relationships between soil/petiole Mg were observed (Falk, Wismer). Soil/petiole B followed patterns of K, Ca, and Mg; soil B was spatially related to high vine size in four sites (Buis, Lambert, Falk, Wismer), and inversely at one site (CDC). Spatial correlation between soil/

petiole B occurred at CDC only. Overall, most soil physical and compositional variables were not consistently associated with metrics of vine performance such as vine size and yield with the exception of soil K, Ca, and Mg.

Linear correlative relationships--soil and tissue composition

Relationships between common elements: As previously mentioned many elements move rapidly through soils but slowly in plants (e.g. Ca and most minor elements), and in such cases

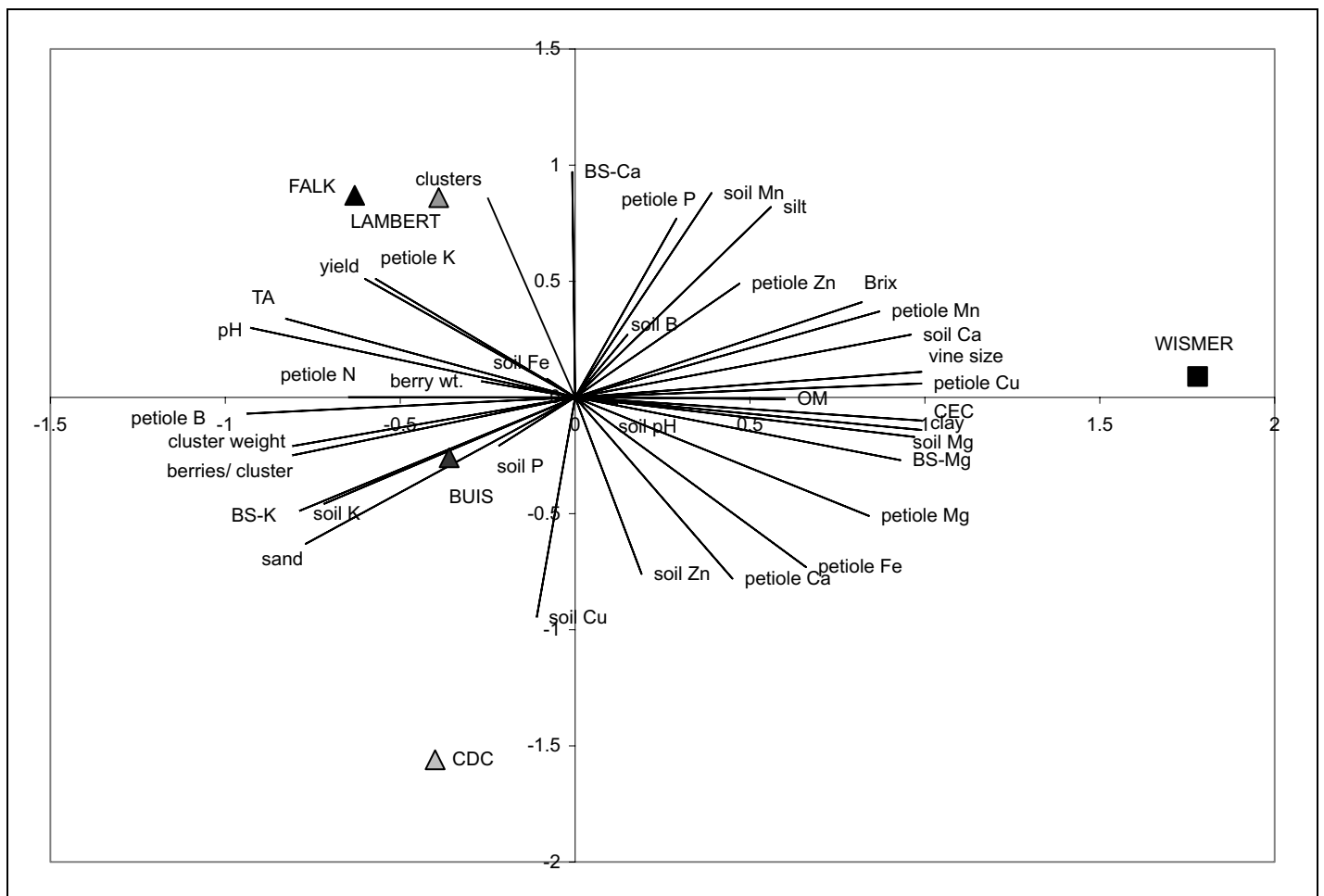


Fig. 9. Principal components analysis of soil, petiole and viticultural data from five Ontario Chardonnay vineyards, 1998.

correlations between soil and tissue composition for like elements were not expected to be high. Positive linear correlations were found between soil/petiole K (two of five sites), and for Ca, Mn, and Cu (one site each) (Table 4). Significant negative correlations were found between soil/petiole Mg (two sites), and between soil/petiole Zn (one site). Soil P and B were not correlated with their petiole concentrations. Of 45 potential correlative relationships, only eight displayed significance. Examining PCA, soil/petiole K, Ca, Mg, and Zn were correlated, P, Fe, and B were inversely correlated, and soil/petiole Cu values were unrelated (Fig. 9).

Soil texture and composition vs. tissue composition relationships

Soil texture: The expectation was that % clay would be associated with most cation-based elements (e.g. NH_4 , K, Ca, Mg) in soils and possibly tissues as well. Among the components of soil texture, % sand was positively correlated with petiole N, K, Mg, and Zn (one site each), and inversely correlated with P, K, Mg, and Mn (one site each) (Table 4). Clay was as expected correlated with P, K, and Ca, and negatively correlated with N, Mg, and Mn, but these were at one site. PCA suggested that % sand was related to petiole N, K, and B, and % clay was associated with petiole P, Ca, Mg, Zn, Cu, Fe, and Mn (Fig. 9). Other variables linked to % clay included: OM, soil pH, CEC, and BS-Ca. A potential 150 relationships existed among the three soil texture variables and the petiolar elements in the five sites, yet only 20 of these were significant. The implications of soil texture variability with respect to vine growth and nutrition may thus be of less importance than initially assumed. Nonetheless,

spatial relationships between soil textural variables and other soil physical properties (OM, CEC, pH, BS-Ca) have been documented elsewhere in Ontario vineyards on similar soil types (Reynolds *et al.*, 2007).

Soil OM, pH, CEC: As with % clay, it was expected that soil OM and CEC would display some relationships to soil and tissue elemental composition. Soil OM was positively correlated with petiole B (two sites) and with K and Ca (one site), and was negatively correlated with Mg (two sites) and Ca, Zn, and Mn (one site) (Table 4). Soil pH displayed positive correlations with K and Ca (one site) and varied inversely with Zn and Mn (one vineyard each). OM content and soil pH are crucial to elemental availability, yet the paucity of significant correlations between these and petiolar elements (13 of 100 possible relationships) places some doubt within the limits this study on their significance relative to elemental uptake by grapevines. CEC likewise has been regarded as being of crucial importance for the availability and potential uptake of plant nutrients, yet CEC was correlated with N, P, K, Ca, and B in only one vineyard, inversely correlated with petiole Mg (two sites), and inversely correlated with Zn, Mn, Cu, and B (one site).

Soil macronutrients and base saturation: Soil P is rarely well correlated with vine nutrition metrics due to non-availability in many agricultural soils. Nonetheless, soil P was positively correlated with petiole K and Ca in two sites and negatively with Mg and Cu (two sites) and Mn and B (one site) (Table 4). Soil K

was correlated with petiole K and Ca (two sites) and with Cu and Fe (one site). Soil K was correlated negatively with petiole Mg and Cu (one vineyard) and Mn (one site). Soil K is antagonistic to Ca and Mg uptake (and vice-versa; Rosen and Carlson, 1984), and the positive relationship between soil K and petiole Ca is inconsistent with expectations. Soil Ca was positively correlated to petiole P, K, Ca, and B (one site each), and negatively correlated to petiole Mg, Mn, and B (two sites) and N, Zn, Cu, and Fe (one site). BS-Ca was likewise related to petiole Ca (two sites) and Mg and B (one site), and negatively correlated to K and Mn (two sites), and N, P, Ca, and B (one site). Apparent synergisms between soil Ca vs. K and B uptake, and antagonisms between soil Ca and Mg uptake are also inconsistent with current knowledge of antagonism and synergism between soil elements (Rosen and Carlson, 1984). Soil Mg was positively related to petiole P and Ca (two sites) and to K and B (one site). Petiole Mg and Mn were inversely correlated with soil Mg (two sites) and petiolar B (one site). Synergisms between soil Mg and Ca uptake are consistent with expectations, but inverse relationships between soil/petiole Mg are difficult to rationalize without evidence of antagonism among Mg, Ca, and K.

Soil micronutrients: Several correlations were observed between concentrations of soil micronutrients and petiole composition (Table 4) despite slow movement of most micronutrients in plants. Soil Zn was positively correlated with petiole K and Ca (two sites) and with N and P (one site) whereas inverse correlations were obtained between soil Zn and petiole Mg and Mn (two sites), and petiolar Zn and Cu (one site). Soil Mn showed little relationship to any petiolar element except Zn, Mn, and Cu (one site). Soil Cu was positively correlated with petiole K and Fe (two sites) and with N, P, Ca and Cu (one site), and inversely with petiole Mg and Mn (one site). Soil Fe was positively correlated with petiole N, P, K, Zn, Cu, and B, and inversely with petiole P and Mg, but in each case, only in one vineyard. Soil B was positively correlated with N, P, K, Ca, and Mn (one vineyard each), and inversely correlated with Mg (two sites) and K and Mn (one site). B may antagonize or enhance elemental uptake, depending on circumstances (Brady and Weil, 2002).

Overall relationships among soil variables: Numerous soil/petiole elemental concentrations showed both positive and negative correlations (Table 4). However, out of a potential 900 correlative relationships within the five sites, 18 soil variables, and 10 petiole variables, only 166 significant correlations (18.4%; positive and negative) were found. Moreover, of these, 91 were attributable to a single site (Wismer Vineyards) in Vineland. An explanation for this phenomenon is not readily available, since the clay loam till-based soil series at the Wismer site (CGU, JDD) were found at other sites. Remaining significant correlations were: Lambert (28), Falk (27), Buis (20), and CDC (four). As already mentioned, many of these permutations may not be expected nor physiologically relevant due to different rates of movement of each element in soils vs. plants, but lack of strong correlations between soil and petiole elemental composition (common elements) suggests that within the limits of this trial, the impact of the respective ranges in the soil variables upon vine nutrition was relatively low, and very site-specific. This implies that a terroir model strongly oriented specifically towards soil composition and its relationship to plant tissue composition (and ultimately berry composition) may be at the very least incomplete.

Considering petiolar variables most impacted by soil variables, K, Ca, Mg, and Mn accounted for 24 to 27 relationships each, out of 150 possible within each array containing one petiolar element, 18 soil variables, and five sites. Each of these elements, which are of crucial importance to vine physiology and ultimate fruit composition, were correlated to most soil texture variables, OM, soil pH, and other soil variables. There were few correlations among soil and petiolar elemental composition, including none between soil/petiole P, Fe, and B. Soil/petiole K were correlated (two sites), as were Ca, Mn, and Cu (one site each). Soil/petiole Mg and Zn showed inverse correlations (Mg, two sites; Zn; one site). PCA suggested no relationships (or weak inverse relationships) between soil/petiole P, Fe, and B, no relationships between soil/petiole Cu, but correlations between soil/petiole K, Ca, Mg, Zn, and Mn (Fig. 9). As previously mentioned, some correlative relationships between common elements (soil/petiole) and between petiole elements vs. other soil composition factors may be low in probability due to the relative rates of movement of each element in soil and plants. Nonetheless, within the context of petiole elemental concentrations and their potential physiological significance, a soil-based terroir model linking soil texture and composition to tissue composition and ultimate berry composition appears to have limited validity. PCA further suggested that OM, soil pH, CEC, and BS-Ca were positively correlated with multiple soil/petiole analytes, including Ca, Mg, Zn, and Mn, plus soil B.

Relationships between non-textural soil variables have been previously demonstrated in an Ontario setting (Reynolds *et al.*, 2007), although in some instances the temporal stability in these relationships (*e.g.* those between soil pH, NO₃, P, K) has been low (Davenport *et al.*, 2003). Inverse correlations between soil/petiole K and both Ca and Mg may reflect nutrient antagonism and are common on Ontario's high Mg soils; these relationships have been demonstrated previously in vineyard situations elsewhere (Morris *et al.*, 1980). Other noteworthy inverse relationships found in this study (*e.g.* petiole N vs. soil/petiole Ca and Mg) have likewise been previously documented (Morris *et al.*, 1980).

Linear correlative relationships--Soil texture and composition vs. yield components

Soil texture: An assumption was made that soil variables would not change substantially during this trial, and data collected in 1998 would be applicable to subsequent seasons. Percent sand was positively correlated in 1998-2001 with vine size (seven instances, three sites), yield (three instances), clusters/vine (five instances), and berry weight (six instances, three sites) (Table 5). Six instances of negative correlations were observed for % sand vs. yield components. Percent clay also displayed inverse relationships with vine size in 1998-2001 (six instances), yield (two instances), clusters/vine (five instances), and berry weight (three instances), and several positive correlations: vine size (one instance), yield (two instances), and berry weight (one instance). Correlative relationships also occurred between soil variables vs. both cluster weight and berries/cluster (data not shown).

Soil OM and pH: These variables showed similar relationships with yield variables (Table 5). In most cases, OM and pH were inversely correlated with vine size (one site only). However, two sites showed positive correlations between OM and vine size in 2000. Positive correlations were observed among these variables and all yield components in 1998 and 2000; however, most 1999

soil pH vs. yield component correlations were negative. The reason for this lack of consistency is unknown. PCA indicated that OM and soil pH were inversely correlated with yield components but directly correlated with vine size (Fig. 9).

Soil/petiole elemental composition: Numerous correlations between yield components and soil elements existed in 1998, fewer in 1999, and almost none in 2000; significant 2000 soil element vs. yield component correlations were all associated with a single site (CDC) (Table 5). CEC, soil Ca, Mg, and B were frequently positively correlated with yield components in 1998-2000 for most sites except CDC. Soil P, Zn, Mn, and Fe displayed several positive correlations, while Cu and K showed few correlations with yield variables. Most minor elements were positively correlated with most yield components but several inverse relationships were observed at CDC. All yield components were correlated based on PCA, and were associated with N, soil/petiole K, and petiole B, but inversely correlated with soil/petiole Ca, Mg, Zn, and Mn, soil B, and petiole P and Fe (Fig. 9). Vine size inversely correlated with yield components, soil/petiole K, and petiole N. These data are in disagreement with Stamatiadis *et al.* (2006), who found correlations between leaf N and vine size.

Linear correlative relationships—vine size vs. yield components and fruit composition: Vine size positively correlated with yield in eight instances (plus three negative correlations) and berry weight in 10 instances (plus one negative correlation) over four years out of a possible 19 occurrences (Table 6). The frequency of significant correlations between vine size and berry composition were also high: Brix (seven, all positive), TA (nine positive, one negative), and pH (nine positive, one negative). There were also several positive correlations between yield and berry weight, and many negative correlations between yield and Brix. These relationships strongly suggest that vine size be considered as a major component in any terroir model.

Linear correlative relationships—soil texture and composition vs. fruit composition: Brix showed no consistent relationships with soil texture throughout this trial (Table 7). No correlations were noticed in 1998. Five positive correlations were observed; Brix vs. sand and % clay (1999; two sites), % silt (1999; one site), and % silt and % clay (2000; one site). However, eight inverse relationships were observed: Brix vs. % sand (1999-2000; three instances), % silt (1999; three sites), and % clay (1999; two sites). Brix also varied directly with variables such as soil P, Cu, and BS-Ca (1998); soil pH, Ca, Mn, CEC, and BS-Ca (1999); and OM, Ca, Mg, Mn, Fe, CEC, and BS-Ca (2000), but inversely with OM, K, Ca, Mg, Zn, Fe, B, and CEC (1998); P, Zn, Mn, and Fe (1999), and; pH, K, Zn, Cu, and B (2000). Relationships between Brix and soil variables, overall, were inconsistent between seasons and very much site-dependent.

TA displayed relationships with soil variables, but there were seasonal and site-based inconsistencies (Table 7). Nine positive and 12 negative correlations between TA and soil texture variables were observed in 1998-2000. Percent sand and TA were directly and inversely related in each of five instances, while % clay and TA were positively and inversely correlated in each of four cases. Several correlations between TA and various soil elements also occurred but none were consistent across seasons and/or sites. Berry pH displayed many of the same relationships with soil

variables as Brix. An inverse pH vs. % sand relationship occurred in one site (1998), but in subsequent years, pH and % sand were directly proportional. pH and % clay were positively correlated (1998) and negatively correlated (1999 and 2000) with one exception. Although a relationship between soil K and berry pH has been demonstrated (Morris *et al.*, 1980), this was seen in only five instances over three years. Other correlations between berry pH and soil composition were observed, but rarely in more than one site. PCA suggested that Brix was inversely correlated with yield components and other variables associated with yield, but TA and pH were directly correlated with yield components (Fig. 9). pH and TA were correlated and also with yield components, and petiole N, K, and B. This relationship between yield components, elevated TA, elevated petiole K, has been ascribed to canopy shading (Smart *et al.*, 1985). Correlations have been reported between mineral nutrition and fruit composition; *e.g.*, excessive soil K has been shown to increase pH and lower TA (Morris *et al.*, 1980).

Other fruit composition variables were not measured, but it is possible that further relationships exist between soil or petiole elemental composition vs. berry composition. Direct connections between soil nutrients and aroma compounds, however, have been difficult to determine. Increased K application increased polyphenol concentration in tea, but Mg had inconsistent effects (Ruan *et al.*, 1999). Reduced or organic forms of N led to higher sensory scores in tomatoes compared to NO₃ treatments (Heeb *et al.*, 2005). Inverse relationships between wine color and phenols vs. soil silt content, and direct relationships with soil carbonates, were demonstrated in Cabernet Sauvignon and Merlot in the Balearic Islands (Gonzalez-Centeno *et al.*, 2013). Relationships between color, anthocyanins, and phenolics vs. yield and vine size/NDVI have also been reported (Bramley, 2005; Bramley *et al.*, 2011a; Cortell *et al.*, 2005; Lamb *et al.*, 2004). Moreover, there is potential for establishing temporally-stable zones of different flavor potential based on monoterpene concentration in aromatic white varieties such as Riesling (Reynolds *et al.*, 2007; Willwerth *et al.*, 2010). Cysteine precursors of odor-active thiol compounds were closely linked to N status in Sauvignon blanc, and therefore zones within vineyards with high N supply can potentially increase varietal typicity in white wine cultivars (Van Leeuwen, 2010). In Cabernet franc, a substantial soil type influence was exerted on 2-methoxy-3-isobutylpyrazine (IBMP) concentration (less IBMP in gravel soils) (Peyrot des Gachons *et al.*, 2005). Low-yielding Cabernet Sauvignon zones in Australia produced wines with higher concentrations of most esters, alcohols, aldehydes, and norisoprenoids (Bramley *et al.*, 2011a). In Ontario, IBMP increased in Cabernet franc wines produced from high yield zones at three sites (Baker *et al.*, 2013). The norisoprenoid β -damascenone has a substantial impact upon odor activity of wines, and although it has odor impact itself, it also enhanced fruity notes of ethyl cinnamate and ethyl caproate and suppressed odor activity of IBMP in red Bordeaux wines, and, its concentration varied with soil type (Pineau *et al.*, 2007).

This study sought applications for geomatic technologies to test two major hypotheses: 1. That soil texture would play a minor role in the determination of yield components, fruit composition, and wine sensory attributes (*i.e.* the “terroir effect”), and; 2. That vine size, crop size and associated fruit environment would play the major roles. This study was possible by the use of vineyard

blocks with heterogeneous soil textures, and, use of geomatic technologies to locate and accurately map vines of various size categories. Ultimately, use of these procedures allowed management of spatially-based soil texture and composition, tissue elemental composition, yield, and berry composition data sets that were used to test the question of direct soil effects on yield components, berry composition, and wine sensory attributes of Chardonnay, by evaluating independent effects of soil and vine vigor on these variables. The main expectation was that soil and vine size might both be shown to have some impact upon fruit composition and wine varietal typicity. Results suggested that: 1. Vine size, yield, and berry weight were stable temporally within individual vineyards despite differences in annual climatic conditions; 2. Soil texture (*e.g.* % sand) was frequently associated with high vine size, yield, and berry weight; 3. Vine size often directly correlated with berry weight; 4. TA was often correlated with vine size. At the same time, soil composition had little relationship to petiole composition, fruit composition or yield except in a few specific cases; *e.g.*, consistent correlations were observed between pH and soil K. These results have confirmed those obtained in much larger winegrowing regions, *e.g.* Mediterranean Europe and Australia.

Two very significant practical applications emerge for this technology and the outcomes of these investigations. The use of geomatic technologies has been successful in large-scale annual crops, but application of these technologies to perennial crops is still emerging in eastern North America. Precision viticulture has been implemented in large wine industries such as Australia, California, France, and Spain, but thus far has not been widely accepted in Canada and the Midwest and Eastern US or elsewhere in cool, humid regions. Use of geomatic technologies on new vineyard sites could show areas of differing potential vine size and capacity. Hence, even relatively small vineyards such as those in this study (1-3 ha) could be divided into more precise sub-blocks that correspond to the projected vine size, and management decisions such as choice of rootstock, vine spacing, and trellis system can be customized for each sub-block. In existing vineyards, use of yield monitors linked to GPS units can allow mapping of vineyard yield, possibly followed by use of variable rate technology to apply inputs that are appropriate for the previous year's yield.

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