THE TERROIR OF WINTER HARDINESS: A THREE YEAR INVESTIGATION OF SPATIAL VARIATION IN WINTER HARDINESS, WATER STATUS, YIELD, AND BERRY COMPOSITION OF RIESLING IN THE NIAGARA REGION USING GEOMATIC TECHNOLOGIES

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Grapevine winter hardiness is a key factor in vineyard success in many cool climate wine regions. Winter hardiness may be governed by several factors in addition to extreme weather conditions – e.g. soil factors (texture, chemical composition, moisture, drainage), vine water status, and yield– that are unique to each site. It was hypothesized that winter hardiness would be influenced by specific terroir factors of a vineyard, and that vines with low water status [based on leaf water potential (leaf ψ)] would be more winter hardy than vines with high water status (less negative leaf ψ). Six different Riesling vineyard blocks throughout the Niagara Region in Ontario, Canada were chosen. Data were collected every six weeks, at fruit set, lag phase, and veraison (soil moisture, leaf ψ), at harvest (yield components, berry composition), and three times during the winter (LT_{50}; the temperature at which 50 % of the buds die; bud death) in the 2010-12 seasons. Interpolation and mapping of the variables was completed using the kriging interpolation method (ArcGIS 10.1) and statistical analyses (linear correlation, k-means clustering, principal components analysis, multilinear regression) were performed using XLSTAT. Clear spatial trends were observed in each vineyard for soil moisture, leaf ψ, yield components, berry composition, and LT_{50}. GIS and statistical analysis revealed that both leaf ψ and berry weight could predict the LT_{50} value, with particularly strong positive correlations observed between LT_{50} and leaf ψ values in most of the vineyard blocks in 2010-11 (4/6 and 5/6, respectively). In the extremely dry 2012 season, leaf ψ (range across sites at veraison 0.9 to 1.4 MPa) was positively correlated to LT_{50}, yield, titratable acidity, pH, and Brix and negatively to soil moisture and monoterpene concentration in Riesling. Overall, vineyards in different appellations showed many similarities (Niagara Lakeshore, Lincoln Lakeshore, Four Mile Creek, Beamsville Bench). These results suggest that there is a spatial component to winter injury, as with other aspects of terroir. Furthermore, this study allows for means by which to compare winter hardiness to other critical variables in order to better understand the terroir of the Niagara region.

Keywords: Soil moisture, leaf water potential, LT50, monoterpenes, GPS, GIS

1 INTRODUCTION

Most winegrowing regions in North America, California excepted, face frequent risks from winter injury. These areas include British Columbia, Ontario, and Nova Scotia in Canada, and numerous states (e.g. WA, NY, MI, PA, OH, and many others) in the US (Wolpert and Howell 1984). The Niagara Peninsula in Ontario is one of these regions where vines must tolerate temperatures < -20C. Expansion of winegrapes into northern Europe may lead to increased risk of winter injury in regions such as Denmark, Sweden, eastern Germany, and Poland.

Although woody plants have the ability to survive extreme temperatures through cold acclimation, rapid fluctuations in air temperatures during winter months can lead to severe trunk, cordon, and/or bud damage. Viticulturists in at-risk regions have learned that site selection is of crucial importance (e.g. plant on slopes, close to large bodies of water, avoidance of high elevation sites, etc.). Numerous cultural practices are also critically important; e.g. winter hardiness can be enhanced by crop level reduction, use of spur pruning, maintaining short vine trunks, etc. What has not been investigated is whether winter hardiness might be governed by those factors that are associated with the determination of the terroir effect of a vineyard, for example soil moisture and vine water status. This investigation, initiated in 2010 and carried out over three seasons, was based on the hypothesis that zones of low soil moisture and/or vine water status would likewise be associated with enhanced bud winter hardiness. Preliminary data were reported elsewhere (Jasinski et al. 2012). A summary of the terroir of winter hardiness in Cabernet franc is also reported herein (Reynolds et al. 2014).

The terroir concept describes the geographical, geological, climatic, and viticultural factors that influence wine composition, and it has important significance in viticulture worldwide (van Leeuwen 2010). Tools as GPS (Global Positioning Systems) or GIS (Geographic Information Systems), first used in agronomic crops, have been used for the past 10-15 years in viticulture to elucidate and characterize "terroir" aspects in new world wine-making regions such as in California (Baldy et al. 1996), Australia (Bramley and Hamilton 2004), or in Canada (Reynolds et al. 2007, 2010), to associate factors such as soil characteristics, water metrics or viticulture management with significant aspects of grape berry composition. Two of the most studied aspects of terroir are water metrics: soil moisture (water soil availability) and leaf ψ [i.e. vine water status (Koundouras et al. 2006, Seguin 1986, Williams and Araujo 2002)]. Many studies have documented relationships between water metrics and berry composition (Kennedy et al. 2002, Koundouras et al. 2006, Medrano et al. 2003) but no clear relationships have been demonstrated between water metrics and winter hardiness (Jasinski 2013).

The objective of this project was to use GPS and GIS tools to map spatial relationships between vine water status (leaf ψ) and water availability (soil moisture) in six Ontario Riesling vineyards during three growing seasons (2010-2012) and bud winter hardiness during the 2010-11, 2011-12, and 2012-2013 winters (represented by LT_{50}, the lethal temperature at which 50% of buds die). Relationships between water metrics, yield and berry composition were also studied. The overall hypothesis was that low leaf ψ and soil moisture would be related to high winter hardiness (i.e. low LT_{50}).

2 MATERIALS AND METHODS

2.1 Sites. Six commercial vineyard blocks each of Riesling were selected for investigation, located in five of the ten sub-appellations of the Niagara Peninsula [Vintners' Quality Alliance (VQA); 2012]. Soil parent material ranged from lacustrine silty clay, reddish hued clay, loamy texture, to reddish hued sandy texture. Soil drainage varied from imperfect/poor to moderately well-drained. Area of vineyard blocks varied from ≈ 3.5 ha (Buis) to ≈0.5 ha (Lowrey). Vine spacing varied from 2.0 m X 1.25 m (vine X row) at Hughes to 3.0 m X 1.3 m at Buis. Training system was Guyot, pendelbogen, or Scott Henry. Floor management in some sites was either clean cultivation or sod maintained in alternate rows. Rootstocks were 101-14, 3309 or SO4 and vine age varied from 7 to 18 years at the initiation of the trial (Jasinski 2013).

2.2 Geomatics and mapping. A Raven Invicta 115 GPS Receiver (Raven Industries, Sioux Falls, SD) with 1.0 to 1.4 m accuracy was used to delineate the shape of each vineyard block and to geolocate each sentinel vine. Mapping and interpolation of the vines was completed using ArcMap v. 10, a component of ArcGIS. Data were organized and imported into ArcMap using Microsoft Excel, and converted into point files using the coordinate system NAD 1983 UTM 17N. Point files for each variable were interpolated using the universal kriging method. Multiple interpolations were created for each variable with the model showing lowest amount of error chosen as the final vector output. Spatial statistics were performed on the vector shapefiles using spatial analyst.

2.3 Soil water status. Soil moisture data (% water by volume) were taken on three separate dates between late June (fruit set) and early September (veraison) in the 2010 to 2012 growing seasons between 0800h and 1800h. 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). Measurements were taken in the row ≈ 10 cm from the base of each vine trunk over a 20 cm depth.

2.4 Vine water status. Midday leaf ψ was determined (Turner 1988) using a pressure chamber Model 3005 Plant Water Status Console (Soil Moisture Equipment Corp., Santa Barbara, CA) between 1100h and 1600h for 15 to 24 fully exposed, mature leaves of similar physiological stage which showed no visible sign of damage and had been in full sunlight. Determinations were made on cloudless days only. There were three sampling dates during the growing season for each site between late June (fruit set) and early September (veraison) 2010 to 2012.

2.5 Differential thermal analysis (DTA). Analysis of buds by DTA was based on the method described by Mills et al. (2006). Canes containing at least eight to 10 buds that were representative of the vine were sampled from every third sentinel vine in late December, January, and February 2010-11, 2011-12, and 2012-13 winter seasons. Freezers were programmed to drop 4 ^{o}C/hr until a minimum temperature of -40 ^{o}C was reached. The median of resulting exothermic peaks from each well was chosen to represent the LT_{50} value (lethal temperature at which 50% of buds die).

2.6 Yield components. In September/October 2010 to 2012, sentinel vines were harvested, and yields and clusters per vine were recorded. At harvest, 100-berry samples were collected randomly from each sentinel vine and stored at -25˚C until analysis. These samples were used for determination of berry weight and various berry composition variables: soluble solids (Brix), pH, and titratable acidity (TA); free and potential volatile terpenes (FVT and PVT). In February/March following bud sampling, the vines were pruned based on the corresponding training system and cane pruning weights were recorded.

2.7 Berry analysis for Brix, TA pH, monoterpenes. Frozen berry samples were heated in 250-mL beakers to 80˚C in a water bath (Fisher Scientific Isotemp 228, Fisher Scientific, Mississauga, ON) for 1 hr to dissolve precipitated tartrates. Samples were thereafter juiced in an Omega 500 fruit juicer. Juice pH and Brix were then obtained using standard methods (Reynolds and Wardle 1989). Juice was centrifuged at 4000 rpm for 10 minutes in an IEC Centra CL2 (International Equipment Co., Needham Heights, MA) centrifuge. The TA of the supernatant was measured with a PC-Titrate autotitrator (Man-Tech Associates, Guelph, ON) to a pH 8.2 end point. Riesling 250-berry samples were analyzed for monoterpenes using the distillation method developed by Dimitriadis and Williams (1984) as modified by Reynolds and Wardle (1989). The free volatile terpene (FVT) and potentially-volatile terpene (PVT) concentrations were expressed in mg/kg.

2.9 Statistical analysis. Statistical procedures including multilinear regression, k-means clustering, and principal components analysis (PCA) were performed using XLStat.

3 RESULTS AND DISCUSSION

3.1 Principal components analysis. *Water status metrics vs. LT_{50}.* PCA suggested existence of correlations between leaf ψ and mean LT_{50} at three of six sites in 2010-11 (Fig. 1) and 2011-12, and four of six sites in 2012-13. Bud survival was inversely correlated with leaf ψ (suggesting high bud survival under low vine water status) at four of six sites in 2010-11, and two sites in 2011-12. Soil moisture showed correlations with LT_{50} at only two sites (2010-11; Fig. 1), but at four in 2011-12, and at two in 2012-13. For the Lakeshore blocks (Buis, George) and Plains blocks (Hughes, Lambert), mean bud LT_{50} was positively associated with soil moisture, leaf ψ, and yield. For the Escarpment blocks (Cave Spring, Lowrey), mean bud LT_{50} was positively linked with soil moisture, negatively linked with leaf ψ, and positively linked with yield. For Riesling blocks in general, low mean bud LT_{50} was indicated by low soil moisture, leaf ψ, and yield. A total of 55% of variables found with linear regression could be explained by soil moisture, leaf ψ, and yield. This suggests that leaf ψ, soil moisture, and yield were related to mean bud LT_{50}.

Past research which indicated a causal relationship between water metrics and vine acclimation (Basinger and Hellman 2006, Gillerman et al. 2006, Koundouras et al. 2006) was supported. Mean bud LT_{50} had direct relationships to water metrics and yield, and indirect relationships to these variables through berry composition. In both 2010 and 2011, greater hardiness (lower mean bud LT_{50}) for Riesling buds was indicated by low soil moisture, low leaf ψ, and low yield. In general, lower yields were related to greater hardiness. As with berry composition relationships regarding berry weight, Brix, pH, and TA, leaf ψ and yield were positively related to one another. Past literature agrees with findings in this paper that lower crop loads and moderate water stress increase hardiness in white varieties (Fennell 2004, Gillerman et al. 2006, Howell et al. 1978). Furthermore, Gillerman et al. (2006) suggest that water deficits are more important towards the end of the growing season in order to promote cold acclimation and dormancy. For Riesling, the location of vineyard blocks did not change the relationships between mean bud LT_{50}, water metrics, and yield to a great extent. Bud hardiness at "Lakeshore" (Buis and George) and "Plains" (Hughes and Lambert) blocks were promoted by low soil moisture, low leaf ψ, and low yield. Bud hardiness at "Escarpment" blocks (Cave Spring and Lowrey) was indicated by high soil moisture, low leaf ψ, and low yield. It is suspected that Cave Spring and Lowrey displayed different trends from the other blocks with regards to soil moisture due to the effect of greater surface water drainage (Hakimi Rezaei and Reynolds 2010).

Other noteworthy relationships. There were only two sites showing yield vs. LT_{50} relationships in 2010-11 (Fig. 1), but four sites showed this relationship in 2011-12, and only two in 2012-13. Soil moisture was positively associated with Brix (five of 12 cases in 2010 and 2011) and monoterpenes (three of 12 cases), and was negatively associated with berry weight (four of 12 cases). Leaf ψ was positively associated with berry weight (six of 12 blocks 2010, 2011) and TA (five of 12 cases), and negatively associated with Brix (eight of 12 cases) and soil moisture (three of 12 cases). Total monoterpene concentration was inversely correlated with leaf ψ at four of six sites [2010 (Fig. 1); 2011], and five of six in 2012. In most circumstances Brix varied directly with monoterpenes and pH and these varied inversely with TA and berry weight (e.g. 2010; Fig. 1).

Soil moisture variation was not consistent with any of the hypothesized relationships with yield and berry composition. For instance, low soil moisture often led to high berry weight, low Brix, low pH, and low monoterpene concentrations. Monoterpene relationships were particularly intriguing since yield was also positively associated with this family of aroma compounds, while low leaf ψ produced high monoterpene concentrations in most circumstances. This suggests that high monoterpenes were related to high soil moisture, high yield, high berry weight, and low leaf ψ. Previous research has also found that monoterpene concentrations increased with lower leaf ψ and berry weight (Reynolds et al. 2010). Issues regarding the role of monoterpenes have previously been mentioned by Reynolds and Wardle (1989), who reported misgivings as to the role of terpenes in the ripening process. Most commonly, terpenes are considered to increase continuously upon the onset of véraison, reaching peak concentrations prior to the plateau of Brix levels. Unlike monoterpene concentrations, other berry composition variables such as berry weight, Brix, pH, and TA produced the expected relationships. Thus, as supported in literature, lower leaf ψ and yields produced smaller berries with higher Brix levels, higher pH, and lower TA (Reynolds et al. 2010, van Leeuwen 2010).

3.2 Spatial variability and spatial relationships. ***Winter hardiness (LT_{50} values) and water status metrics.*** Spatial variability in soil moisture was apparent at all sites and seasons. Spatial variability was temporally stable throughout the growing season in most blocks. Leaf ψ likewise displayed evidence of spatial variability in all sites in 2010 (Fig. 2) and other seasons. Spatial variability in leaf ψ was temporally stable throughout the growing season. Substantial spatial variability occurred at all locations in 2010-11 in terms of bud LT_{50} (Fig. 2) as well as in other seasons. At some sites there were clear spatial relationships between LT_{50} values and both leaf ψ (Fig. 2) and soil moisture. These relationships did not appear to be reduced or enhanced in frequency in dry seasons (2010, 2012) vs. wet seasons (2011). These relationships between LT_{50} and leaf ψ were particularly noteworthy, being supported by multilinear regression models at numerous sites.

Yield and berry weight. Spatial variability in yield and berry weight was apparent at all sites and seasons. Soil moisture, leaf ψ, and LT_{50} correlated spatially with yield and berry weight at some sites, suggesting that not only low soil moisture and low water status but also low yields enhanced bud hardiness. Yield and berry weight were correlated inversely with numerous fruit composition variables such as Brix, pH, FVT, and PVT. This is noteworthy—the concentration effect achieved from reduced berry size can frequently be associated with enhanced fruit composition. Soil moisture, leaf ψ, LT_{50}, yield, and berry weight were all correlated spatially, suggesting that low soil moisture, low water status, and low yields were associated with bud hardiness.

Berry composition. Spatial variability in all berry composition variables was apparent at all sites. Where most of the other variables showed distinctive directional variation, berry composition factors showed more variability. Soil moisture, leaf ψ, LT_{50}, yield, and berry weight frequently correlated inversely with Brix, TA, pH, and PVT at most sites. This was supported with multilinear regression models (Jasinski 2013). This suggests that low soil moisture, low vine water status, and low yields enhanced bud hardiness, that these variables were also associated with low berry weight, and furthermore, that soil and vine water status were inversely related spatially with most berry composition variables of consequence.

4 CONCLUSIONS

Low leaf ψ was spatially correlated to low soil moisture and to low LT_{50} values for <u>most</u> site x season combinations. High LT_{50} values were spatially correlated to high soil moisture and to high leaf ψ; i.e. high water status appeared to reduce the vine's ability to survive extreme winter temperatures. In most circumstances, low yield and low vine size were spatially correlated to low LT_{50}—i.e. small and low-yielding vines were more capable of surviving lethal temperatures compared to larger vines. In conclusion, zones of low LT_{50} corresponded to those with low leaf ψ, soil moisture, yield, and berry weight, and with high Brix, FVT, and PVT. This suggests that deficit irrigation, cluster thinning, and appropriate canopy management practices may also impact favorably on winter hardiness. Knowing where bud injury is most likely to occur within vineyard blocks could also influence/optimize placement of cold injury abatement technologies such as wind machines.

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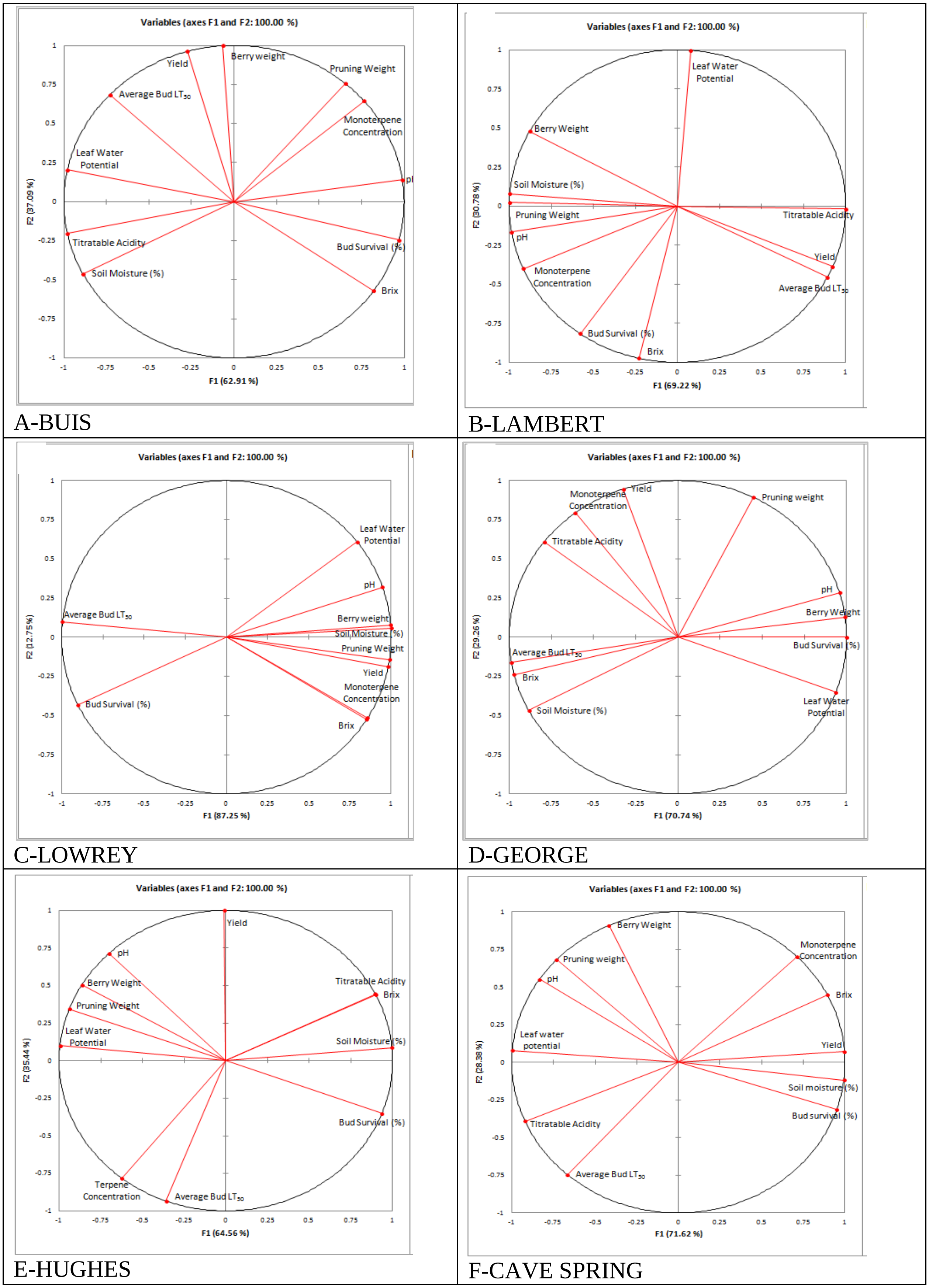

Figure 1. Principal component analysis diagrams of six Ontario Riesling vineyards, 2010-11. A= Buis, B= Lambert, C= Lowrey, D= George, E= Hughes, F= Cave Spring.

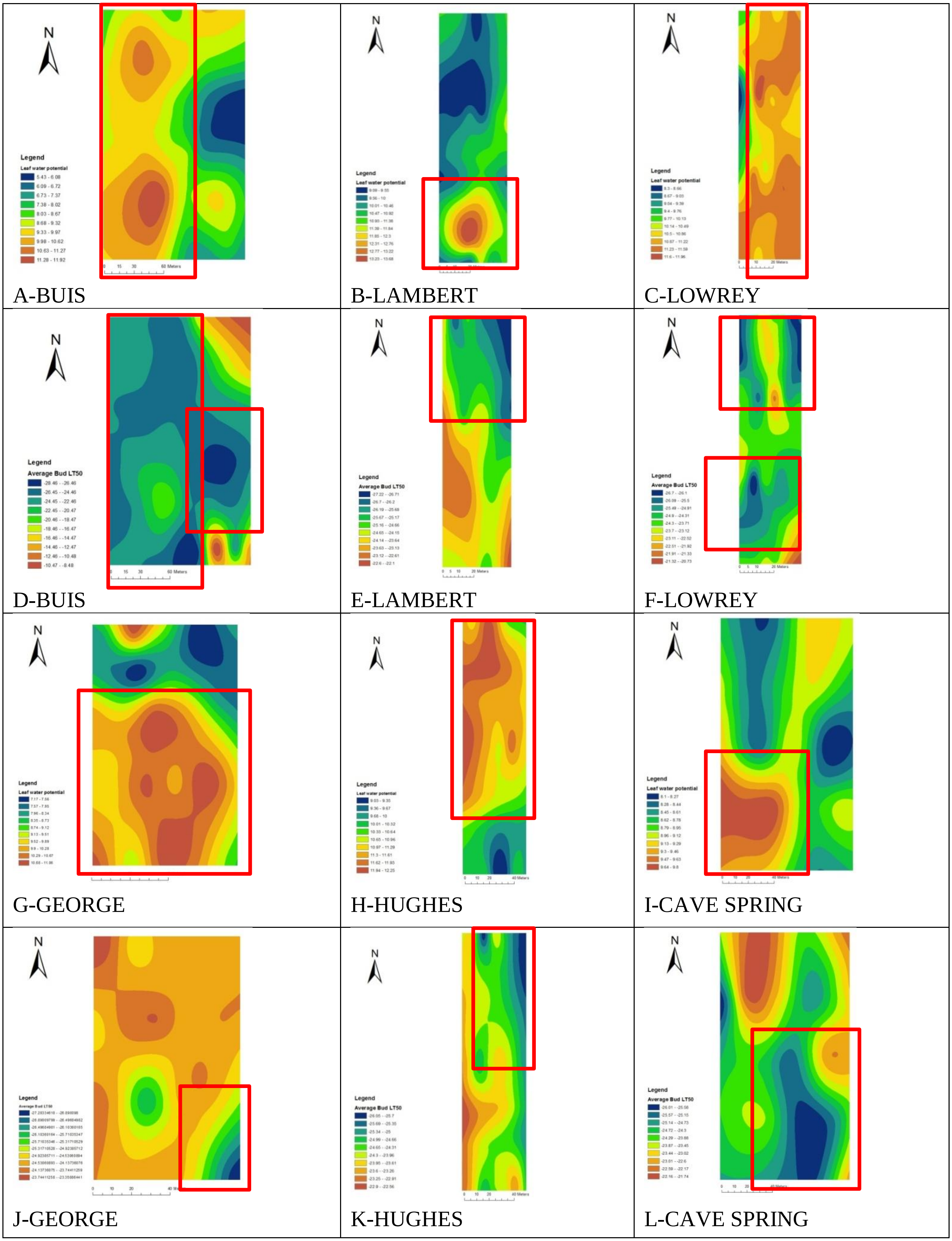

Figure 2. Spatial relationships between mean midday leaf water potential (ψ; 2010) and mean LT_{50} (2010-11) from six Riesling sites in the Niagara Peninsula of Ontario. Orange leaf ψ zones indicate lowest values; blue LT_{50} zones likewise indicate lowest values.