USE OF REMOTE SENSING TO UNDERSTAND THE TERROIR OF THE NIAGARA PENINSULA. APPLICATIONS IN A RIESLING VINEYARD

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Abstract

Aim: The purpose of this study was to determine if multispectral high spatial resolution airborne imagery could be used to segregate zones in vineyards to target fruit of highest quality for premium winemaking. We hypothesized that remotely sensed data would correlate with vine size and leaf water potential (ψ), as well as with yield and berry composition.

Methods and results: Hypotheses were tested in a 10-ha Riesling vineyard [Thirty Bench Winemakers, Beamsville (Ontario)]. The vineyard was delineated using GPS and 519 vines were geo-referenced. Six sub-blocks were delineated for study. Four were identified based on vine canopy size (low, high) with remote sensing in 2005. Airborne images were collected with a four-band digital camera every 3-4 weeks over 3 seasons (2007-2009). Normalized difference vegetation index (NDVI) values (NDVI-red, green) and greenness ratio were calculated from the images. Single-leaf reflectance spectra were collected to compare vegetation indices (VIs) obtained from ground-based and airborne remote-sensing data. Soil moisture, leaf ψ, yield components, vine size, and fruit composition were also measured. Strong positive correlations were observed between VIs and vine size throughout the growing season. Vines with higher VIs during average to dry years had enhanced fruit maturity (higher °Brix and lower titratable acidity). Berry monoterpenes always had the same relationship with remote sensing variables regardless of weather conditions.

Conclusions: Remote sensing images can assist in delineating vineyard zones where fruit will be of different maturity levels, or will have different concentrations of aroma compounds. Those zones could be considered as sub-blocks and processed separately to make wines that reflect those terroir differences. Strongest relationships between remotely sensed VIs and berry composition variables occurred when images were taken around veraison.

Significance and impact of the study: Remote sensing may be effective to quantify spatial variation in grape flavour potential within vineyards, in addition to characteristics such as water status, yield, and vine size. This study was unique by employing remote sensing in cover-cropped vineyards and using protocols for excluding spectral reflectance contributed by inter-row vegetation.

Key words: Grapevine water relations, soil moisture, leaf water potential, vine vigour, monoterpenes

Résumé

Objectif: L'objectif de cette étude était de déterminer si l'imagerie aérienne multispectrale à haute résolution spatiale pourrait être utilisée pour séparer les zones de vignobles dont les fruits correspondent à la plus haute qualité pour la production de vin de qualité supérieure. Nous avons émis l'hypothèse que les données de télédétection pourraient être corrélées avec la surface de la canopée et le potentiel hydrique foliaire (ψ), le rendement, et la composition des baies.

Méthodes et résultats: Les hypothèses ont été testées sur un vignoble de Riesling de 10 ha [Thirty Bench Winemakers, Beamsville (Ontario)]. Le vignoble a été délimité à l'aide de GPS et 519 vignes ont été géo-référencées. Six parcelles ont été délimitées pour l'étude. Quatre de ces parcelles ont été caractérisées selon leurs expressions végétatives (faible, forte), lors d'un relevé aérien en 2005. Les images aériennes du vignoble ont été effectuées avec une caméra numérique multispectrale (quatre bandes spectrale) toutes les 3-4 semaines, sur trois saisons (2007-2009). Les valeurs d'indice NDVI (normalised difference vegetation index) (NDVI-rouge et vert) et le ratio de verdure ont été calculés à partir des images. Les spectres de réflectance des feuilles individuelles ont été mesurés afin de comparer les indices de végétation (IVs) obtenus à partir des images de télédétection. L'humidité du sol, le ψ, le rendement, l'expression végétative de la vigne et la composition des fruits ont aussi été mesurées.

Conclusions: Les images de télédétection permettent de délimiter des zones intra-parcellaire présentant différent niveaux de maturités et de composés d'aromatiques. Ces zones peuvent être considérées comme des sous-parcelles de terroir et pourront être traitées séparément pour élaborer des vins en prenant en compte ces différences. Les plus fortes relations entre les IVs et les variables de composition de baies ont été observées lorsque les image étaient obtenues autour de la véraison.

Importance et impact de l'étude: La télédétection peut être un outil efficace pour déterminer la variation spatiale d'un vignoble par rapport à la qualité du raisin, taille de la vigne, rendement et taux d'humidité. Cette étude était unique en ayant recours à l'expression végétative dans les vignes cultivées par la végétation entre les rangs et par la suite en utilisant des protocoles permettant d'exclure la réflectance spectrale, contribuée par cette végétation.

Mots clés: État hydrique, déficit hydrique, humidité du sol, potentiel hydrique, vigueur de la vigne, monoterpènes

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INTRODUCTION

Many studies have shown that fruit composition is impacted by vine vigour, whereby high vigour vines tend to compromise berry composition and quality (Bramley *et al.*, 2011a-c; Hall *et al.*, 2002; Johnson *et al.*, 2003). Moreover, high vine vigour and high canopy density will also negatively impact crop size the following growing season, by shading the forming buds and consequently reducing fruitfulness (May *et al.*, 1976; Sanchez and Dokoozlian, 2005). As well, others have shown that soil and vine water status both have a great effect on vine vigour, canopy development and fruit maturity (Hardie and Considine, 1976; Koundouras *et al.*, 1999; Van Leeuwen, 2010; Van Leeuwen *et al.*, 2003, 2004). Thus, it is of utmost importance to define and determine vine vigour accurately. Many techniques exist to estimate vine vigour manually in the field. The two principal methods are measurement of weight of cane prunings produced during the previous growing season (referred herein as vine size) and, the calculation of a leaf area index (Johnson *et al.*, 2003).

Unfortunately, both methods are laborious procedures in vineyards. Over the past 12 years, methods have been devised to assess vigour in other crops by remote sensing (Hall *et al.*, 2002; Turner, 2001; White *et al.*, 2001). The technology has been used to assess field crop vigour from airborne images and thereafter employ precision agriculture techniques such as fertilizer application from these data. But the main difference between a vineyard (perennial crop) and an annual field crop (i.e., corn, soybeans, wheat) is that annual crops have complete ground cover (Hall *et al.*, 2003), while vines are planted in separate and discrete rows, making data extraction from airborne images more difficult for use in precision viticulture. The difficulty in many vineyards, particularly those in eastern North America and Europe, is to differentiate vine canopy from the ground cover between the rows. Initially, research studies conducted under non-cover cropped conditions in Australia demonstrated a direct link between the values of vegetation indices (VIs) calculated from data extracted from air- or ground-based leaf reflectance and the vigour of vines (Hall *et al.*, 2003; Lamb *et al.*, 2002; Stamatiadis *et al.*, 2006). Vine vigour has been directly correlated to vine water status and to berry composition, mainly in Australia (Bramley, 2005; Bramley and Hamilton, 2004; Bramley *et al.*, 2011a-c) and California (Turner, 2001) vineyards. Precision viticulture techniques have been employed as well in New Zealand Sauvignon blanc vineyards (Trought and Bramley, 2011; Trought *et al.*, 2008), in addition to Mediterranean Europe (Acevedo-Opazo *et al.*, 2008a,b; Santesteban *et al.*, 2013).

Riesling was the grape cultivar of interest in the present study due to its aromatic characteristics, such that its quality has been defined not only by soluble solids, pH and titratable acidity, but also flavour potential, primarily monoterpenes. Vine vigour has been shown to have a great effect on berry monoterpene synthesis (Reynolds and Wardle, 1989). Prior work in the region made use of geospatial technologies to examine spatial variability in Riesling to explore relationships between monoterpenes and vine size (Reynolds *et al.*, 2007, 2010a) and vine water status (Willwerth *et al.*, 2010). In this context, an objective of this study was to ascertain if there was also a correlation between vigour and remote-sensing data and if remote sensing could be used to assess the basic berry composition (soluble solids, pH and titratable acidity), as well as potential berry monoterpene concentration. A sub-objective was to test the efficacy of the timing of acquisition of these remotely sensed data. We hypothesized that vine vigour and vine water status could be directly assessed by remote sensing, by calculating VIs using data extracted from low elevation high spatial resolution airborne imagery. It was also hypothesized that remote sensing could be used prior to harvest to delineate zones where the grapes are of superior quality and have higher berry monoterpene concentrations. Relationships between water status, yield and berry composition data are discussed elsewhere (Reynolds *et al.*, 2010b). Relationships between water status, yield and berry composition data vs. ground-based and airborne measurements of leaf reflectance are presented here.

MATERIALS AND METHODS

1. Study site and vine management

The study site and the methods used are described in detail in Reynolds *et al.* (2010b). The study took place on a 10-ha Riesling block located at Thirty Bench Vineyards, Beamsville, Ontario. The company had previously designated three sub-blocks based upon location; these were referred to as Wooden Post (WP) in the western part of the main block, Steel Post (SP) in the eastern part and Triangle (TR), an area to the east separated from the other blocks by a small wooded ravine. These were subsequently subdivided into six sub-blocks using high resolution, low elevation digital images from an airborne remote-sensing flight over the vineyard in autumn 2005 (Figure 1). Vine canopy variation in the 2005 images

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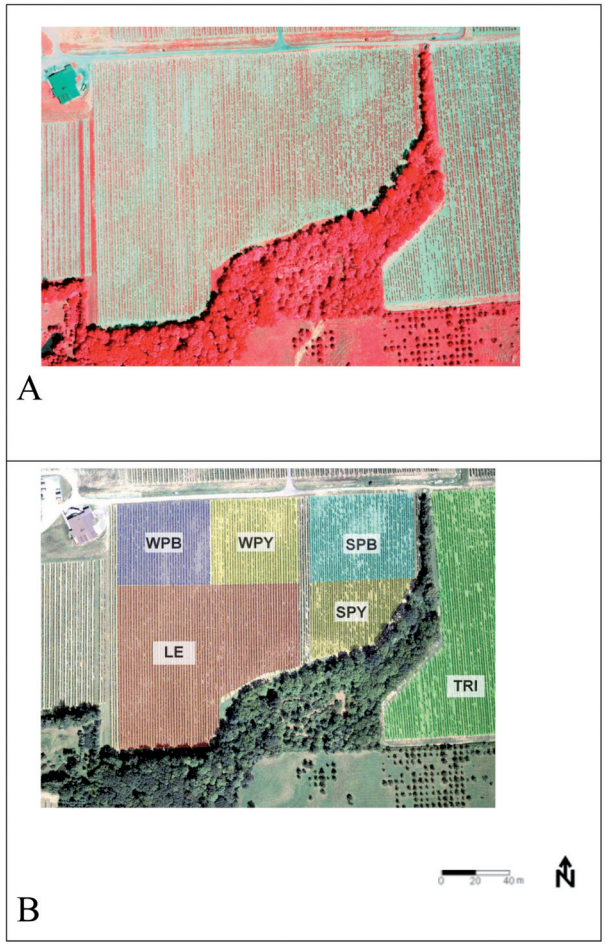


Figure 1. Colour infrared (CIR) and true-colour composite airborne images of the Thirty Bench Winemakers Riesling block with six sub-blocks identified (WPB, WPY, SPB, SPY, LE and TRI). A) CIR image; B) True-colour composite image.

suggested that some parts of the vineyard had different potential vigour levels. Thus the WP and SP sub-blocks were split into high (WP-Y, SP-Y) and low vigour (WP-B, SP-B) sections and another distinct area was defined to the south of WP, referred to as Les Erables (LE). Vines were of slightly different ages but were the same clone (Weis 21B) and rootstock (SO 4) throughout. Triangle, the oldest sub-block, was planted in 1981. The two Steel Post sub-blocks were planted in 1983 and the Wooden Post and Les Erables sub-blocks were planted in 1984. Vines were planted at 2.4 m x 1.2 m (row x vine) spacing, trained to a double Guyot trellis system and pruned to two 12-node canes as well as two-node renewal spurs. Canopies were managed during the growing season with regular hedging and basal leaf removal was performed in the fruiting zone on the east side of the vines prior to berry touch. Floor management was permanent sod in alternate rows (i.e. every other row) with about 1-m herbicided strips under the vines. Each sub-block received the same viticultural treatment during the growing season.

2. Experimental design

Experimental units. Sentinel vines were chosen within each block to form a regular grid pattern across the entire study site. The number of sentinel vines in each sub-block was proportional to its size: Les Erables (LE; 162 sentinel vines); Wooden Post high and low vigour (WPY, WPB; 72 sentinel vines each), Steel Post high and low vigour (SPY, SPB; 44 and 90 sentinel vines, respectively) and Triangle (TR; 79 sentinel vines). All sentinel vines were geolocated by a global positioning system (GPS900, Leica Geosystems, Calgary, AB) in 2006. Ten variables [soil moisture, yield components (yield per vine, clusters per vine, cluster weight, berries per cluster, berry weight), weight of cane prunings (vine size) and berry composition (soluble solids, titratable acidity, pH)] were measured on all 519 sentinel vines and an additional three variables [leaf water potential (ψ), leaf reflectance, berry monoterpenes] were measured for a subset of 134 sentinel vines distributed across the six sub-blocks.

Global Positioning Systems (GPS) and Geographical Information Systems (GIS). GPS was used to delineate the shape and size of the vineyard and the vineyard blocks as well as to geolocate all sentinel vines used for data collection. Post-collection differential correction was performed using GPS Pathfinder Office (Version 3.10; Trimble Navigation Ltd., Sunnyvale, CA) to sub-metre accuracy using the Port Weller, ON base station correction. Final accuracy was ≈ 30-50 cm. The geo-location data files were then used to create spatial representations of the measured variables using geographic information system (GIS) software (MapInfo Professional 9.0 & Vertical Mapper 3.0, Northwood Geoscience, Ottawa, ON). GIS software was used for capturing, storing, analysing, managing and presenting data that were spatially referenced. The inverse distance weighting (IDW; W=2) interpolation was used to create a continuous surface from the point data and contour maps with up to seven intervals across the six sub-blocks were then generated for all variables. The intention was to ultimately delineate up to 18 sub-sub-blocks (three; i.e. high, medium and low zones in each sub-block) based on spatial variation in leaf ψ and vine size within the maps created.

Soil composition. Soil samples (≈ 200 g) were collected using a 3 cm x 75 cm (diameter x length) soil probe at or near each of a subset of 134 of the

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519 sentinel vines (≈ 20 cm from the trunk) in May 2008 and then analyzed by Agri-Food Labs, Guelph, ON. Spatial distribution of the soil texture (% sand, silt and clay) as well as major elements (P, K, Ca, Mg), pH, organic matter (OM) and cation exchange capacity (CEC) were mapped. Soil sampling methods were consistent with those described by Reynolds *et al*. (2007, 2010a).

3. Soil and vine water status

Soil moisture. A portable time-domain reflectometer (TDR; FieldScout TDR 300 Soil Moisture Probe, Spectrum Technologies Inc., Plainfield, IL) was used to acquire measurements of soil moisture (m^3 water/m^3 soil) every 2 weeks from mid-June onwards. Measurements were taken on both the southern and northern sides of the trunk by inserting the 20 cm rods fully into the soil. All 519 sentinel vines were used for data collection.

Leaf water potential (ψ). Midday leaf ψ was measured using the Compact Plant Water Status Console (Soil-Moisture Equipment Corp., Santa Barbara, CA), described by Turner (1988). For each sentinel vine, the leaf ψ measurements were made every 2 weeks, on the same days as soil moisture. Leaf ψ readings were collected on sunny days and between 1000h and 1600h on two fully expanded, exposed mid-shoot leaves taken from a primary (fruiting) cane. The whole procedure, from cutting the leaf from the vine to increasing the pressure, took < 20 seconds to reduce transpiration losses, which can be a source of error (Turner and Long, 1980). A 134-vine subset of the sentinel vines was used for data collection. Using the mapping techniques described in Reynolds *et al.* (2010b), ψ maps were created for each block and divided into high (HWS), medium (MWS) and low water status (LWS) zones.

4. Airborne imagery

At 3-4 week intervals during the growing season airborne images of the site were taken from a small airplane. Multispectral, high spatial resolution images were produced by a four-band digital camera system (Opto-Knowledge Systems Inc., Torrance, CA) with passband interference filters centred on the blue (450 nm), green (550 nm), red (670 nm) and near-infrared (NIR; 770 nm) wavebands. The camera resolution of 1280 x 1024 pixels produced an effective pixel size of 0.38 x 0.38 m on the ground from the 1100-m flight elevation. Image gain settings were adjusted using a white Tyvek® target placed on the ground in the vineyard for each flight to compensate for light conditions. Flights were conducted as close to solar noon as possible under sunny, clear conditions to minimize shadow effects. The first images of the year were usually taken around the beginning of June when canopies were developed enough to be clearly visible (Figure 1A).

Image processing software (ENVI, ITT Visual Information Solutions, Boulder, CO) was used to create two types of multi-band images; red- green-blue colour (RGB; true-colour composite image) and colour-infrared (CIR). The CIR image (Figure 1A) provided a visual indication of the variation in photosynthetic biomass due to stage of development, health and amount of vegetation present. Healthy leaves reflect a high proportion of incident NIR energy and absorb strongly in the red part of the electromagnetic spectrum (Lillesand *et al.*, 2008). The NIR band is displayed as the red layer in a CIR image (Lamb *et al.*, 2002; Lillesand *et al.,* 2008). Areas that appear bright red in CIR images represent vegetation (green under natural conditions) while cyan-coloured zones represent parts of the vineyard with bare soil and no canopy (no photosynthetic activity). The RGB image (Figure 1B), overlaid with block identification colours corresponded to the natural (or "true") colours seen by the human eye. They were used to locate and identify features in the co-registered CIR images. The co-registered single-band images from the digital camera system were geo-referenced using a set of known and easily recognizable control points (e.g., trellis end posts, building features) distributed across the vineyard and tagged with GPS coordinates. The cubic spline interpolation facility in ENVI was used to complete the geo-referencing of the composite RGB and CIR images.

Using the band digital number (DN) values of the CIR image pixels, ENVI software was used to calculate three different VIs as NDVI red, NDVI green and greenness ratio defined below:

$$\text{NDVI red} = \frac{R_{NIR} - R_{red}}{R_{NIR} + R_{red}} \quad (1)$$

$$\text{NDVI green} = \frac{R_{NIR} - R_{green}}{R_{NIR} + R_{green}} \quad (2)$$

$$\text{greenness ratio} = \frac{R_{NIR}}{R_{green}} \quad (3)$$

where the pixel brightness level is substituted for the reflectance, R, in the calculation of each VI. Images based on the VIs were displayed in ENVI for interpretation of spatial variation. The value of NDVI

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red is between -1 and 1, with higher values being indicative of greenness (Hall *et al.*, 2003). NDVI green is based on the amount of green light reflected in the 540 to 560 nm band, which is high for green surfaces. The greenness ratio measures the "greenness" or healthiness of the canopy. All these VIs were shown to be correlated with the water status of Pinot noir vines in the Napa Valley (Rodríguez-Pérez *et al*., 2007), when NDVI showed very strong correlations with both yield and fruit quality in two studies conducted in Chile (Best *et al*., 2005) and Northern Italy (Brancadoro *et al*., 2006).

5. Data acquisition

The original intent was to extract data for the sentinel vines from the images using the Vinecrawler algorithm developed by Hall *et al*. (2003) to automatically isolate vines of interest. Unfortunately, that algorithm requires that spaces between the rows be either clean-cultivated or sprayed with an herbicide to eliminate spectral reflectance from the floor vegetation. Inter-rows at Thirty Bench Vineyards were vegetated throughout the growing season. Thus, the method we developed was inspired by the Vinecrawler algorithm but actually involved a manually supervised procedure to locate and extract sentinel vine information from the images. The first task was to determine the position of the centre of each sentinel vine. GPS data of the vine locations were imported into ENVI as a point data overlay. A region of interest (ROI) of adjacent pixels was defined around each GPS point representing the canopy developed by the vine during the growing season. Three ROI sizes were tested: (a) one pixel centred on the vine trunk (0.38 x 0.38 m; Figure 2A); (b) nine pixels (3x3 pixels) centred on the middle of the vine and covering an area slightly larger than the canopy width (≈1.1 x 1.1 m; Figure 2B), or; (c) 25 pixels (5x5 pixels) centred on the middle of the vine and including the full canopy plus > 50% of the interrow space on either side of the vine (Figure 2C). The preferred method was ultimately the 3x3 pixel ROI. It was believed that its coverage would comprise predominantly sentinel vine canopy reflectance even if a vine was asymmetrically-arranged relative to its trunk, but it could also include a small part of the floor vegetation on either side of the row. A single-pixel ROI could have greatly misrepresented the vine canopy reflectance due to cumulative positioning errors occurring in image registration and GPS location, or to irregularly shaped vines. The 5x5 pixel ROI would have included a large amount of inter-row vegetation reflectance that would have seriously compromised accuracy of VIs calculated for each vine. Data from each ROI (one

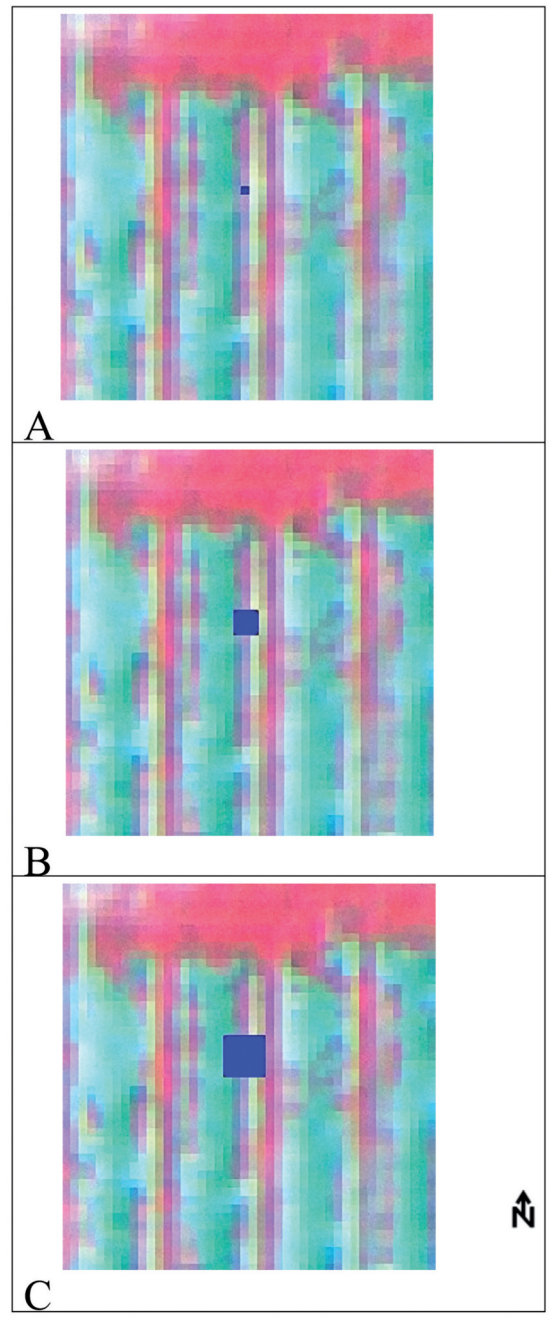


Figure 2. Different sizes of regions of interest (ROI) used to extract data from airborne images and their respective ground coverage for, Thirty Bench Winemakers, Beamsville, Ontario. A) ROI of 1 pixel; B) ROI of 9 pixels; C) ROI of 25 pixels.

ROI per vine) were exported to an Excel spreadsheet (Excel®, Microsoft Corp., Redmond, CA). The nine pixels were averaged to get a single value for each waveband and VIs were calculated with the aforementioned formulae. Airborne images were acquired on June 29, July 20, August 14 and 28, 2007; June 27, July 28 and August 20, 2008 and; June 25, August 7 and September 4, 2009.

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6. Ground-based leaf reflectance

Single-leaf reflectance spectra were measured with a StellarNet EPP2000 spectrometer connected to a laptop computer running SpectraWiz Software (StellarNet Inc., Tampa, FL). A 5-W halogen light source provided illumination to the abaxial surface of a single leaf held in place against a non-reflective black felt pad under an opaque hemispherical sample holder. A fibre optic cable oriented at ≈45° to the leaf surface collected reflected light for the spectrometer. Spectral reflectance over the range from 350 to 850 nm at 2-nm intervals was measured. A white surface reference spectrum was measured periodically using a matte white Teflon® square in the holder and a dark reference was taken from the black surface of the holder with the light turned off and no leaf in place. Ground-based leaf reflectance was measured on or around the same date as the aerial image capture to better compare the results, except in 2006. That year leaf reflectance data were collected twice, in late June and late July. Measurements were made for the subset of 134 sentinel vines and three fully expanded mature leaves with no visible defects were measured for each vine. Spectral data were exported to a spreadsheet used to average the results from the three leaves and calculate broadband reflectance values equivalent to those obtained from the spectral bands in the digital airborne images.

The three VIs of NDVI red, NDVI green and greenness ratio (GR) were then determined. In addition a red-edge inflection point (REIP), which is an indicator of chlorophyll concentration, was calculated as follows from Guyot and Baret (1988):

$$R_{red-edge} = \frac{R_{670} + R_{780}}{2} \quad (4)$$

$$REIP = 700 + 40\left[\frac{R_{red\text{-}edge} - R_{700}}{R_{740} - R_{700}}\right] \quad (5)$$

where R is the spectrometer reflectance value for a particular wavelength. REIP is the wavelength where the maximum gradient within the "red edge" of vegetation occurs, caused by the rapid increase in reflectance between the red band of visible light and the infrared. A shift to shorter wavelengths for the REIP indicates loss of chlorophyll, while a shift to longer wavelengths is a measure of leaf maturity (Turner, 2001).

7. Yield components and berry sampling

Harvest date was chosen each season by the winery. Prior to harvest, water status interpolation maps were created based upon leaf ψ and at harvest the number of clusters and total weight of fruit per vine were recorded. While harvesting, 100- and 400-berry samples were taken randomly from each sentinel vine. The 100-berry samples were taken from all 519 sentinel vines, while the 400-berry samples were taken for eventual determination of the berry monoterpenes from the subset of 134 vines used throughout the season for leaf ψ and spectral reflectance measurements. Each berry sample was placed in a labelled Ziplock bag and stored at -25 °C for further analysis. During the dormant period, weight of cane prunings was collected for all 519 sentinel vines to estimate vine vigour. As for leaf ψ, vine size maps were created for each block and divided into high (HVS), medium (MVS) and low vine size (LVS) zones.

8. Berry sample preparation and analysis

Each 100-berry and 400-berry sample was weighed to determine the mean berry weight. The frozen berry samples were then heated in 250-mL beakers to an internal temperature of 80 °C in a Fisher Scientific Isotemp 228 water bath (Fisher Scientific, Ottawa, ON) to dissolve any precipitated tartaric acid. The heated berry samples were then cooled, juiced in a laboratory juicer (Omega Products Inc., Harrisburg, PA, model 500) and an approximately 35-mL portion was clarified using a IEC Centra CL2 Centrifuge (International Equipment Co., Needham Heights, MA). Soluble solids (°Brix) were measured on the unclarified berry juice samples using a temperature-compensated Abbé bench refractometer (American Optical Corp., Buffalo, NY, model 10450). The pH was measured using an Accumet pH/ion meter Model AR50 (Fisher Scientific, Ottawa, ON). Titratable acidity (TA) was measured on 5-mL clarified samples using a Man-Tech PC-Titrate autotitrator (Man-Tech Associates Inc., Guelph, ON, model PC-1300-475). Samples were titrated to an pH 8.2 end-point with 0.1 N NaOH. Results were expressed as tartaric acid equivalents (g/L). Monoterpenes were analyzed for the 400-berry samples using the method developed by Dimitriadis and Williams (1984) and modified by Reynolds and Wardle (1989). The free volatile terpene (FVT) and potentially-volatile terpene (PVT) concentrations were expressed as mg/kg.

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9. Statistical analysis

The SAS statistical package (SAS Institute, Cary, NC) was used for statistical analysis. Analysis of variance (ANOVA) was used to analyse zonal effects on yield components, vine size, berry weight and composition and soil and vine water status. Results were also subjected to principal component analysis (PCA). Correlations were also determined between soil composition, soil texture, yield components and berry composition for all vintages. MapInfo and Vertical Mapper were used to construct maps of soil texture and composition, yield components, vine size, berry composition, soil and vine water status and all VIs.

RESULTS

In addition to extraction of useful field and berry composition data, a sub-objective of this study was also to determine when to conduct remote sensing flights for best results. Thus, the correlation matrices for each flight date within each vintage will be discussed first to address the issue of optimal flight date(s).

1. Correlation matrices

2006 season. Airborne images were not acquired in 2006, but correlations were examined between field and berry composition data and ground-based leaf reflectance (Table 1). All leaf reflectance VIs were highly correlated ($p<0.0001$) to each other. Thus, the mean seasonal values for each calculated VI were the only measurements used. Leaf ψ (absolute value; a.v.) showed inverse correlations ($p<0.01$) with both NDVI green and GR, but not with either NDVI red or REIP. This suggests that when leaf ψ was low (low water status), the values for those two VIs were also low. The same relationships were found between soil moisture and NDVI red, NDVI green and GR. Yield was consistently correlated to NDVI red, NDVI green and GR ($p<0.0001$), but not to REIP. Berry weight and cluster number did not show any consistent correlations. Brix and TA also did not show any consistent correlations with the different VIs. Berry pH and FVT were the only two berry composition variables that were correlated; berry pH was weakly correlated to NDVI red ($p<0.05$), NDVI green ($p<0.01$) and GR ($p<0.05$).

2007 season. For 2007, all ground-based leaf reflectance VIs were correlated to each other, suggesting that for further analysis, mean seasonal values could be used (Table 2). The same observation can be made with the airborne data. VIs derived from both ground-based and airborne data (hereafter referred to as air-based VIs) showed positive correlations with each other (mostly $p<0.01$ or $p<0.05$ depending on the particular VI and data collection date). The June airborne data did not show correlations with the ground-based VIs (data not shown). Thus, it can be accepted that airborne data should be used instead of ground-based VIs; airborne images showed good relative differences throughout the vineyard in terms of canopy activity. Air-based VIs showed positive correlations with respect to yield (all VIs, all dates), with $p<0.0001$ for all dates except the June flight, for which $p<0.01$. Vine size was correlated to all VIs for all flights. For the June flight data, cluster number was consistently correlated to all VIs ($p<0.0001$). FVT and PVT were well correlated ($p<0.01$ in most cases) with all three VIs, except for the June flight. There were also inverse relationships (mostly $p<0.01$) between air-based VIs (all indices and all flights) and leaf ψ (a.v.). Brix was negatively correlated with VIs for the June flight ($p<0.01$) and positively correlated for the August flight ($p<0.0001$), but both air-based VIs and Brix were not correlated to the seasonal mean VIs. Since only the strongest correlations can be considered relevant, positive correlations for the August flight are the ones worthy of greatest attention.

2008 season. The correlation matrix for 2008 (Table 3) showed similar trends as 2007: ground- and air-based leaf reflectance data were highly positively correlated to each other (except early in the season). Overall, airborne data gave a good idea of differences assessable with ground-based VIs. Air-based VIs were highly correlated to each other for each sampling date ($p<0.0001$) and therefore mean values could be confidently used for further analysis. Several variables showed positive correlations with VIs. Vine size, yield and cluster number were highly correlated ($p<0.0001$) with all VIs for all flight dates. Brix was only correlated with VIs calculated from the May (data not shown) to July images and with the seasonal means. Finally, FVT was correlated to air-based VIs, but only for May ($p<0.01$) and early July images ($p<0.05$) and with the seasonal mean ($p<0.05$). Soil moisture was negatively correlated with all VIs for all flight dates, as was leaf ψ (a.v.), with the exception of the May images. TA and pH were not correlated with the VIs.

2009 season. The 2009 correlation matrix showed trends similar to those in the previous vintages (Table 4). There were numerous correlations between the ground- and air-based VIs, except from June images (data not shown). As per 2007 and 2008, both ground- and air-based VIs were positively correlated

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Table 1. Correlation matrices for all field/berry composition and leaf reflectance variables measured at a 10-hectare Riesling vineyard site at Thirty Bench Winemakers (Beamsville, Ontario) in 2006.

Variables	Sand	Clay	CEC	pH	OM	Mean LWP	Mean SM	Clusters	Yield	Berry wt.	TA	pH	FVT	PVT
gr NDVI-R June	0.026	-0.111	-0.153	-0.235	0.185	-0.175	**-0.180**	**0.200**	**0.250**	0.089	**0.230**	**0.155**	**-0.319**	-0.217
gr NDVI-G June	0.137	-0.200	-0.122	-0.168	**0.327**	**-0.320**	**-0.141**	0.091	**0.310**	0.048	0.095	**0.129**	-0.110	-0.123
gr GR June	0.126	-0.198	-0.117	-0.165	**0.315**	**-0.324**	**-0.136**	0.083	**0.298**	0.035	0.083	**0.125**	-0.102	-0.115
gr REIP June	0.097	-0.211	**-0.317**	**-0.361**	**0.328**	-0.101	**-0.145**	**0.204**	**0.328**	0.097	-0.057	0.081	-0.045	0.022
gr NDVI-R July	0.193	-0.137	**-0.422**	**-0.583**	**0.307**	-0.215	**-0.327**	0.111	**0.192**	0.085	-0.018	0.070	0.113	0.059
gr NDVI-G July	**0.488**	**-0.473**	**-0.601**	**-0.760**	**0.586**	**-0.332**	**-0.565**	**0.163**	**0.439**	0.104	-0.089	**0.121**	**-0.266**	-0.150
gr GR July	**0.486**	**-0.476**	**-0.614**	**-0.773**	**0.581**	**-0.327**	**-0.571**	**0.154**	**0.428**	0.088	-0.096	**0.122**	-0.261	-0.119
gr REIP July	-0.009	0.228	-0.050	-0.034	0.027	-0.054	-0.018	0.047	0.103	0.109	0.047	0.086	**0.274**	-0.050
Mean gr NDVI-R	0.160	-0.158	**-0.400**	**-0.560**	**0.331**	**-0.256**	**-0.350**	**0.199**	**0.286**	0.117	**0.121**	**0.146**	-0.122	-0.104
Mean gr NDVI-G	**0.405**	**-0.438**	**-0.501**	**-0.641**	**0.601**	**-0.416**	**-0.477**	**0.160**	**0.462**	0.100	-0.023	**0.154**	-0.257	-0.173
Mean gr GR	**0.413**	**-0.449**	**-0.526**	**-0.674**	**0.601**	**-0.416**	**-0.500**	**0.153**	**0.455**	0.084	-0.043	**0.153**	-0.256	-0.146
Mean gr REIP	0.022	0.027	-0.220	-0.227	0.194	-0.084	-0.106	**0.157**	**0.277**	**0.141**	0.003	0.114	0.150	0.011

Variables	gr NDVI-R June	gr NDVI-G June	gr GR June	gr REIP June	gr NDVI-R July	gr NDVI-G July	gr GR July	gr REIP July	Mean gr NDVI-R	Mean gr NDVI-G	Mean gr GR	Mean gr REIP
gr NDVI-R June	**1**	**0.574**	**0.561**	**0.129**	0.100	**0.197**	**0.188**	**-0.128**	**0.673**	**0.427**	**0.396**	0.010
gr NDVI-G June	**0.574**	**1**	**0.994**	**0.480**	-0.049	**0.314**	**0.286**	0.038	**0.310**	**0.728**	**0.673**	**0.364**
gr GR June	**0.561**	**0.994**	**1**	**0.456**	-0.055	**0.308**	**0.281**	0.032	**0.298**	**0.722**	**0.673**	**0.344**
gr REIP June	**0.129**	**0.480**	**0.456**	**1**	**0.144**	**0.361**	**0.340**	0.009	**0.184**	**0.494**	**0.460**	**0.705**
gr NDVI-R July	0.100	-0.049	-0.055	**0.144**	**1**	**0.582**	**0.589**	0.044	**0.809**	**0.399**	**0.431**	0.116
gr NDVI-G July	**0.197**	**0.314**	**0.308**	**0.361**	**0.582**	**1**	**0.989**	**0.194**	**0.550**	**0.882**	**0.905**	**0.369**
gr GR July	**0.188**	**0.286**	**0.281**	**0.340**	**0.589**	**0.989**	**1**	**0.169**	**0.550**	**0.860**	**0.901**	**0.336**
gr REIP July	**-0.128**	0.038	0.032	0.009	0.044	**0.194**	**0.169**	**1**	-0.047	**0.158**	**0.143**	**0.735**
Mean gr NDVI-R	**0.673**	**0.310**	**0.298**	**0.184**	**0.809**	**0.550**	**0.550**	-0.047	**1**	**0.548**	**0.554**	0.085
Mean gr NDVI-G	**0.427**	**0.728**	**0.722**	**0.494**	**0.399**	**0.882**	**0.860**	**0.158**	**0.548**	**1**	**0.989**	**0.431**
Mean gr GR	**0.396**	**0.673**	**0.673**	**0.460**	**0.431**	**0.905**	**0.901**	**0.143**	**0.554**	**0.989**	**1**	**0.396**
Mean gr REIP	0.010	**0.364**	**0.344**	**0.705**	0.116	**0.369**	**0.336**	**0.735**	0.085	**0.431**	**0.396**	**1**

Coloured cells are significant. Red: $p<0.0001$; blue: $p<0.01$; yellow: $p<0.05$. Abbreviations: OM: organic matter; CEC: cation exchange capacity; SM: soil moisture; LWP: leaf water potential; gr: ground-based measurements; NDVI-R and NDVI-G: normalized difference vegetation index (red and green); GR: greenness ratio; REIP: red edge inflection point.

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Table 2. Correlation matrices for all the field/berry composition and vegetation indices calculated at a 10-hectare Riesling vineyard site at Thirty Bench Winemakers (Beamsville, Ontario) in 2007.

Variables	Sand	Clay	CEC	pH	OM	SM 24/08	SM 06/09	Mean SM	LWP 17/08	LWP 06/09	Mean LWP	Yield	Clusters	Berry wt.	Vine size	Brix	TA	pH
gr NDVI-R	0.077	-0.168	0.034	0.015	0.160	0.083	-0.060	0.215	-0.107	-0.196	-0.112	0.194	-0.087	**0.358**	0.155	**0.270**	-0.168	**0.467**
gr NDVI-G	**0.354**	**-0.364**	-0.121	-0.136	**0.361**	-0.135	-0.125	0.086	0.052	**-0.272**	-0.035	**0.387**	0.137	**0.369**	**0.467**	0.039	-0.090	**0.285**
gr GR	**0.356**	**-0.308**	-0.138	-0.186	**0.449**	-0.156	-0.097	0.100	-0.058	**-0.342**	-0.096	**0.422**	0.193	**0.448**	**0.469**	0.078	-0.003	**0.238**
NDVI-R 29/06	-0.094	0.109	-0.052	-0.036	0.037	**0.168**	**0.149**	**0.126**	-0.107	-0.051	-0.148	**0.137**	**0.259**	**0.197**	**0.217**	**-0.216**	**0.235**	0.067
NDVI-R 20/07	**0.271**	**-0.303**	**-0.330**	**-0.421**	**0.482**	-0.064	-0.061	-0.083	-0.189	-0.210	**-0.358**	**0.195**	0.077	**0.418**	**0.361**	0.054	-0.062	**0.241**
NDVI-R 14/08	0.063	-0.128	**-0.206**	**-0.226**	**0.435**	-0.022	-0.019	0.053	**-0.345**	**-0.280**	**-0.390**	**0.372**	**0.137**	**0.490**	**0.483**	0.056	-0.055	**0.270**
NDVI-R 28/08	0.087	-0.171	**-0.262**	**-0.265**	**0.462**	-0.007	-0.067	0.010	**-0.262**	**-0.297**	**-0.400**	**0.234**	-0.003	**0.544**	**0.435**	**0.250**	**-0.238**	**0.378**
Mean NDVI-R	0.112	-0.156	**-0.256**	**-0.289**	**0.416**	0.035	0.021	0.036	**-0.290**	**-0.248**	**-0.393**	**0.282**	**0.166**	**0.472**	**0.437**	-0.016	0.024	**0.260**
NDVI-G 29/06	0.014	-0.016	-0.087	-0.089	0.115	**0.187**	**0.174**	**0.117**	-0.059	-0.003	**-0.251**	**0.148**	**0.243**	**0.192**	**0.251**	**-0.150**	**0.172**	**0.111**
NDVI-G 20/07	0.091	-0.110	**-0.323**	**-0.400**	**0.313**	-0.081	-0.047	-0.017	-0.150	**-0.306**	**-0.261**	**0.244**	**0.108**	**0.379**	**0.291**	-0.050	0.030	**0.137**
NDVI-G 14/08	-0.038	-0.001	-0.163	**-0.235**	**0.389**	-0.071	-0.076	0.036	**-0.361**	**-0.369**	**-0.401**	**0.321**	0.096	**0.476**	**0.357**	0.020	-0.008	**0.225**
NDVI-G 28/08	0.012	-0.109	**-0.251**	**-0.203**	**0.456**	0.025	-0.003	**0.103**	**-0.361**	**-0.375**	**-0.406**	**0.314**	0.036	**0.629**	**0.495**	**0.211**	**-0.201**	**0.447**
Mean NDVI-G	0.027	-0.076	**-0.285**	**-0.329**	**0.434**	-0.003	-0.003	0.063	**-0.334**	**-0.395**	**-0.453**	**0.335**	**0.143**	**0.559**	**0.446**	0.002	0.004	**0.294**
GR 29/06	0.016	0.005	-0.051	-0.060	0.102	**0.201**	**0.178**	**0.114**	-0.077	-0.028	**-0.261**	**0.137**	**0.268**	**0.166**	**0.226**	**-0.180**	**0.217**	0.083
GR July 20	0.102	-0.146	**-0.336**	**-0.417**	**0.298**	**-0.112**	-0.070	-0.049	-0.111	**-0.288**	-0.225	**0.198**	0.052	**0.338**	**0.276**	-0.022	-0.012	**0.121**
GR 14/08	0.001	-0.051	-0.107	-0.171	**0.359**	-0.079	-0.095	-0.002	**-0.318**	**-0.402**	**-0.377**	**0.263**	0.041	**0.431**	**0.285**	0.045	-0.058	**0.232**
GR 28/08	0.022	-0.102	**-0.233**	-0.175	**0.441**	0.034	0.010	**0.108**	**-0.354**	**-0.396**	**-0.419**	**0.277**	0.005	**0.612**	**0.490**	**0.224**	**-0.208**	**0.446**
Mean GR	0.049	-0.092	**-0.232**	**-0.274**	**0.398**	0.021	0.012	0.049	**-0.299**	**-0.399**	**-0.454**	**0.286**	**0.138**	**0.506**	**0.405**	-0.019	0.021	**0.273**

Variables	Mean gr NDVI-R	Mean gr NDVI-G	Mean gr GR	NDVI-R 14/08	NDVI-R 28/08	Mean NDVI-R	NDVI-G 14/08	NDVI-G 28/08	Mean NDVI-G	GR 14/08	GR 28/08	Mean GR	FVT	PVT
gr NDVI-R	**1**	**0.648**	**0.547**	**0.389**	**0.316**	**0.274**	**0.310**	**0.334**	**0.245**	**0.308**	**0.332**	0.213	0.141	0.165
gr NDVI-G	**0.648**	**1**	**0.854**	**0.428**	**0.469**	**0.323**	**0.257**	**0.444**	**0.250**	**0.290**	**0.449**	**0.254**	**0.288**	**0.251**
gr GR	**0.547**	**0.854**	**1**	**0.403**	**0.402**	**0.344**	**0.264**	**0.426**	**0.296**	**0.281**	**0.432**	**0.290**	**0.316**	**0.365**
Mean NDVI-R	**0.274**	**0.323**	**0.344**	**0.892**	**0.639**	**1**	**0.765**	**0.689**	**0.877**	**0.697**	**0.659**	**0.874**	**0.366**	**0.240**
Mean NDVI-G	**0.245**	**0.250**	**0.296**	**0.799**	**0.590**	**0.877**	**0.884**	**0.729**	**1**	**0.813**	**0.703**	**0.965**	**0.440**	**0.275**
Mean GR	0.213	**0.254**	**0.290**	**0.783**	**0.590**	**0.874**	**0.837**	**0.699**	**0.965**	**0.835**	**0.682**	**1**	**0.454**	**0.224**

Coloured cells are significant. Red: $p<0.0001$; blue: $p<0.01$; yellow: $p<0.05$. Abbreviations: OM: organic matter; CEC: cation exchange capacity; SM: soil moisture; LWP: leaf water potential; TA: titratable acidity; FVT: free volatile terpenes; PVT: potentially-volatile terpenes; gr: ground-based measurements; NDVI-R and NDVI-G: normalized difference vegetation index (red and green); GR: greenness ratio; REIP: red edge inflection point. The dates associated with SM, LWP, NDVI-R and NDVI-G, GR and REIP refer to sampling points throughout the season.

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Table 3. Correlation matrices for all the field/berry composition and vegetation indices calculated at a 10-hectare Riesling vineyard site at Thirty Bench Winemakers (Beamsville, Ontario) in 2008.

Variables	Sand	Clay	CEC	pH	OM	SM 11/06	SM 28/07	SM 25/08	Mean SM	LWP 10/09	LWP 22/09	Mean LWP	Yield	Clus-ters	Berry wt.	Vine size	Brix	TA	pH	FVT	PVT
gr NDVI-R 27/06	**0.35**	**-0.28**	-0.20	**-0.36**	**0.27**	**-0.26**	**-0.32**	**-0.36**	**-0.30**	-0.11	-0.18	-0.07	0.09	-0.06	-0.02	0.10	-0.02	0.09	**0.30**	-0.08	-0.18
gr NDVI-R 28/07	**0.21**	**-0.27**	-0.09	-0.12	0.13	0.07	-0.06	0.03	0.03	0.12	-0.02	-0.03	0.02	-0.05	0.10	-0.16	**-0.24**	-0.06	-0.01	**-0.28**	**-0.19**
gr NDVI-R 20/08	-0.01	0.05	0.04	0.01	0.03	**0.17**	-0.06	0.11	0.06	0.01	0.08	-0.12	-0.01	-0.06	0.01	-0.05	0.01	0.08	-0.01	-0.09	0.04
gr NDVI-R	**0.20**	**-0.22**	-0.07	-0.13	0.14	0.09	-0.11	0.011	0.02	0.09	0.02	-0.09	0.01	-0.10	0.10	-0.13	**-0.20**	-0.01	0.04	**-0.28**	-0.16
gr NDVI-G 28/07	0.15	**-0.20**	-0.11	-0.16	**0.28**	**-0.26**	**-0.22**	**-0.23**	**-0.22**	**-0.31**	-0.10	-0.14	**0.32**	**0.25**	**0.21**	**0.37**	0.03	0.12	**0.21**	0.03	-0.15
gr NDVI-G 20/08	0.04	-0.11	-0.15	-0.13	**0.28**	**-0.26**	**-0.17**	**-0.17**	**-0.17**	**-0.29**	-0.12	**-0.24**	**0.27**	0.14	**0.18**	**0.43**	0.07	0.09	**0.24**	0.15	-0.01
gr NDVI-G	0.11	**-0.18**	-0.14	**-0.17**	**0.31**	**-0.29**	**-0.23**	**-0.24**	**-0.22**	**-0.35**	-0.11	**-0.21**	**0.31**	**0.20**	**0.25**	**0.46**	0.10	0.08	**0.27**	0.10	-0.05
gr GR 28/07	0.14	**-0.19**	-0.09	-0.14	**0.26**	**-0.23**	**-0.20**	**-0.20**	**-0.20**	**-0.29**	-0.10	-0.15	**0.28**	**0.22**	**0.22**	**0.34**	0.04	0.08	**0.22**	0.03	-0.14
gr GR 20/08	0.05	-0.10	-0.14	-0.13	**0.30**	**-0.23**	-0.16	-0.14	-0.15	**-0.28**	-0.11	**-0.26**	**0.23**	0.10	0.17	**0.42**	0.09	0.07	**0.26**	**0.17**	0.01
gr GR	0.11	**-0.17**	-0.12	-0.15	**0.31**	**-0.26**	**-0.22**	**-0.21**	**-0.19**	**-0.34**	-0.11	**-0.23**	**0.27**	0.16	**0.24**	**0.44**	0.12	0.06	**0.28**	0.11	-0.04
gr REIP 27/06	**-0.46**	**0.48**	**0.28**	**0.48**	**-0.44**	**0.44**	**0.25**	**0.29**	**0.29**	0.21	**0.38**	-0.02	**-0.28**	-0.21	-0.10	**-0.26**	0.24	-0.10	**-0.46**	**0.44**	**0.52**
gr REIP 28/07	**-0.25**	**0.35**	0.16	**0.22**	**-0.28**	0.17	**0.17**	**0.19**	0.15	0.17	**0.23**	0.12	**-0.30**	**-0.23**	**-0.18**	**-0.24**	0.13	-0.06	**-0.18**	0.11	**0.18**
gr REIP 20/08	-0.01	0.02	0.15	**0.18**	**-0.22**	**0.21**	**0.23**	**0.19**	**0.21**	**0.35**	0.11	**0.31**	**-0.32**	**-0.21**	**-0.18**	**-0.45**	-0.15	-0.16	**-0.22**	**-0.19**	-0.10
gr REIP	**-0.22**	**0.29**	**0.23**	**0.31**	**-0.34**	**0.29**	**0.25**	**0.28**	**0.25**	**0.32**	**0.24**	**0.19**	**-0.38**	**-0.27**	**-0.20**	**-0.43**	0.01	-0.10	**-0.30**	0.04	0.15
NDVI-R 01/07	**-0.19**	0.07	-0.01	-0.01	-0.04	**-0.26**	**-0.20**	**-0.28**	**-0.26**	**-0.42**	**-0.25**	**-0.23**	**0.27**	**0.30**	-0.02	**0.12**	0.05	0.03	-0.02	0.17	-0.09
NDVI-R 29/07	0.05	-0.11	**-0.24**	**-0.25**	**0.29**	**-0.20**	**-0.17**	**-0.10**	**-0.15**	**-0.23**	**-0.20**	**-0.42**	**0.17**	**0.10**	**0.16**	**0.26**	0.04	**0.09**	0.07	0.04	-0.11
NDVI-R 21/08	0.17	**-0.31**	**-0.29**	**-0.35**	**0.33**	**-0.40**	**-0.34**	**-0.35**	**-0.37**	**-0.35**	**-0.30**	**-0.30**	**0.30**	**0.23**	**0.13**	**0.32**	0.04	0.08	0.04	0.10	-0.13
NDVI-R	-0.04	-0.09	**-0.19**	**-0.23**	**0.19**	**-0.36**	**-0.29**	**-0.33**	**-0.34**	**-0.47**	**-0.34**	**-0.36**	**0.32**	**0.30**	0.06	**0.28**	**0.09**	0.08	0.02	**0.18**	-0.12
NDVI-G 01/07	-0.08	-0.01	-0.08	-0.10	0.02	**-0.31**	**-0.23**	**-0.35**	**-0.31**	**-0.47**	**-0.29**	-0.10	**0.33**	**0.40**	-0.08	**0.21**	**0.13**	0.02	0.01	**0.19**	-0.07
NDVI-G 29/07	0.05	-0.10	**-0.27**	**-0.24**	**0.28**	**-0.19**	**-0.16**	-0.08	**-0.13**	-0.15	**-0.18**	**-0.34**	**0.14**	**0.10**	**0.15**	**0.24**	0.05	0.04	0.08	0.04	-0.01
NDVI-G 21/08	0.02	-0.15	-0.17	**-0.21**	**0.30**	**-0.24**	**-0.27**	**-0.21**	**-0.24**	**-0.25**	**-0.21**	**-0.33**	**0.24**	**0.16**	**0.17**	**0.24**	0.02	0.08	0.07	0.15	-0.06
NDVI-G	-0.02	-0.09	**-0.21**	**-0.23**	**0.22**	**-0.33**	**-0.28**	**-0.31**	**-0.31**	**-0.42**	**-0.31**	**-0.28**	**0.32**	**0.33**	0.05	**0.30**	**0.13**	0.05	0.05	**0.20**	-0.08
GR 01/07	-0.03	-0.05	-0.08	-0.13	0.02	**-0.30**	**-0.20**	**-0.34**	**-0.30**	**-0.45**	**-0.27**	-0.05	**0.30**	**0.39**	**-0.10**	**0.19**	**0.18**	0.01	-0.01	**0.20**	-0.05
GR 29/07	0.01	-0.06	**-0.26**	**-0.20**	**0.21**	**-0.15**	**-0.11**	-0.04	**-0.09**	-0.11	-0.16	**-0.33**	0.08	0.06	**0.15**	**0.21**	0.07	0.05	**0.09**	0.08	-0.04
GR 21/08	0.01	-0.16	-0.14	**-0.20**	**0.27**	**-0.24**	**-0.26**	**-0.21**	**-0.23**	**-0.27**	**-0.21**	**-0.30**	**0.22**	**0.16**	**0.13**	**0.21**	0.02	0.08	0.07	0.17	-0.07
GR	-0.01	-0.10	**-0.21**	**-0.23**	**0.20**	**-0.31**	**-0.25**	**-0.28**	**-0.28**	**-0.39**	**-0.29**	**-0.27**	**0.28**	**0.30**	0.04	**0.28**	**0.15**	0.05	0.06	**0.22**	-0.06

Variable	gr NDVI-R 28/07	gr NDVI-R 20/08	Mean gr NDVI-R	gr NDVI-G 28/07	gr NDVI-G 20/06	Mean gr NDVI-G	gr GR 28/07	gr GR 20/08	Mean gr GR	gr REIP 28/07	gr REIP 20/08	Mean gr REIP	NDVI-R 29/07	NDVI-R 21/08	Mean NDVI-R	NDVI-G 29/07	NDVI-G 21/08	Mean NDVI-G	GR 29/07	GR 21/08	Mean GR
gr NDVI-R	**0.89**	**0.59**	**1**	**0.37**	**0.17**	**0.29**	**0.38**	**0.19**	**0.31**	**-0.59**	**-0.19**	**-0.46**	-0.04	-0.05	**-0.25**	-0.05	-0.12	**-0.28**	-0.06	-0.12	**-0.29**
gr NDVI-G	**0.21**	**0.27**	**0.29**	**0.89**	**0.88**	**1**	**0.86**	**0.86**	**0.99**	**-0.62**	**-0.74**	**-0.83**	**0.34**	**0.50**	**0.41**	**0.27**	**0.37**	**0.36**	**0.23**	**0.38**	**0.34**
gr GR	**0.23**	**0.30**	**0.31**	**0.89**	**0.86**	**0.99**	**0.89**	**0.87**	**1**	**-0.61**	**-0.72**	**-0.80**	**0.33**	**0.48**	**0.40**	**0.27**	**0.37**	**0.35**	**0.23**	**0.37**	**0.33**
gr REIP	**-0.38**	**-0.38**	**-0.46**	**-0.75**	**-0.75**	**-0.83**	**-0.71**	**-0.73**	**-0.80**	**0.83**	**0.80**	**1**	**-0.32**	**-0.49**	**-0.36**	**-0.25**	**-0.33**	**-0.32**	**-0.21**	**-0.33**	**-0.29**
NDVI-R	**-0.28**	-0.02	**-0.25**	**0.39**	**0.42**	**0.41**	**0.37**	**0.40**	**0.40**	-0.16	**-0.50**	**-0.36**	**0.72**	**0.79**	**1**	**0.65**	**0.73**	**0.95**	**0.59**	**0.72**	**0.93**
NDVI-G	**-0.28**	-0.03	**-0.28**	**0.33**	**0.35**	**0.36**	**0.32**	**0.34**	**0.35**	-0.14	**-0.45**	**-0.32**	**0.68**	**0.75**	**0.95**	**0.69**	**0.75**	**1**	**0.65**	**0.75**	**0.98**
GR	**-0.29**	-0.04	**-0.29**	**0.32**	**0.33**	**0.34**	**0.30**	**0.32**	**0.33**	-0.12	**-0.43**	**-0.29**	**0.69**	**0.74**	**0.93**	**0.73**	**0.74**	**0.98**	**0.71**	**0.75**	**1**

Coloured cells are significant. Red: $p<0.0001$; blue: $p<0.01$; yellow: $p<0.05$. Abbreviations: OM: organic matter; CEC: cation exchange capacity; SM: soil moisture; LWP: leaf water potential; TA: titratable acidity; FVT: free volatile terpenes; PVT: potentially-volatile terpenes; gr: ground-based measurements; NDVI-R and NDVI-G: normalized difference vegetation index (red and green); GR: greenness ratio; REIP: red edge inflection point. The dates associated with SM, LWP, NDVI-R and NDVI-G, GR and REIP refer to sampling points throughout the season.

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Table 4. Correlation matrices for all the field/berry composition and vegetation indices calculated at a 10-hectare Riesling vineyard site at Thirty Bench Winemakers (Beamsville, Ontario) in 2009.

Variables	Sand	Clay	CEC	pH	OM	SM 24/08	SM 10/09	Mean SM	LWP 24/08	LWP 10/09	Mean LWP	Yield	Clusters	Berry wt.	Vine size	Brix	TA	pH	FVT	PVT
gr NDVI-R 07/08	-0.07	0.06	-0.10	**-0.19**	0.05	-0.08	-0.03	-0.13	-0.12	**-0.18**	-0.17	0.04	0.02	0.17	**0.19**	-0.07	0.12	0.14	0.04	-0.06
gr NDVI-R 04/09	-0.03	0.07	-0.01	-0.09	-0.06	-0.17	**-0.28**	**-0.33**	**-0.20**	-0.07	**-0.19**	**0.31**	**0.29**	**0.28**	**0.27**	0.10	**-0.42**	-0.02	-0.04	**-0.20**
gr NDVI R	0.06	-0.04	-0.05	-0.14	0.08	-0.10	**-0.22**	**-0.26**	**-0.22**	-0.08	-0.12	0.15	0.15	**0.27**	0.16	0.05	**-0.21**	0.05	0.04	-0.09
gr NDVI-G 07/08	-0.04	0.04	-0.14	**-0.19**	**0.19**	0.03	-0.07	-0.06	**-0.28**	**-0.27**	**-0.21**	**0.44**	**0.26**	**0.34**	**0.54**	-0.06	-0.03	**0.31**	0.16	0.10
gr NDVI G 04/09	**-0.22**	0.11	0.04	0.04	**0.21**	-0.02	-0.02	-0.10	-0.15	**-0.25**	**-0.17**	**0.27**	0.17	**0.40**	**0.41**	0.09	-0.17	**0.25**	0.04	-0.02
gr NDVI-G	-0.16	0.10	0.01	0.03	**0.23**	0.09	0.07	0.028	**-0.20**	**-0.28**	-0.16	**0.28**	0.16	**0.35**	**0.43**	0.02	-0.04	**0.35**	0.12	0.12
gr GR 07/08	-0.06	0.04	-0.12	-0.17	**0.20**	0.04	-0.06	-0.04	**-0.26**	**-0.25**	**-0.17**	**0.42**	**0.24**	**0.34**	**0.55**	-0.07	-0.01	**0.31**	0.15	0.09
gr GR 04/09	**-0.21**	0.09	0.03	0.01	**0.20**	-0.02	-0.04	-0.11	-0.16	**-0.23**	-0.15	**0.24**	0.15	**0.38**	**0.38**	0.08	-0.16	**0.23**	0.04	-0.01
gr GR	-0.16	0.10	0.01	0.01	**0.23**	0.08	0.05	0.03	**-0.20**	**-0.27**	-0.15	**0.28**	0.16	**0.34**	**0.44**	0.01	-0.04	**0.35**	0.12	0.11
gr REIP 07/08	0.10	-0.12	**0.23**	**0.30**	**-0.17**	0.06	0.14	0.17	**0.28**	**0.38**	**0.34**	**-0.44**	**-0.27**	**-0.43**	**-0.56**	0.04	0.09	**-0.38**	-0.14	-0.02
gr REIP 04/09	0.13	-0.10	0.02	0.08	-0.04	0.11	0.13	**0.23**	**0.26**	**0.23**	**0.30**	**-0.39**	**-0.31**	**-0.42**	**-0.42**	-0.06	**0.32**	-0.17	-0.01	0.10
gr REIP	0.08	-0.06	0.11	0.15	**-0.19**	0.04	0.11	**0.17**	**0.29**	**0.29**	**0.26**	**-0.38**	**-0.27**	**-0.43**	**-0.45**	-0.02	**0.19**	**-0.31**	-0.12	-0.05
NDVI R 05/08	**0.24**	**-0.37**	**-0.34**	**-0.41**	**0.41**	**-0.25**	**-0.30**	**-0.34**	**-0.57**	**-0.43**	**-0.46**	**0.16**	**0.11**	**0.11**	**0.18**	-0.01	**0.26**	**0.36**	**0.19**	0.14
NDVI R 01/09	**0.30**	**-0.36**	**-0.32**	**-0.48**	**0.35**	**-0.17**	**-0.37**	**-0.32**	**-0.57**	-0.12	**-0.31**	**0.16**	0.05	0.07	**0.21**	0.02	0.03	**0.18**	0.11	**0.19**
Mean NDVI R	**0.29**	**-0.38**	**-0.39**	**-0.47**	**0.45**	**-0.20**	**-0.27**	**-0.27**	**-0.60**	**-0.35**	**-0.44**	**0.14**	0.06	0.07	**0.15**	-0.08	**0.34**	**0.28**	**0.19**	**0.22**
NDVI G 05/08	**0.27**	**-0.39**	**-0.29**	**-0.41**	**0.35**	**-0.26**	**-0.35**	**-0.37**	**-0.61**	**-0.37**	**-0.43**	**0.18**	**0.11**	**0.10**	**0.16**	-0.00	**0.23**	**0.28**	**0.20**	0.10
NDVI G 01/09	**0.29**	**-0.36**	**-0.33**	**-0.49**	**0.35**	**-0.20**	**-0.39**	**-0.33**	**-0.57**	-0.12	**-0.28**	**0.17**	0.06	0.06	**0.15**	-0.03	0.07	**0.10**	0.07	**0.19**
Mean NDVI G	**0.31**	**-0.40**	**-0.36**	**-0.47**	**0.39**	**-0.21**	**-0.33**	**-0.31**	**-0.63**	**-0.33**	**-0.41**	**0.15**	0.08	0.07	**0.13**	-0.08	**0.31**	**0.22**	0.16	**0.21**
GR 05/08	**0.26**	**-0.39**	**-0.28**	**-0.40**	**0.33**	**-0.26**	**-0.35**	**-0.37**	**-0.59**	**-0.34**	**-0.41**	**0.17**	**0.10**	0.07	**0.14**	0.01	**0.22**	**0.26**	**0.19**	0.09
GR 01/09	**0.29**	**-0.35**	**-0.34**	**-0.50**	**0.34**	**-0.19**	**-0.39**	**-0.33**	**-0.57**	-0.11	**-0.28**	**0.15**	0.04	0.03	**0.14**	-0.02	0.07	**0.10**	0.06	**0.19**
Mean GR	**0.30**	**-0.39**	**-0.37**	**-0.47**	**0.39**	**-0.21**	**-0.33**	**-0.31**	**-0.63**	**-0.31**	**-0.41**	**0.13**	0.06	0.05	**0.12**	-0.07	**0.30**	**0.22**	0.15	**0.20**

Variables	gr NDVI-R 07/08	gr NDVI-R 04/09	Mean gr NDVI-R	gr NDVI-G 07/08	gr NDVI-G 04/09	Mean gr NDVI-G	gr GR 07/08	gr GR 04/09	Mean gr GR	gr REIP 07/08	gr REIP 04/09	Mean gr REIP	NDVI-R 05/08	NDVI-R 01/09	Mean NDVI-R	NDVI-G 05/08	NDVI-G 01/09	Mean NDVI-G	GR 05/08	GR 04/09	Mean GR
Mean gr NDVI-R	**0.38**	**0.72**	**1**	**0.23**	**0.40**	**0.35**	**0.22**	**0.41**	**0.35**	**-0.41**	**-0.67**	**-0.70**	**0.26**	**0.32**	0.10	**0.30**	**0.27**	0.17	**0.30**	**0.25**	0.16
Mean gr NDVI-G	0.04	**0.30**	**0.35**	**0.77**	**0.81**	**1**	**0.77**	**0.78**	**0.99**	**-0.62**	**-0.56**	**-0.77**	**0.32**	**0.26**	**0.24**	**0.28**	**0.20**	**0.23**	**0.25**	**0.18**	**0.20**
Mean gr GR	0.04	**0.32**	**0.35**	**0.79**	**0.82**	**0.99**	**0.80**	**0.81**	**1**	**-0.62**	**-0.56**	**-0.76**	**0.35**	**0.28**	**0.26**	**0.29**	**0.22**	**0.24**	**0.27**	**0.19**	**0.22**
Mean gr REIP	**-0.21**	**-0.61**	**-0.70**	**-0.66**	**-0.65**	**-0.77**	**-0.65**	**-0.63**	**-0.76**	**0.76**	**0.87**	**1**	**-0.37**	**-0.38**	**-0.25**	**-0.38**	**-0.31**	**-0.27**	**-0.35**	**-0.29**	**-0.25**
Mean NDVI R	0.04	-0.04	0.10	**0.36**	0.14	**0.24**	**0.36**	0.15	**0.26**	**-0.28**	-0.12	**-0.25**	**0.86**	**0.79**	**1**	**0.82**	**0.78**	**0.93**	**0.80**	**0.76**	**0.92**
Mean NDVI G	0.04	0.05	0.17	**0.33**	0.16	**0.23**	**0.32**	0.16	**0.24**	**-0.27**	**-0.17**	**-0.27**	**0.82**	**0.78**	**0.93**	**0.87**	**0.83**	**1**	**0.85**	**0.82**	**0.99**
Mean GR	0.06	0.04	0.16	**0.31**	0.13	**0.20**	**0.31**	0.13	**0.22**	**-0.26**	-0.16	**-0.25**	**0.81**	**0.77**	**0.92**	**0.85**	**0.83**	**0.10**	**0.84**	**0.82**	**1**

Coloured cells are significant. Red: $p<0.0001$; blue: $p<0.01$; yellow: $p<0.05$. Abbreviations: OM: organic matter; CEC: cation exchange capacity; SM: soil moisture; LWP: leaf water potential; TA: titratable acidity; FVT: free volatile terpenes; PVT: potentially-volatile terpenes; gr: ground-based measurements; NDVI-R and NDVI-G: normalized difference vegetation index (red and green); GR: greenness ratio; REIP: red edge inflection point. The dates associated with SM, LWP, NDVI-R and NDVI-G, GR and REIP refer to sampling points throughout the season.

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with many variables. The correlation with yield was strong for all air-based VIs (p<0.0001 for NDVI green; p<0.01 for NDVI red and GR) and for all the flight dates except June. Vine size was strongly correlated with all VIs (p<0.0001 for NDVI red; p<0.01 for NDVI green and GR) on all flight dates except those in June. Correlations between berry weight and cluster number vs. VIs were not strong (p<0.05) and only with August images. Moreover, berry weight was only correlated to NDVI green and NDVI red, whereas cluster number was correlated to all three VIs. As in 2007 and 2008, leaf ψ (a.v.) and soil moisture were negatively correlated to air-based VIs. Soil moisture showed a high level of correlation (p<0.0001) for all VIs and dates, whereas leaf ψ showed a high level of correlation (p<0.0001) with all three VIs calculated from the August image and the seasonal mean and a lower level of correlation (p<0.01) with the indices from the September image. Leaf ψ and soil moisture were not correlated with indices from the June image. Brix correlated with the three VIs (p<0.0001 with NDVI red and NDVI green; p<0.01 with GR), but only for the June images.

2. Analysis of variance

2006 season. ANOVA was applied specifically to distinguish between sub-sub-blocks and also to define which variables were of greatest significance to be used in PCA. In addition to ANOVA of standard field measurements (e.g., yield components, vine size, soil and vine water status, berry composition), there were 12 additional variables—the four VIs collected on two different dates plus the mean indices. Data for vine size and VIs derived from airborne images were not collected in 2006. All VIs were highly significant to discriminate 18 sub-sub-block x water status combinations (p <0.0001; data not shown). Thus, there were 33 significant variables out of 36 analyzed. After grouping similar variables, 18 variables were used for PCA.

2007 season. The 2007 season was hot and dry and 14 sub-block x water status combinations were delineated. ANOVA was performed for sub-block x water status combinations first. There were initially 48 variables including VIs calculated from both airborne images and ground-based measurements of leaf reflectance. All VIs calculated from the airborne images were highly significant (p < 0.0001; data not shown) to discriminate water status categories (sub-sub-blocks). This was not the case for ground-based VIs. Thus, there were 44 significant variables for discrimination. After some were grouped, 22 variables were used for PCA. An ANOVA was also run for sub-block x vine size combinations. In this case, six of 48 were not significant to discriminate the different sub-sub-blocks; none of the ground-based VIs were significant, whereas those calculated from the airborne images were highly significant (p < 0.0001; data not shown). After some variables were grouped, 22 variables were used for PCA.

2008 season. Twelve sub-block x water status and 18 sub-block x vine size combinations were delineated in 2008. Ground-based VIs did not significantly discriminate any sub-sub-block combinations, except for ground-based NDVI red (p < 0.0001 for water status and vine size); all others were not significant. All air -based VIs were significant (p < 0.0001, data not shown) to discriminate the different water status combinations. Of the 65 variables used in the ANOVA, 14 variables were not significant. After some were grouped, 21 variables were used to run PCA. There were also initially 65 variables for the sub-block x vine size combinations, of which five variables were not significant to discriminate the sub-sub-blocks. Among the VIs calculated from ground-based leaf reflectance data, NDVI red measured on August 20 was the only one that was not significant; air-based VIs were all highly significant (p < 0.0001; data not shown). After grouping, 24 variables were used for PCA.

2009 season. Twelve sub-block x water status and 18 sub-block x vine size combinations could be delineated in 2009. There were 59 variables used for ANOVA, of which three were not significant, including the ground-based VIs calculated from data collected on August 7. The other VIs calculated from the airborne imagery were highly significant (p < 0.0001; data not shown). After grouping, 26 variables were used for PCA. For the sub-block x vine size combinations, 65 variables were used for ANOVA, of which five were not significant. All air-based and most ground-based VIs were highly significant (p < 0.0001), except for NDVI red calculated on August 7 from the ground leaf reflectance. After similar variables were grouped, 25 variables were used for PCA.

3. Principal component analysis

2006 season. The PCA biplot for the two first axes, F1 and F2, represented 48.2 % (F1) and 14.3 % (F2) of the variability in the 2006 data set (Figure 3A). The SPY, SPB and TR sub-blocks were with one exception to the right of F2, whereas WPY, WPB and LE sub-blocks were to the left. Eigenvectors for ground-based NDVI red, NDVI green and GR were

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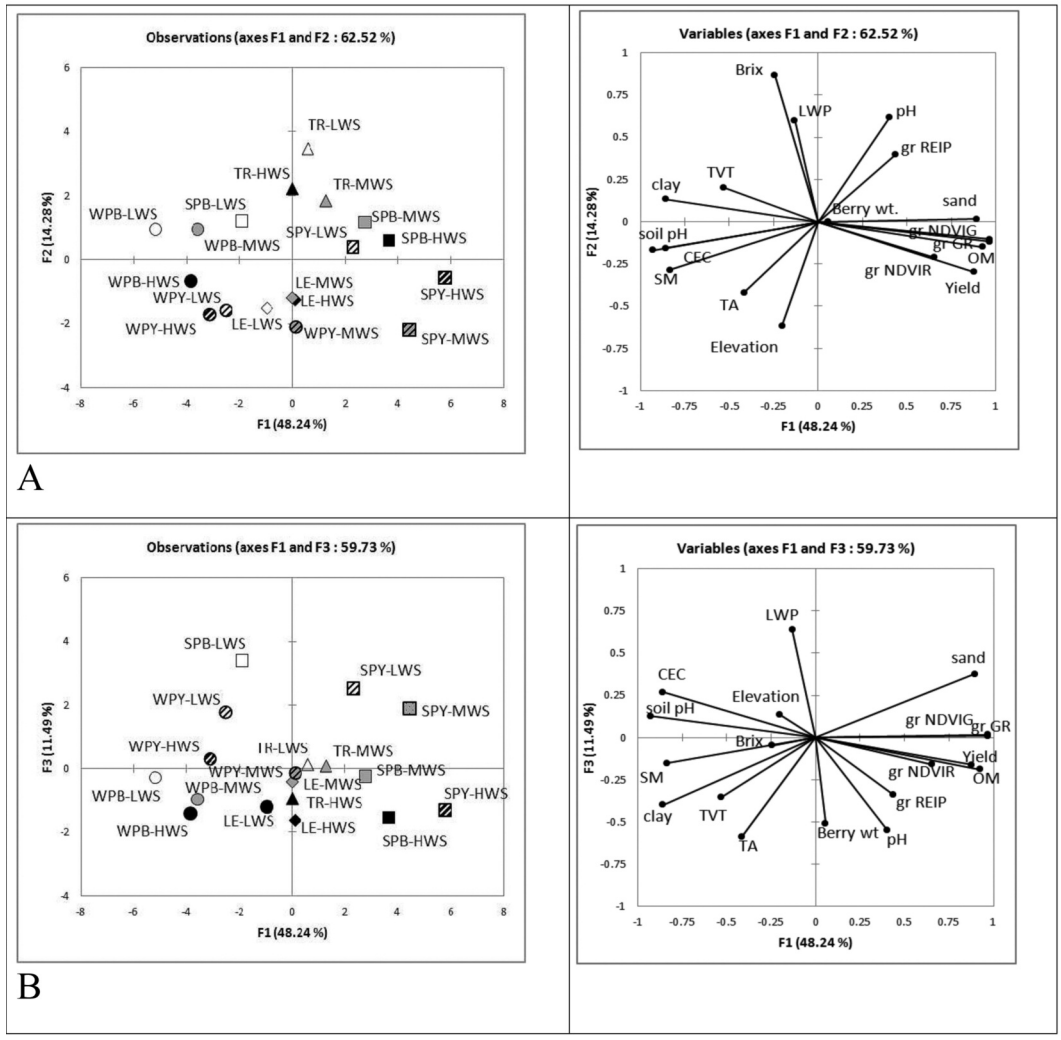


Figure 3. Principal component analysis using three factors to display relationships between mean values of 18 significant variables and 18 block x water status combinations at a 10-hectare site at Thirty Bench Winemakers (Beamsville, Ontario) in 2006. A) Axes F1 and F2; B) Axes F1 and F3.

Sub-block abbreviations: WPB: Wooden Post Blue; WPY: Wooden Post Yellow; SPB: Steel Post Blue; SPY: Steel Post Yellow; LE: Les Erables; TR: Triangle; HWS: high water status; MWS: medium water status; LWS: low water status; variable abbreviations: OM: organic matter; CEC: cation exchange capacity; SM: soil moisture; LWP: leaf water potential; TA: titratable acidity; TVT: total volatile terpenes; gr: ground-based; NDVIR/NDVIG: normalized difference vegetation index red/green; GR: greenness ratio; REIP: red edge inflection point.

clustered together to the right of the F2 axis, along with yield, berry weight and % sand. Several soil variables (i.e., % clay, soil pH, CEC and soil moisture) as well as TA and TVT (FVT + PVT) were oriented to the left of F2. Leaf ψ (a.v.) and Brix were not strongly associated with either group of variables. This suggests that a vine with a higher GR would more likely be associated with higher yields, but with lower TA and TVT, soil moisture and % clay. REIP was weakly associated with the cluster of eigenvectors that included NDVI and showed positive relationships to berry pH, Brix and leaf ψ and negative relationships to TVT, soil moisture, TA and % clay. The second biplot representing two other dimensions: F1 (48.2 %) and F3 (11.5 %) indicated as with F1 vs. F2, all VIs were correlated to each other, as well as to yield, berry pH and OM and were negatively correlated to soil moisture, TVT, TA, % clay, soil pH and CEC (Figure 3B). REIP and leaf ψ (a.v.) were inversely correlated.

2007 season. The first biplot represents relationships between all variables and the sub-block x water status combinations for the F1/F2 axes (Figure 4A). The first three factors accounted for 42.0 %, 19.2 % and 16.7 % of the variability, respectively. Sub-block clusters found in 2006 were to some degree observable. One cluster in the upper right quadrant grouped all TR, SPY and SPB sub-blocks; the SPB-LWS was in the upper left quadrant. The LE, WPY

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and WPB sub-blocks were below F1 in a second cluster, with the majority in the lower right quadrant. All VIs, from the August flight or the mean values, were separated by low angles and were part of the same cluster to the right of F2, hence positively related to vine size, all yield components, soil moisture, berry TVT, pH and inversely to leaf ψ (a.v.). This suggested that vines with high VI values (NDVI red, NDVI green, GR) had potentially high vine size, yield, leaf ψ (high water status), berry TVT and pH. There were no strong relationships between VIs and soil texture. Five samples of the two leaf ψ combinations (MWS and LWS), representing one-third of the samples, were negatively associated with the remotely sensed variables. The grouping consisting of TR, SPB and SPY was positively related to the VIs.

The second PCA represented sub-block x vine size combinations (Figure 4B). F1 and F2 were associated with 49.8 % and 27.4 % of the variability, respectively. Two sub-block clusters were identified. The TR and LE sub-blocks were above F1, while the WPY and WPB sub-blocks were below it. There were two obvious vine size clusters: HVS, on the right side of the biplot associated with the vine size

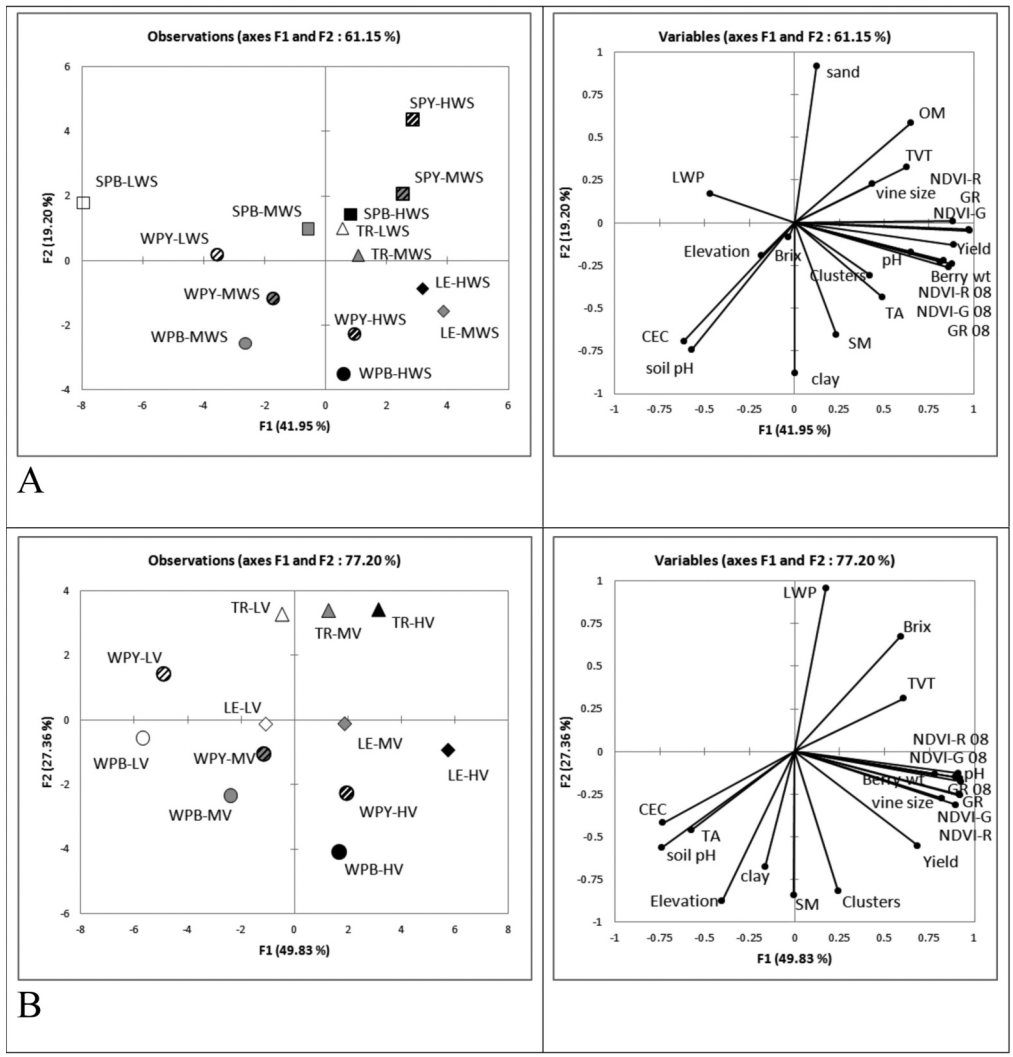


Figure 4. A) Principal component analysis using two factors to display relationships between mean values of 22 significant variables and 14 block x water status combinations at a 10-hectare site at Thirty Bench Winemakers (Beamsville, Ontario) in 2007. B) Principal component analysis using two factors to display relationships between mean values of 20 significant variables and 12 block x vine size combinations.

Sub-block abbreviations: WPB: Wooden Post Blue; WPY: Wooden Post Yellow; SPB: Steel Post Blue; SPY: Steel Post Yellow; LE: Les Erables; TR: Triangle; HWS: high water status; MWS: medium water status; LWS: low water status; HV: high vine size; MV: medium vine size; LV: low vine size; variable abbreviations: OM: organic matter; CEC: cation exchange capacity; SM: soil moisture; LWP: leaf water potential; TA: titratable acidity; TVT: total volatile terpenes; NDVI-R/NDVI-G: mean normalized difference vegetation index red/green; GR: mean greenness ratio. NDVI-R, NDVI-G and GR 08 refer to measurements taken in August.

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eigenvector (HVS and MVS WP and LE sub-sub-blocks) and LVS in the left quadrants (MVS and LVS WP, LE and TR sub-sub-blocks). All VI eigenvectors were clustered and highly positively related to vine size, all yield components, berry pH, TVT and Brix; and negatively related to TA, soil pH and CEC. VIs were not related to soil texture, leaf ψ and soil moisture. Relationships between sub-block clusters and VIs depended largely on vine size: the sub-block effect was low. LVS sub-sub-blocks corresponded to low VI values. HVS combinations were highly related to high VI values, as suggested by the position of the vine size vector.

2008 season. The PCAs based on sub-blocks x water status combinations represented 42.8 % and 29.9 %, respectively (Figure 5A). A cluster below F1 and mainly in the bottom left quadrant consisted predominantly of LE, WPY and WPB sub-blocks; the SPY and SPB samples were grouped above F1, while the TR sub-block combinations were in the lower right quadrant. Clusters that grouped water status combinations were also apparent; most HWS and MWS sub-sub-blocks were in or near the lower left quadrant. All VIs were clustered on the right side of F2, except ground-based NDVI red. This suggests poor correlation between air- and ground-based NDVI red. VIs were positively related to vine size,

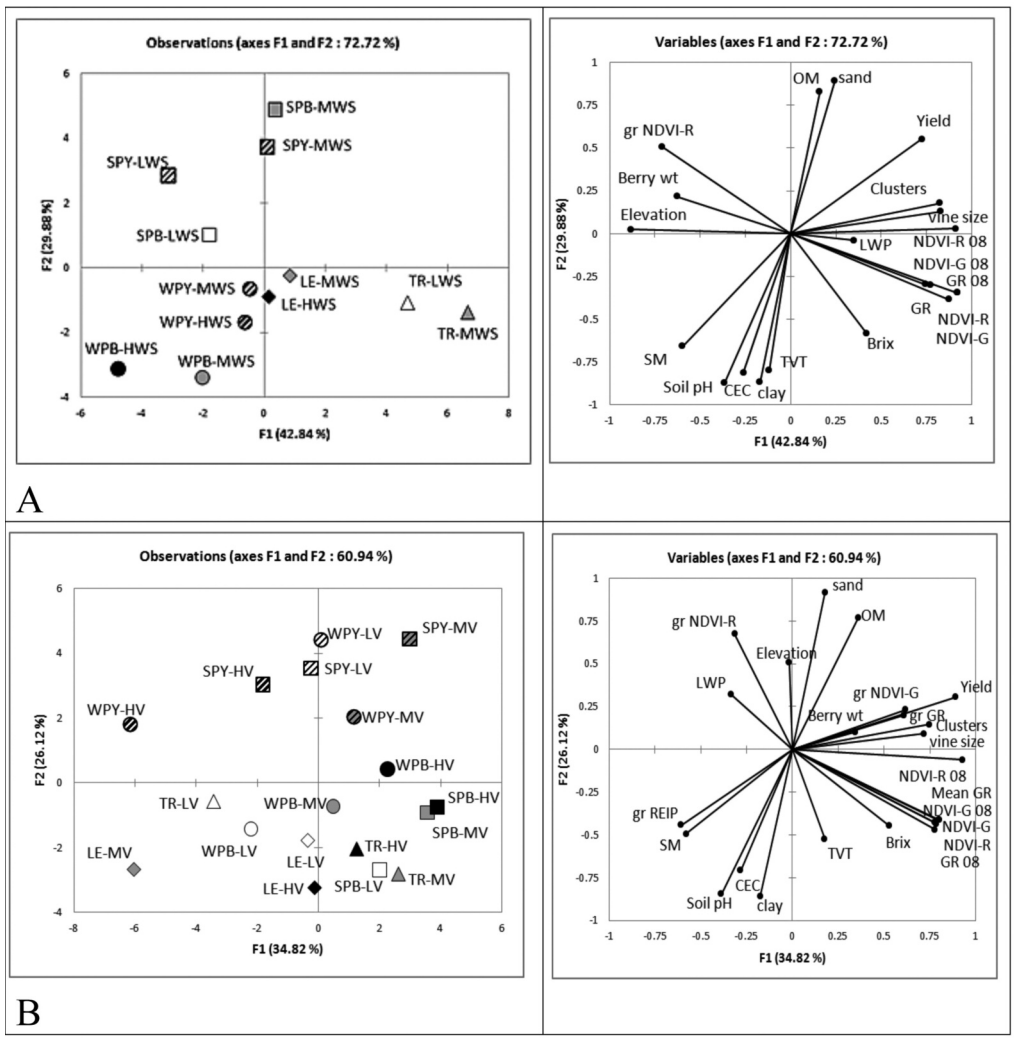


Figure 5. A) Principal component analysis using two factors to display relationships between mean values of 21 significant variables and 12 block x water status combinations at a 10-hectare site at Thirty Bench Winemakers (Beamsville, Ontario) in 2008. B) Principal component analysis using two factors to display relationships between mean values of 24 significant variables and 18 block x vine size combinations.

Sub-block abbreviations: WPB: Wooden Post Blue; WPY: Wooden Post Yellow; SPB: Steel Post Blue; SPY: Steel Post Yellow; LE: Les Erables; TR: Triangle; HWS: high water status; MWS: medium water status; LWS: low water status; HV: high vine size; MV: medium vine size; LV: low vine size; variable abbreviations: OM: organic matter; CEC: cation exchange capacity; SM: soil moisture; LWP: leaf water potential; TA: titratable acidity; TVT: total volatile terpenes; NDVI red/NDVI green: mean normalized difference vegetation index red/green; GR: mean greenness ratio; REIP: red edge inflection point. NDVI-R, NDVI-G and GR 08 refer to measurements taken in August while gr NDVI-R, NDVI-G and GR refer to ground-based measurements.

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yield, clusters per vine, Brix and leaf ψ (a.v), although the short length of the leaf ψ vector relative to those of the VIs suggested weak relationships. Negative relationships were apparent between VIs and both soil moisture and berry weight. There were no apparent relationships between VIs and several soil variables (texture, soil pH, CEC) or TVT. The first sub-block cluster (comprised of LE, WPY and WPB) was negatively related to the VIs. The second cluster (SPY and SPB) was unrelated to the VIs, being positioned ≈90° from the eigenvectors. The TR combinations were positively related to the VIs. The LWS combinations for both SPY and SPB were opposite to the VI eigenvectors; therefore low water status was associated with low VI values.

The PCA of vine size combinations is depicted for F1/F2 the axes; the first three factors represented 34.8 %, 26.1 % and 16.0 % for F1, F2 and F3, respectively (Figure 5B). Sub-block- and vine size-related clusters could be discerned whereby two main sub-block groups were apparent: the first below F1 consisted of LE, TR, SPB and WPB, while the second above F1 grouped SPY and WPY. There was clustering by vine size: the first cluster to the right of F2 included primarily MVS and HVS, while a LVS group was found below F1 and to the left of F2. All VI eigenvectors were grouped to the right of F2. Ground-based NDVI green and GR were related to the air-based VIs, whereas NDVI red and REIP were inversely correlated to them. Air-based VIs were related to vine size, all yield components, Brix and TVT and were negatively related to soil moisture and leaf ψ (a.v). Soil variables (texture, pH and CEC) were unrelated to VIs. Since the separation line between the two sub-block clusters was represented by F1-axis and all VI eigenvectors were along that same axis, there was no sub-block cluster specifically associated with VI values. With respect to vine size sub-sub-blocks, with all the eigenvectors on the right side of the biplot and the MVS and HVS sub-sub-blocks on the same side, one can conclude that if vine size is high, so too is the VI value. On the other hand, if the vine size is low, one would more likely find a low VI value.

2009 season. The first PCA biplot shows the sub-block x water status combinations (Figure 6A). F1, F2 and F3 represented 32.8 %, 27.2 % and 11.6 % of the variability, respectively. There was no obvious grouping of the water status sub-sub-blocks and water status appeared to have played a minor role in VI determination. Three sub-block clusters were delineated; the first one in in or near the top right quadrant consisted of WPB, WPY and LE; the second cluster to the left of the F2-axis grouped SPB and SPY; the third cluster in the lower right quadrant included the TR sub-block. The eigenvectors were not as well grouped as in 2007 and 2008: the air-based VIs were grouped together, except for September GR to the right of F2. Ground-based VIs were either not related to air-based VIs (e.g. REIP and NDVI red), or negatively related to them (e.g. GR and NDVI green). Ground-based VIs were positively related to vine size, all yield components, Brix, berry pH and TVT and negatively related to berry TA, TVT, ground REIP, leaf ψ (a.v.) and soil moisture. Air-based VIs were positively related to % sand and OM and inversely related to % clay, soil pH and CEC. Sub-block cluster trends were: the first cluster (LE, WPY and WPB) was negatively related to air-based VIs; the second cluster (SPB and SPY) was positively associated with the VIs; the third and last cluster, consisting mainly of the TR sub-block, did not relate to the air-based VIs, but was associated with ground-based VIs.

The second PCA concerned the sub-block x vine size combinations (Figure 6B). F1, F2 and F3 represented 39.2 %, 26.2 % and 12.6 % of the variability, respectively. LVS sub-sub-blocks were above F1, while the second cluster below F1 consisted of MVS and HVS. As for the sub-blocks, most SPY and SPB sub-sub-blocks were above F1 (mainly in the upper right quadrant) and most WPY and WPB, LE and TR were below F1, with TR sub-sub-blocks in the lower right quadrant. All air-based VI eigenvectors were grouped together: there was a good connection between late season and mean VIs, TA and % sand. However, they were not well-correlated to the ground-based VIs, vine size and all yield components. Negative relationships between air-based VIs were observed for Brix, leaf ψ (a.v.), soil moisture, % clay, soil pH and CEC. The LVS cluster was opposite to the VI eigenvectors, while MVS and HVS groups were strongly related to high VI values. The cluster that was composed primarily of SPY, SPB and TR had higher VI values, while the WPB, WPY and LE were less related to the different VIs.

4. Spatial variability

2006 season. Maps representing spatial variability for all four ground-based VIs are in Figure 7A-D. The four maps for each VI were quite similar; high values were in the SPY block while lowest were generally in WPB and part of SPB. The same trends were found with the four VIs, suggesting that one might have difficulty deciding which VI would be the best to use to get the most relevant information. The spatial variability in the VIs corresponded visually to leaf ψ, whereby high VI values paralleled

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high ψ (a.v.) values (leaf ψ data not shown; q.v. Reynolds *et al*., 2010b).

2007 season. Maps were created for spatial variability of both ground-based (Figure 7E-G) and air-based VIs (Figure 8A-C). In the first set of maps, the lowest values for each of the three VIs (NDVI red, NDVI green and GR) were in SPB and WPB. Highest values were found in WPY and SPY. Similar spatial patterns were observed in 2006, which suggests that ground-based leaf reflectance VIs were stable over time. Highest values of VIs from airborne images were in LE, SPY and the western part of WPB (Figure 8). The lowest values were in SPB, WPY and the eastern part of WPB. Thus, the two sets of VI observations were slightly different. For air-based VIs, the spatial variability trend was very similar from one index to another. As in 2006, there were putative spatial relationships between the VIs and leaf ψ, particularly the ground-based VIs.

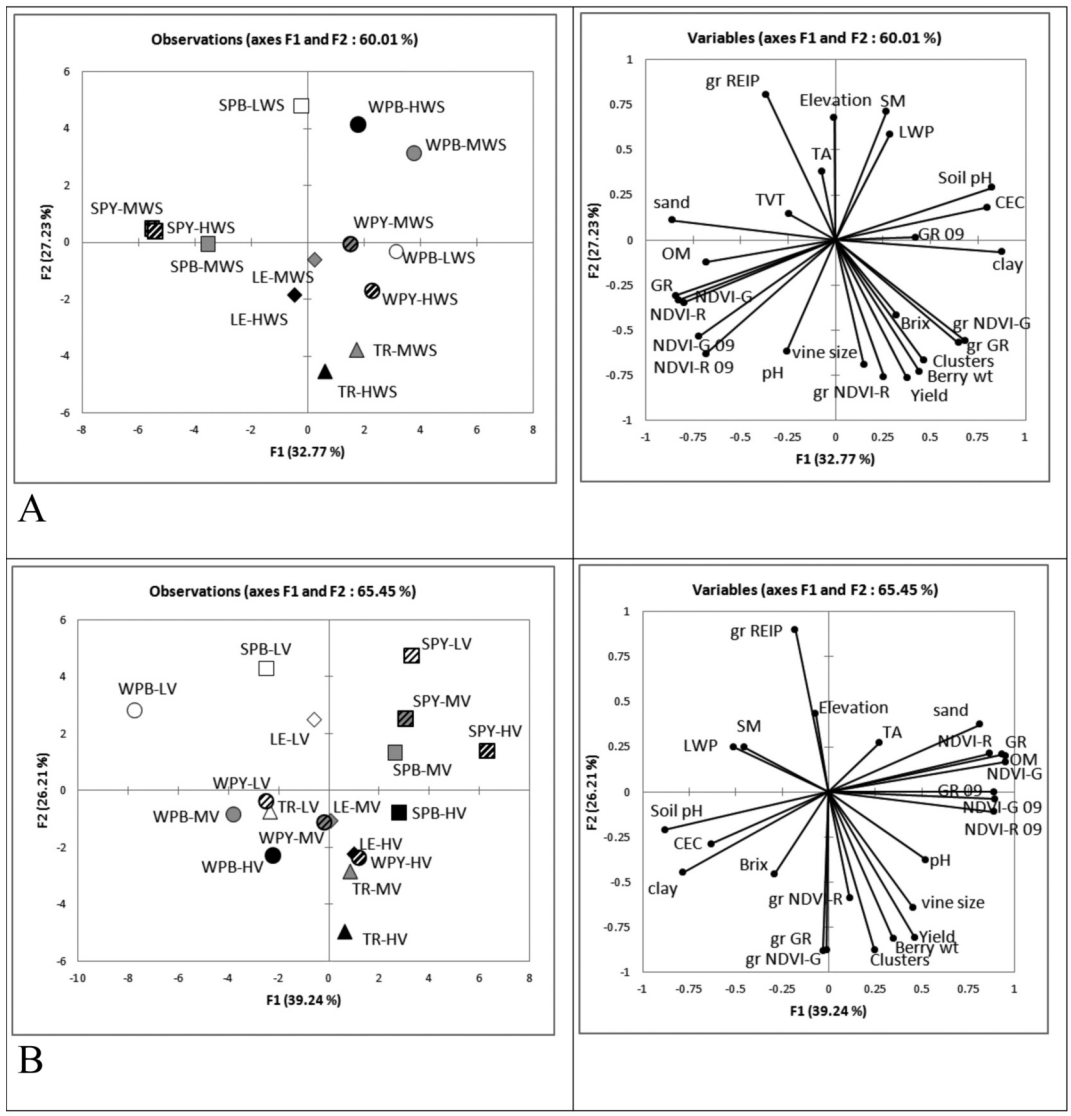


Figure 6: A) Principal component analysis using two factors to display relationships between mean values of 26 significant variables and 13 block x water status combinations at a 10-hectare site at Thirty Bench Winemakers (Beamsville, Ontario) in 2009. B) Principal component analysis using two factors to display relationships between mean values of 25 significant variables and 18 block x vine size combinations

Sub-block abbreviations: WPB: Wooden Post Blue; WPY: Wooden Post Yellow; SPB: Steel Post Blue; SPY: Steel Post Yellow; LE: Les Erables; TR: Triangle; HWS: high water status; MWS: medium water status; LWS: low water status; HV: high vine size; MV: medium vine size; LV: low vine size; variable abbreviations: OM: organic matter; CEC: cation exchange capacity; SM: soil moisture; LWP: leaf water potential; TA: titratable acidity; TVT: total volatile terpenes; NDVI red/NDVI green: mean normalized difference vegetation index red/green; GR: mean greenness ratio; REIP: red edge inflection point. NDVI-R, NDVI-G and GR 09 refer to measurements taken in September while gr NDVI-R, NDVI-G and GR refer to ground-based measurements.

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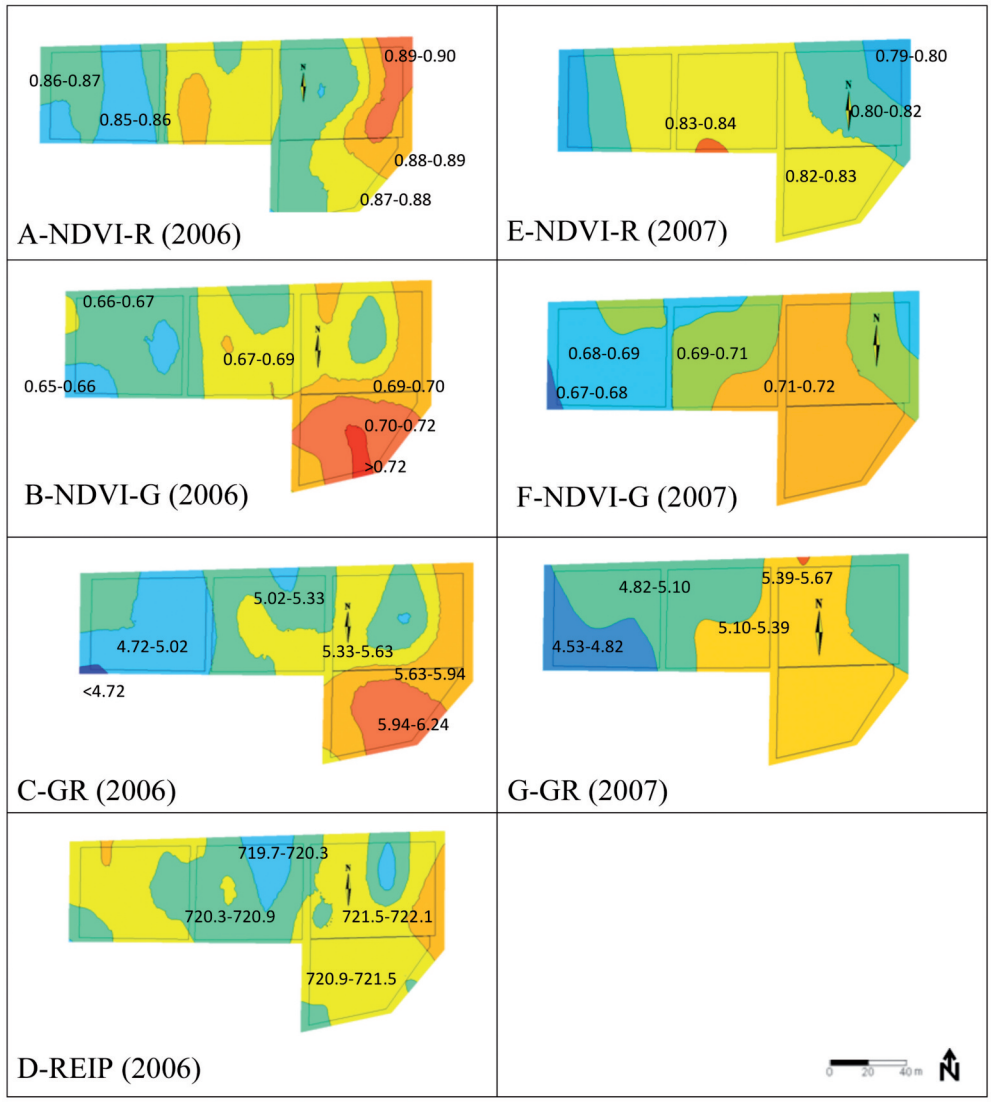


Figure 7. Ground-based vegetation index maps for four sub-blocks at Thirty Bench Winemakers (Beamsville, Ontario) in 2006 (A-D) and 2007 (E-G).

Data for Les Erables and Triangle blocks were not collected in 2006 and 2007. A,E) Normalized difference vegetation index red (NDVI-R); B,F) Normalized difference vegetation index green (NDVI-G); C,G) greenness ratio (GR); D,H) red edge inflection point (REIP).

2008 season. Maps were created for the spatial variability of the three air-based (Figure 8D-F) and four ground-based VIs (Figure 9A-D). The ground-based GR did not help discriminate areas within the vineyard (Figure 9C). The three other VIs were more relevant for that purpose and it appears that areas where the NDVI values were higher (both SP blocks) typically had low REIP values. Comparing Figure 9A-D to Figure 8D-F, the differences between ground-based and air-based VIs were easily observable. Areas that had a high VI value obtained with the ground-based equipment showed the opposite with airborne imagery: in this last case, SPB, SPY, WPB and the western part of LE had low VIs, when the highest values were found in TR, WPY and the eastern part of LE. This spatial pattern corresponded closely to that of both soil moisture and leaf ψ; high airborne VIs were associated spatially with lowest soil moisture and leaf ψ (Reynolds *et al*., 2010b).

2009 season. The maps representing the ground-based VIs showed that there was a negative correlation between REIP and the three other VIs (both NDVI values and GR; Figure 9E-H). The highest VI values were found in TR, WPY and LE, whereas the lowest ones were in both SPB blocks and WPB. As per the previous vintages, maps of the VIs derived from the airborne images (Figure 10) were very different from the ones obtained with the ground sensor. Highest values were found in SPY,

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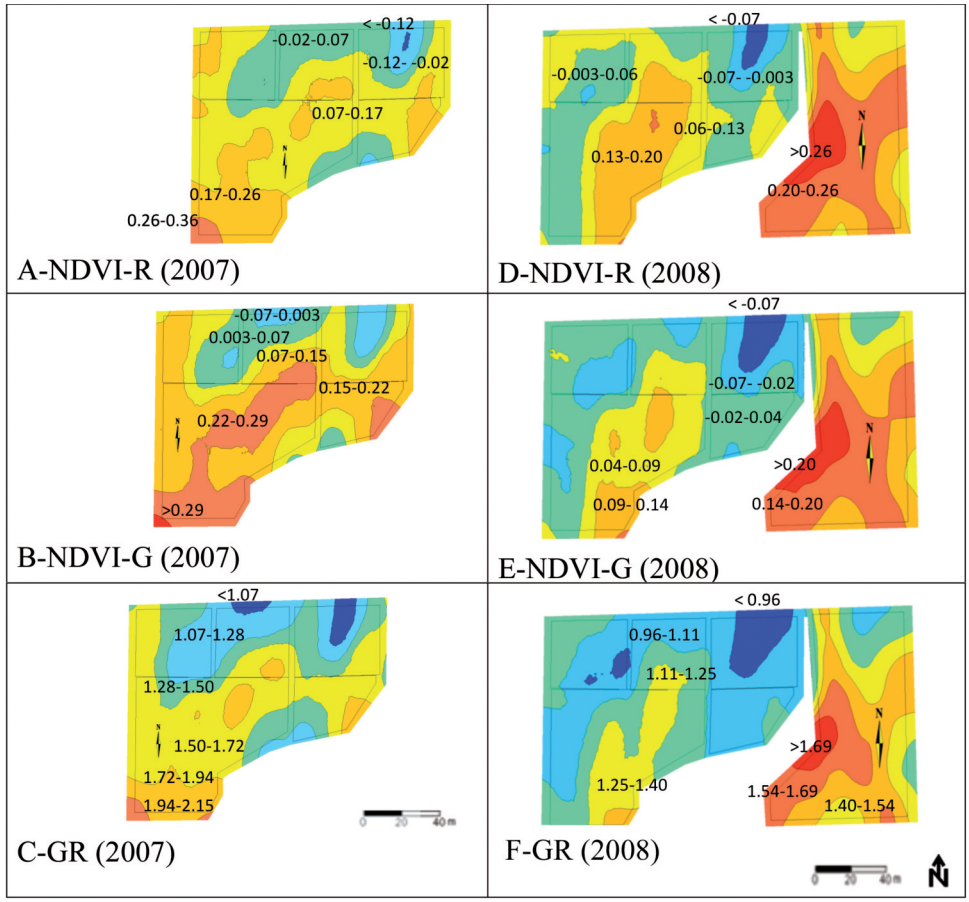


Figure 8. Vegetation index maps derived from airborne imagery acquired over five sub-blocks (2007; A-C) and six sub-blocks (2008; D-G) at Thirty Bench Winemakers (Beamsville, Ontario).

Remote-sensing data for the Triangle block were not collected in 2007. A,D) Normalized difference vegetation index red (NDVI-R); B,E) Normalized difference vegetation index green (NDVI-G); C,F) greenness ratio (GR); G) Red edge inflection point (REIP, 2008).

WPY and the western parts of both LE and TR, when the lowest values were in WPB, SPB and the eastern parts of LE and TR. The spatial variability was essentially identical to that observed in the previous vintages, i.e., identical differences were observed year after year in a same vineyard. However, the spatial correlation between ground and airborne-based VIs illustrates what was found on the PCAs: there was no correlation across the different vintages between those variables. Nonetheless, spatial pattern of the ground-based VIs corresponded closely to that of both soil moisture and leaf ψ except for REIP; high VIs were again associated spatially with lowest soil moisture and leaf ψ (Reynolds *et al.*, 2010b). Airborne VIs did not show any apparent spatial relationship with current season soil moisture or leaf ψ data; however, the spatial pattern of airborne VIs corresponded closely to soil moisture and leaf ψ spatial variation of previous seasons (Reynolds *et al.*, 2010b).

DISCUSSION

By examining the correlation matrices, several very useful assumptions can be made about grape quality and vine biology. In particular, taking airborne images around mid-August, (i.e. mid-veraison) would enable one to discriminate parts of a vineyard for vine size, yield, berry pH, TA and monoterpenes as well as Brix to a certain extent (Lamb *et al.*, 2004). But before making general conclusions based upon these observations alone, it would be prudent to additionally assess if particular weather conditions may have had impacts upon the water status/berry composition relationships in any of the vintages, since temporal stability may vary between vintages (Bramley, 2005; Lamb, 2000; Leinonen and Jones, 2004) or occasionally between sampling dates within a given vintage (Lamb *et al.*, 2004). A major strength of this study is that over the four vintages extremely different weather conditions were experienced, from drought in 2007 to excessive precipitation in 2009

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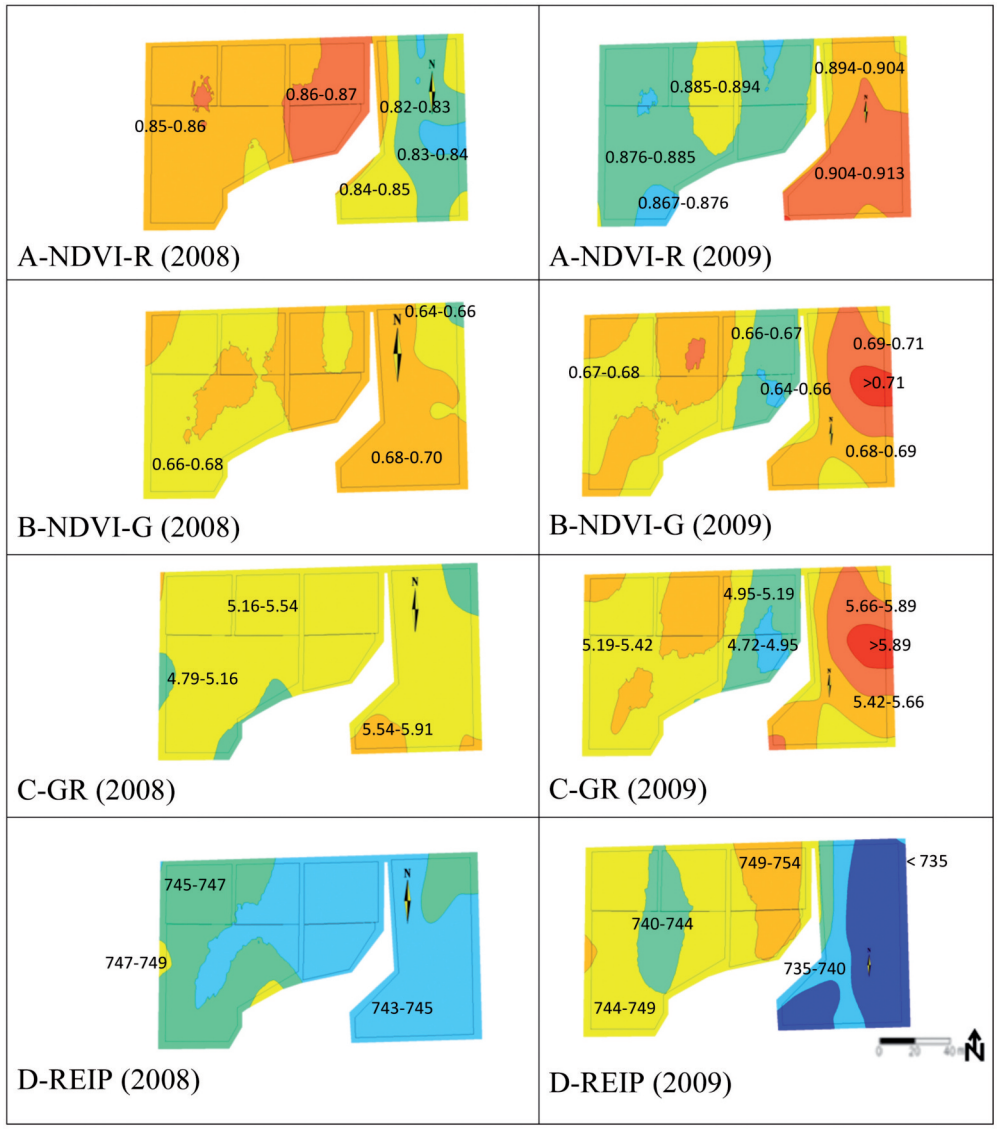


Figure 9. Vegetation index (ground-based) maps for six sub-blocks at Thirty Bench Winemakers (Beamsville, Ontario) in 2008 (A-D) and 2009 (E-H).

A,E) Normalized difference vegetation index red (NDVI-R); B,F) Normalized difference vegetation index green (NDVI-G); C,G) greenness ratio (GR); D.H) Red edge inflection point (REIP). Figure 10: Vegetation index maps derived from airborne imagery acquired over six sub-blocks at Thirty Bench Winemakers (Beamsville, Ontario) in 2009. A) Normalized difference vegetation index red (NDVI-R); B) Normalized difference vegetation index green (NDVI-G); C) greenness ratio (GR).

and two seasons with moderate precipitation in 2006 and 2008. The PCAs helped assessing those relationships.

1. Airborne remote sensing vs. ground-based measurements

Normally, ground-based and air-based VIs are well correlated (Lamb *et al.*, 2004; Johnson and Scholasch, 2005; Johnson *et al.*, 2003). NDVI values extracted from the airborne images were uncharacteristically low when one compares the maps illustrating spatial variability of ground- and air-based VIs (Figures 7-10). Air-based NDVI values normally range from -1 to +1, typically approaching unity for highly vegetated targets (Hall *et al.*, 2002) and the ground-based NDVI red values we observed were generally > 0.8. However, the air-based NDVI red values calculated were much lower, rarely > 0.3 and frequently < 0.2 (Table 5). Also, correlations depicted by the PCAs between airborne remote sensing and ground-based leaf reflectance were lower than expected (Lamb *et al.*, 2004; Johnson and Scholasch, 2005; Johnson *et al.*, 2003). In a few cases where a ground-based VI was a discriminating factor, the ground-based VIs were either positively or negatively correlated with those calculated from

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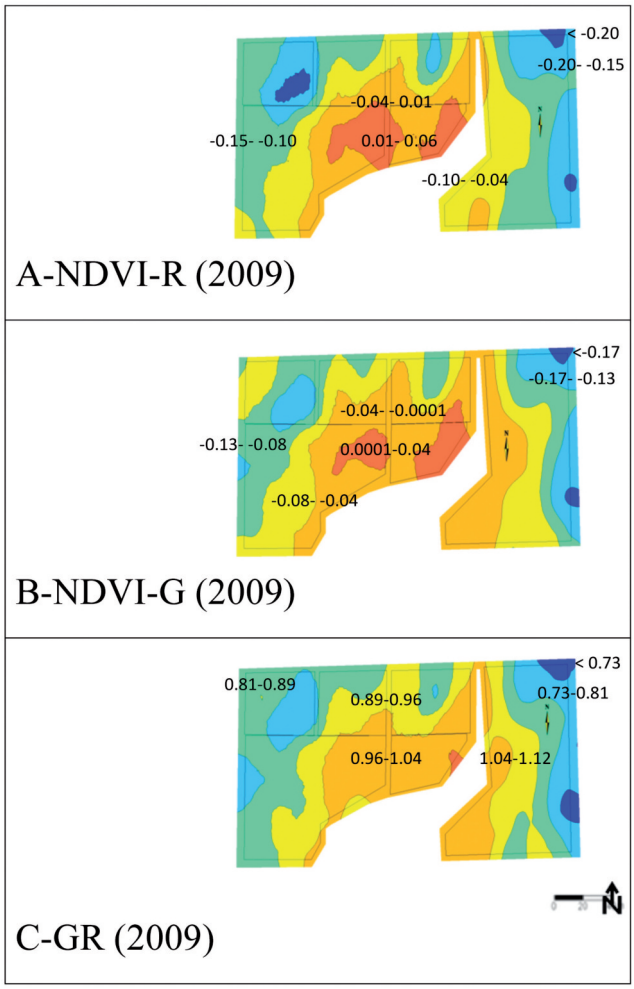


Figure 10. Vegetation index maps derived from airborne imagery acquired over six sub-blocks at Thirty Bench Winemakers (Beamsville, Ontario) in 2009. A) Normalized difference vegetation index red (NDVI-R); B) Normalized difference vegetation index green (NDVI-G); C) greenness ratio (GR).

airborne images. Two reasons may explain why the VI values were so different depending on the data collection method. First, the ROI used to extract band brightness values at each GPS vine location in the airborne image (i.e., 3 x 3 pixels) may have in most cases comprised a mix of vine canopy, floor vegetation and bare soil pixel values (da Costa *et al*., 2007; Hall *et al*., 2003; Lanjeri *et al*., 2004). The use of a multi-pixel ROI was necessary because vine trunks are not perfectly centred under the canopy, the canopy growth may be asymmetrical and the positioning of points used to locate vine trunks as well as the control points for image geo-referencing were subject to cumulative GPS inaccuracies. Data extraction based on 3 x 3 pixels in Australian vineyards (Lamb *et al*., 2004) would have likely comprised a greater proportion of vine canopy due to the wider canopies compared to the vertically-shoot positioned vines in this study. Second, only a small part of the leaf population was sampled during ground-based leaf reflectance data collection. Healthy, fully expanded leaves were randomly chosen, but the final sample was very small as measurements were made on only three leaves per vine. In an airborne image the entire canopy, including areas that may have been affected by disease or nutrient deficiency would be included. The combined effects of the two situations would be a systematic underestimation of the value of VIs extracted from the images in comparison with ground-based observations. A more acceptable ground-based option could have been use of a hand-held non-imaging wide band instrument or an apparatus similar to the GreenSeeker technology (Walsh *et al*., 2013). The problem with such an instrument is that an operator needs the same natural sunlight intensity from one data set to the other, which would have been difficult during vintages such as 2009. Poor correlations between ground- and air-based VIs have been observed when air-based data are collected early in the season (Lamb *et al*., 2004).

2. Relationships with vine and soil water status

Many studies have identified inverse relationships between VIs or other forms of thermal imaging (e.g. crop water stress index) and various metrics of vine water status (Acevedo-Opazo *et al*., 2008a,b; Moller *et al*., 2007; Taylor *et al*., 2010). Throughout the vintages during which airborne images were taken, all three showed negative correlations between airborne remote sensing and leaf ψ (a.v.) consistent with many others who have shown inverse correlations between NDVI and various metrics of vine water relations (Jones *et al*., 2002; Leinonen and Jones, 2004; Santesteban *et al*., 2013). An increase in leaf ψ (a.v.; low water status) suggests that the vines were potentially under water stress. In this case, the vine would have used mechanisms such as stomatal closure to conserve water. This phenomenon would have slowed down transpiration and raised the temperature of the leaves. Increase of temperature may have been related to an increase of red band reflectance (Jones *et al*., 2002). The reduction of transpiration would have also been accompanied by a reduction in photosynthetic activity, consequently a decrease of NIR reflection (Jones *et al*., 2002; Leinonen and Jones, 2004). This explains why negative relationships between leaf ψ (a.v.) and airborne remote sensing were generally observed. Weather conditions did not appear to have any effect on that relationship; once vine water status decreased

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Table 5. Ranges in variables Thirty Bench Vineyards, Beamsville, ON. 2006-2009.

Variable	2006	2007	2008	2009
Vine size (kg)[a]	----	0.06-1.7	0.03-3.3	0.06-1.9
Yield per vine (kg)[a]	0.5-11.9	0.1-7.5	1.0-11.1	0.08-7.3
Clusters per vine[a]	10-110	1-58	1-77	1-54
Berry weight (g)[a]	0.65-2.34	0.78-1.90	1.29-2.49	0.98-2.26
Brix[a]	14.4-24.0	15.2-23.3	12.9-25.2	16.9-21.2
Titratable acidity (g/L)[a]	7.8-13.2	6.5-12.5	8.0-14.9	6.9-12.7
pH[a]	3.01-3.67	3.13-3.63	3.00-3.79	2.93-3.68
Free volatile terpenes (mg/L)[b]	0.15-1.75	0.10-1.15	0.02-0.63	0.23-1.15
Potentially volatile terpenes (mg/L)[b]	1.17-4.13	0.92-3.98	0.75-2.64	1.46-4.88
Soil moisture (%)[a]	12.7-49.2	4.7-15.6	9.2-30.4	9.2-35.4
Leaf water potential (MPa)[b]	-1.34 - -0.65	-1.54 - -1.19	-0.81 - -0.47	-0.91 - -0.48
NDVI-red (ground-based)[b]	0.83-0.97	0.77-0.86	0.79-0.90	0.85-0.92
NDVI-green (ground-based)[b]	0.58-0.78	0.65-0.75	0.54-0.74	0.61-0.73
Greenness ratio (ground-based)[b]	3.71-8.22	4.25-6.58	3.35-6.71	4.18-6.52
REIP (ground-based)[b]	716-724	----	739-758	738-755
NDVI-red (air-based)[a]	----	-0.22-0.45	-0.19-0.38	-0.31-0.14
NDVI-green (air-based)[a]	----	-0.16-0.38	-0.21-0.28	-0.24-0.09
Greenness ratio (air-based)[a]	----	0.79-2.74	0.66-1.96	0.64-1.21

[a]Based on n=519.
[b]Based on n=134.

and stomatal closure took place, it could be seen on airborne images in terms of decreased VIs.

Soil moisture has normally been positively correlated to most VIs (Hall *et al*., 2002; Lamb, 2000), although soil conductivity (measured by EM38) may not be easily predicted using remote sensing (Bramley *et al*., 2011). Soil vs. VI relationships are known to be seasonally-based (Hall *et al*., 2002). Soil moisture in this study was positively correlated to airborne remote sensing variables in 2007 and negatively correlated in 2008 and 2009: it seems that there was a clear separation of dry/wet weather conditions. In 2007, plants were under drought conditions, so water uptake was limited. An increase in VIs occurred with increases in soil moisture. This was again due to reduced transpiration and photosynthesis in response to the drought. In 2008 and 2009, the opposite situation was found; soil moisture was generally extremely high. The high soil water content would have potentially restricted root activity due to an excess of water. Consequently, in those two vintages, a reduction in soil moisture was correlated to an increase of VI values: lower soil moisture permitted normal conditions in the root zone, allowing the plant to increase gas exchange. Increases in soil moisture would have resulted in excess water, reducing gas exchange.

Vine size or vine vigour (usually expressed as leaf area index) vs. VI relationships have been demonstrated by several researchers (Johnson, 2003; Johnson and Scholasch, 2005; Lamb, 2000). With respect to vine size, positive correlations were found between this variable and VIs in all three vintages. Therefore, regardless of growing conditions, a high VI value was always associated with high vine size.

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That observation was similar to those of others when assessing vine vigour using multispectral airborne imagery (Hall *et al.*, 2002, 2003; Homayouni *et al.*, 2008).

3. Relationships with berry composition

Clear relationships between VIs and berry composition variables are less common than those between VIs and soil moisture, vine water status, vine vigour and yield. Nonetheless, relationships were demonstrated between proximally-sensed VIs and fundamental berry composition variables such as soluble solids, TA and pH in a New Zealand Sauvignon blanc vineyard (Trought and Bramley, 2011). In this study, with respect to airborne remote sensing vs. berry composition and in particular Brix, TA and monoterpenes, an increase of the VIs was associated with an increase of canopy surface area and consequently an increase of the photosynthetic activity. That activity facilitated fruit maturity in case of dry or normal years. Consequently, positive correlations were observed between VIs and Brix in 2007 and 2008. If the growing conditions were anomalous (i.e., very wet), as in 2009, high VI values were associated with low Brix. Correlations between VIs and TA were the complete opposite. In 2008, TA was not a significant variable to discriminate the sub-block combinations. However, for the two other vintages, higher VIs were correlated to lower TA in 2007 and higher TA in 2009. During an anomalous year such as 2009, vines with higher VI values were characterized by poor fruit maturity (low Brix and high TA); if the conditions were extremely dry (e.g., 2007), a higher VI value meant that the plant was more physiologically active, so Brix was higher and TA lower (enhanced technological maturity).

Typically berry secondary metabolites are inversely correlated with NDVI. Total phenols and colour in Cabernet Sauvignon were both inversely related to NDVI (Lamb *et al.*, 2004). The last of the berry composition variables, FVT and PVT, were always associated with high VIs and therefore also to high vine size and photosynthetically-active vines. Monoterpenes are synthesized due to reactions catalysed by phenyltransferases, which ultimately produce geranyl diphosphate (Beale, 1991). Bouvier *et al.* (2000) also suggested that synthesis was photo-regulated. Therefore in order to maximize synthesis of monoterpene precursors, vines need maximum sunlight and sufficient canopy surface for sunlight capture. In this study, vines with larger canopies were characterized by higher VI values. Therefore, if the VIs were high, higher synthesis rates of monoterpene precursors was likely, with concomitantly higher berry FVT and PVT. This is what was found from 2007 to 2009. It seems counter-intuitive that monoterpenes were not related to technological fruit maturity (Brix, TA, pH). Airborne remote sensing might allow indirect assessment of potential monoterpene concentration of grapes, whereas assessing standard fruit maturity might require additional weather data (growing degree days, total sun exposure of the canopy, precipitation, soil moisture) to know if the current vintage is considered as wet, balanced or dry and if vines got enough quantity of light and heat to mature grapes.

4. Choice of flight date

Taking airborne images around mid-veraison should enable one to discriminate parts of a vineyard for vine size, yield and berry composition (Lamb *et al.*, 2004; Trought and Bramley, 2011). Based upon the various relationships observed between variables in this study, the following variables and optimum flight intervals are suggested: 1. Vine size: generally anytime; it was highly correlated with all the VIs throughout the growing season; 2. Yield: same as vine size; it can be assessed anytime, except very early in the season; it was correlated with all the VIs; 3. Berry monoterpenes: could be assessed using all the VIs, but only on images taken later in the season, i.e., August or September; 4. TA, pH: correlations with all VIs were highest in images taken around mid-season, i.e., July or August; 5. Brix: its pattern of correlation changed over time. A positive correlation with the VIs was observed in May/July 2008 and in August 2007 and a negative one in June 2007 and 2009. Therefore, overall it is advisable to take airborne images later in the season: this way vine size, yield, pH, TA and berry monoterpenes could be confidently assessed. Consequently, for ANOVA and PCAs, only the three VIs calculated from the last airborne images of the season were used, as well as their mean values. This was particularly noteworthy for August/September images, as these were very similar to the annual means.

CONCLUSIONS

Two hypotheses were proposed prior to starting this study. The first one was that vine water status and vine vigour would both be correlated to airborne remote-sensing data in the form of VIs. The second was that VIs derived from airborne remote-sensing data would also be correlated with berry composition: Brix, TA, pH and berry monoterpene concentration. With respect to the first hypothesis, correlations between vine size and airborne remote sensing were very strong and all VIs were excellent

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tools to assess vine vigour in all four vintages. High vigour vines generally had denser canopies, a feature which was easily observable on CIR images, so they were presumably more photosynthetically active. Correlative relationships between VIs and leaf ψ were generally very strong and not weather dependent. In general, lower leaf ψ (a.v.— higher vine water status) was associated with higher VI values. Under high vine water status, the vigour of those vines was also concomitantly higher. This relationship between water status and vigour was observable from multi-spectral airborne remote-sensing images. Regarding the second hypothesis, relationships between VIs fruit maturity components (Brix, TA and pH) and berry TVT were different. Strong correlations were found between vine size, VIs and TVT. For standard fruit maturity components, their relationship to airborne remote sensing was different depending on the weather conditions: in a normal to dry year, an increase of the VIs was associated with better technological fruit maturity (higher Brix and pH and lower TA). In a wet year it was the complete opposite: vines higher in VIs produced fruit with a lower maturity. This work is the first in Canada and eastern North America that has made use of airborne remote sensing in vineyards and the first work in North America that has shown putative relationships between remotely sensed variables and aroma compounds in grapes; however, it must be stressed that most R values did not exceed 0.5, despite p values of < 0.0001. These results suggest that remote sensing can help decision-makers in delineating zones within a vineyard where the fruit will be of a different maturity level, or more concentrated in aroma compounds. Those zones, delineated with airborne imagery, can be considered as terroir sub-blocks and could be processed separately in order to make wines that will reflect the effects of those terroir differences. The best time to fly over vineyards and collect images was veraison, ca. mid-August. Analysis of wines made from those different zones could show if they differ sensorially, particularly if fruit composition is different between sub-blocks.

LITERATURE CITED

Acevedo-Opazo C., Tisseyre B., Guillaume S. and Ojeda H., 2008a. The potential of high spatial resolution information to define within-vineyard zones related to vine water status. *Precision Agric*., **9**, 285-302.

Acevedo-Opazo C., Tisseyre B., Ojeda H., Ortega-Farías S. and Guillaume S., 2008b. Is it possible to assess the spatial variability of vine water status? *J. Int. Sci. de la Vigne et du Vin*, **42**, 203–219.

Beale M.H., 1991. Biosynthesis of C_5-C_{20} terpenoid compounds. *Natural Products Reports,* **8**, 441-454.

Best S., León L. and Claret M., 2005. Use of precision viticulture tools to optimize the harvest of high quality grapes. Proceedings of FRUTIC 05: Information and Technology for Sustainable Fruit and Vegetable Production. Montpellier, France. 12-16 September 2005.

Bouvier F., Suire C., d'Harlingue A., Backhaus R.A. and Camara J., 2000. Molecular cloning of geranyl diphosphate synthase and compartmentation of monoterpenes synthesis in plant cells. *Plant Journal,* **24,** 241-252.

Bramley R.G.V., 2005. Understanding variability in winegrape production systems. 2. Within vineyard variation in quality over several vintages. *Austral. J. Grape and Wine Res*., **11**, 33-42.

Bramley R.G.V., 2010. Precision viticulture: Managing vineyard variability for improved quality outcomes. Pages 445–480. *In*: Managing wine quality. Volume 1. Viticulture and wine quality. A.G. Reynolds (Ed.). Woodhead Publishing, Cambridge, UK.

Bramley R.G.V. and Hamilton R.P., 2004. Understanding variability in winegrape production systems. 1. Within vineyard variation in yield over several vintages. *Austral. J. Grape Wine Research*, **10**, 32–45.

Bramley R.G.V., Ouzman J. and Boss P.K., 2011a. Variation in vine vigour, grape yield and vineyard soils and topography as indicators of variation in the chemical composition of grapes, wine and wine sensory attributes. *Austral. J. Grape Wine Res*., **17**, 217-229.

Bramley R.G.V., Ouzman J. and Thornton C., 2011b. Selective harvesting is a feasible and profitable strategy even when grape and wine production is geared towards large fermentation volumes. *Austral. J. Grape Wine Res*., **17**, 298-305.

Bramley R.G.V., Trought M.C.T. and Praat J.-P., 2011c. Vineyard variability in Marlborough, New Zealand: characterising variation in vineyard performance and options for the implementation of Precision Viticulture. *Austral. J. Grape and Wine Res*., **17**, 83-89.

Brancadoro L., Failla O., Dosso P. and Serina F., 2006. Use of satellite in precision viticulture: the Franciacorta experience. *Proceedings of the VIth International Terroir Congres*s, p. 276-279.

Da Costa J.P., Michelet F., Germain C., Lavialle O. and Grenier G., 2007. Delineation of vine parcels by segmentation of high resolution remote sensed images. *Precision Agric*., **8**, 95-110.

Dimitriadis E. and Williams P.J., 1984. The development and use of a rapid analytical technique for estimation of free and potentially volatile monoterpene flavorants of grapes. *Am. J. Enol. Vitic*., **35**, 66-71.

©Vigne et Vin Publications Internationales (Bordeaux, France)

Guyot G. and Baret F., 1988. Utilisation de la haute résolution spectrale pour suivre l'état des couverts végétaux. *In: Proc. 4th Int Colloquium on Spectral Signatures of Objects in Remote Sensing*. ESA SP-287, T.D. Guyenne and J.J. Hunt (Eds.), January 18-22, 1988, Aussois, France, pp. 279-286.

Hardie W.J. and Considine J.A., 1976. Response of grapes to water-deficit stress in particular stages of development. *Am. J. Enol. Vitic*., **27**, 55-61.

Hall A., Lamb D., Holzapfel B. and Louis J., 2002. Optical remote sensing applications in viticulture - a review. *Austral. J. Grape Wine Research*, **8**, 37-47.

Hall A., Louis J. and Lamb D., 2003. Characterising and mapping vineyard canopy using high-spatial-resolution aerial multispectral images. *Computers and Geosciences*, **29**, 813-822.

Homayouni S., Germain Ch., Lavialle O., Grenier G., Goutouly J.P., Van Leeuwen C., Da Costa J.P., 2008. Abundance weighting for improved vegetation mapping in row crops: application to vineyard vigour monitoring. *Can. J. Remote Sensing,* **34**, Suppl.2, S228-S239.

Johnson L.F., 2003. Temporal stability of an NDVI-LAI relationship in a Napa Valley vineyard. *Austral. J. Grape Wine Res*., **9**, 96-101.

Johnson L.F., Roczen D.E., Youkhana S.K., Nemani R.R. and Bosch D.F., 2003. Mapping vineyard leaf area with multispectral satellite imagery. *Computers and Electronics in Agriculture*, **38**, 33-44.

Johnson L.F. and Scholasch T., 2005. Remote sensing of shaded area in vineyards. *HortTechnology*, **15**, 859-863.

Jones H.G., Stoll M., Santos T., de Sousa C., Chaves M.M., Grant O.M., 2002. Use of infrared thermography for monitoring stomatal closure in the field: application to grapevine. *J. Exp. Bot*., **53**, 2249-2260.

Koundouras S., van Leeuwen C., Seguin G. and Glories Y., 1999. Influence of water status on vine vegetative growth, berry ripening and wine characteristics in Mediterranean zone (example of Nemea, Greece, variety Saint George, 1997). *J. Int. Sci. Vigne Vin*, **33**, 149-160.

Lamb D.W., 2000. The use of qualitative airborne multispectral imaging for managing agricultural crops—a case study in south-eastern Australia. *Austral. J. Exp. Agric*., **40**, 725-738.

Lamb D.W., Hall A. and Louis J., 2002. Airborne remote sensing of vines for canopy variability and productivity. *Austral. Grapegrower Winemaker*, (**449**), 89-92.

Lamb D.W., Weedon M.M. and Bramley R.G.V., 2004. Using remote sensing to predict grape phenolics and colour at harvest in a Cabernet-Sauvignon vineyard: Timing observations against vine phenology and optimising image resolution. *Austral. J. Grape Wine Res*., **10**, 46-54.

Lanjeri S. Segarra D. and Melia J., 2004. Interannual crop variability in the Castilla-La Mancha region during the period 1991-1996 with the Landsat Thematic Mapper images. *Int. J. Remote Sensing*, **25**, 2441-2457.

Leinonen I. and Jones H.G., 2004. Combining thermal and visible imagery for estimating canopy temperature and identifying plant stress. *J. Exp. Bot*., **55**, 1423-1431.

Lillesand T.M., Kiefer R.W. and Chipman J.W., 2008. *Remote Sensing and Image Interpretation*, 6th Edition. Ed. Wiley. 756p.

May P., Clingeleffer P.R. and Brien C.J., 1976. Sultana (*Vitis vinifera* L.) canes and their exposure to light. *Vitis*, **14**, 278-288.

Möller M., Alchanatis V., Cohen Y., Meron M., Tsipris J., Naor A., Ostrovsky V., Sprintsin M. and Cohen S., 2007. Use of thermal and visible imagery for estimating crop water status of irrigated grapevine. *J. Experimental Botany*, **58**, 827-836.

Reynolds A.G., de Savigny C. and Willwerth J.J., 2010a. Riesling terroir in Ontario vineyards. The roles of soil texture, vine size and vine water status. *Progres Agricole et Viticole,* **127** (10), 212-222.

Reynolds A.G., Marciniak M., Brown R.B., Tremblay L. and Baissas L., 2010b. Using GPS, GIS and airborne imaging to understand Niagara terroir. *Progrès Agric. Vitic.,* **127** (12), 259-274.

Reynolds A.G., Senchuk I.V., Van der Reest C. and De Savigny C., 2007. Use of GPS and GIS for elucidation of the basis for terroir. Spatial variation in an Ontario Riesling vineyard. *Am. J. Enol. Vitic*., **58**, 145-162.

Reynolds A.G. and Wardle D.A., 1989. Impact of several canopy manipulation practices on growth, yield, fruit composition and wine quality of Gewurztraminer. *Am. J. Enol. Vitic*., **40**, 121-129.

Rodriguez-Pérez J.R., Riaño D., Carlisle E., Ustin S. and Smart D.R., 2007. Evaluation of hyperspectral reflectance indexes to detect grapevine water status in vineyards. *Am. J. Enol. Vitic*., **58**, 302-317.

Santesteban L.G., Guillaume S., Royo J.B. and Tisseyre B., 2013. Are precision agriculture tools and methods relevant at the whole-vineyard scale? *Precision Agric*., **14**, 2-17.

Sanchez L.A. and Dokoozlian N.K., 2005. Bud microclimate and fruitfulness in *Vitis vinifera* L. *Am. J. Enol. Vitic*., **56**, 319-329.

Stamatiadis S., Taskos D., Tsadilas C., Christofides C., Tsadila E. and Schepers J.S., 2006. Relation of ground-sensor canopy reflectance to biomass production and grape color in two Merlot vineyards. *Am. J. Enol. Vitic*., **57**, 415-422.

©Vigne et Vin Publications Internationales (Bordeaux, France)

Taylor J.A., Acevedo-Opazo C., Ojeda H. and Tisseyre B., 2010. Identification and significance of sources of spatial variation in grapevine water status. *Austral. J. Grape Wine Res*., **16**, 218-226.

Trought M.C.T. and Bramley R.G.V., 2011. Vineyard variability in Marlborough, New Zealand: Characterising spatial and temporal changes in fruit composition and juice quality in the vineyard. *Austral. J. Grape Wine Res.,* **17**, 72-82.

Trought M.C.T., Dixon R., Mills T., Greven M., Agnew R., Mauk J.L. and Praat J.-P., 2008. The impact of differences in soil texture within a vineyard on vine vigour, vine earliness and juice composition. *J. Int. Sci. Vigne Vin*, **42**, 67–72.

Turner N.C., 1988. Measurement of plant water status by the pressure chamber technique. *Irrigation Science,* **9**, 289-308.

Turner N.C. and Long M.J., 1980. Errors arising from rapid water loss in the measurement of leaf water potential by the pressure chamber technique. *Austral. J. Plant Physiol*., **7**, 257.

Turner K., 2001. Integrating remote sensing data with a GIS application for precision agriculture customers. *In: Proceedings of the 21st Annual ESRI user conference*. ESRI, Redlands CA.

Van Leeuwen C., 2010. Terroir: the effect of the physical environment on vine growth, grape ripening and wine sensory attributes. Pages 273-315. *In: Managing Wine Quality, Volume 1: Viticulture and Wine Quality*, Reynolds A. Ed., Woodhead Publishing Ltd., Oxford, UK.

Van Leeuwen C., Friant P., Choné X., Trégoat O., Koundouras S. and Dubourdieu D., 2004. The influence of climate, soil and cultivar on terroir. *Am. J. Enol. Vitic*., **55**, 207-217.

Van Leeuwen C., Trégoat O., Choné X., Jaeck M.-E., Rabusseau S. and Gaudillère J.-P., 2003. Le suivi du régime hydrique de la vigne et son incidence sur la maturation des raisins. *Bull. OIV*, **17** (867-868), 367-378.

Walsh O.S., Klatt A.R., Solie J.B., Godsey C.B. and Raun W.R., 2013. Use of soil moisture data for refined GreenSeeker sensor based nitrogen recommendations in winter wheat (*Triticum aestivum* L.). Precision Agric., **14**, 343–356.

White M., Johnson L. and Nemani R., 2001. Adding science to intuition: application of remote sensing and ecosystem modelling to vineyard management. *Australian and New Zealand Grapegrower and Winemaker, Annual Technical Issue*, **449**, 45-47.

Willwerth J.J., Reynolds A.G. and Lesschaeve I., 2010. Terroir factors: Their impact in the vineyard and on the sensory profiles of Riesling wines. *Progrès Agric. Vitic.*, **127** (8), 159-168.

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