REMOTE SENSING OF VINEYARD MANAGEMENT ZONES: IMPLICATIONS FOR WINE QUALITY

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ABSTRACT. *High–spatial resolution multispectral imagery was acquired at mid–season 1997 by an airborne digital camera system and used to establish management zones within a 3–ha commercial wine vineyard in California's Napa Valley. Image processing included off–axis brightness correction, band–to–band alignment, ground registration and conversion to a Vegetation Index to enhance sensitivity to canopy density. The image was then stratified by Vegetation Index and color–coded for visual discrimination. An output image was generated in TIFF–World format for input to mapping software on the grower's laptop computer. The imagery was used to delineate low–, moderate–, and high–vigor zones within the study block. Supporting field measurements per zone then included canopy structure (woody biomass, canopy transmittance), vine physiology (leaf water potential, chlorophyll content), and fruit biochemistry. Grapes from each zone were fermented separately and the resulting wines were formally evaluated for difference and quality. The low– and high–vigor zones were clearly distinct from one another with respect to most measurements. Block subdivision enabled the production of a "reserve" (highest) quality wine for the first time ever from this particular block.*

Keywords. *Remote sensing, Precision viticulture, Management zones, Vine vigor, Image processing, Geospatial technology.*

Winegrowers have known for centuries that grapes harvested from different areas in the vineyard can produce wines with different flavors. Even when such biological factors as variety, clone, and rootstock are identical, grape quality, maturity, and resulting wines are influenced by subtle differences in physical characteristics of the vineyard, to include soil type, microclimate, slope, exposure, soil water holding capacity, and drainage (Smart, 1985; Smart and Robinson, 1991; Wilson, 1998).

In certain regions of France, grapes have been grown for more than 1700 years. Vintners in these regions have had abundant time to understand how vintage varies throughout the vineyard, and generally, field boundaries have been established to minimize within–field differences in growing conditions. By contrast, the majority of vineyard development in California's Napa Valley has occurred since the mid–1960's. The valley tends to be characterized by relatively large fields ("blocks") that often encompass heterogeneous physical conditions. Growers tend to treat the entire block as a single "minimum management unit" for cultivation and harvest.

The goal of this study was to evaluate the use of airborne, digital, multispectral imagery for delineation of sub–block management zones. Imagery was used to divide a study block into zones of differing apparent vigor, field measurements of canopy and fruit attributes were obtained, grapes were harvested and fermented per zone, and wine evaluations were performed with respect to uniqueness and quality.

Our expectation was that the additional expenditure of labor and resources required for block subdivision might be rewarded in two ways. First, winemakers blend wines from different lots to create a desired taste and color in the final consumer product. Therefore, a greater number of distinct wine lots will provide the winemaker with increased latitude in blending options. Second, we speculated that increased uniformity of each individual wine lot might serve to increase quality. Either outcome would effectively increase crop value. Image processing methods were largely based on a previous study that applied remote sensing to monitoring of phylloxera (*Daktulosphaira vitifoliae* [Fitch]) infestation in vineyards (Johnson et al., 1996; Baldy et al., 1996; Lobitz et al., 1997).

METHODS

STUDY SITE

An operational 3–ha block of Chardonnay was selected for study. The block was part of Mondavi's 200–ha Carneros

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vineyard, located southwest of the city of Napa, California, at approximately 38° 15'N, 122° 22'W. The block was planted in 1991 on Haire series (clay–loam) soils. A multi–wire vertical trellis system was used. Rows were 2.4 m apart, oriented northeast to southwest; within–row vine spacing was 1.5 m. The block was clean cultivated, meaning that all undergrowth vegetation was removed.

Much of the Carneros property occupies hilly terrain. The study block was no exception, encompassing up to 45 m of relief along–row. The quality of the clone was high. However, the block was highly non–uniform due to topographically induced differences in drainage and microclimate, and as a result has historically produced fair to poor wines.

Airborne Imagery

Digital imagery was acquired for the vineyard on 31 July 1997 after completion of foliar expansion. An Airborne Data Acquisition and Registration (ADAR) System Model 5500 (Positive Systems, Inc., Whitefish, Mont) was used aboard a light aircraft. The system was comprised of four cameras, approximately boresighted. Each camera was fitted with a filter to record 8–bit imagery in one of the following spectral channels: blue (450–540 nm), green (520–600 nm), red (610–680 nm), and reflected (or "near") infrared (760–1000 nm). Spatial resolution was 2 m/pixel, given the nominal flight altitude of 4300 m above ground level. All imagery was collected under clear skies within two hours of solar noon.

An image frame centered on the study block was selected for processing and analysis. A correction was applied to compensate for brightness falloff as a function of distance from image center. This effect, which was introduced by the camera lens, was previously characterized in an optical calibration laboratory. Image–to–image registration was performed order to compensate for pointing inconsistencies among cameras and thus improve band alignment.

The atmosphere was assumed uniform above the entire study block and no attempt was made to correct the imagery for atmospheric effects. This assumption is reasonable when looking for relative differences within a localized area, and at a single point in time, as reported here. Compensation for atmospheric effects may become more of a necessity when comparing fields that are widely separated spatially, or in comparing the same field at different times of the growing season.

A normalized difference vegetation index (NDVI) was derived for each pixel (as [infrared–red]/[infrared+red]) to emphasize differences in the amount of leaf area per unit ground area (Tucker, 1979), commonly referred to by growers as canopy density. Canopy density is a function of both the horizontal (percent green cover) and vertical distribution (layering) of leaves. Automated classification based on the Iterative Self–Organizing Data Analysis algorithm (Duda and Hart, 1973) was used to assign each pixel to 1 of 12 groups based on NDVI. A previous study found that this simple approach yielded a reasonably strong relationship ($r^2 = 0.76$) to vine pruning weights, a measure of canopy density (Johnson et al., 1996). Each group was assigned a different color on the output "classified NDVI" image to enhance visual discrimination. Latitude and longitude coordinates were recorded along the perimeter of the test block with a Nav–5000 (Magellan Systems, San Dimas, Calif.) global positioning system (GPS). Readings from a U.S. Coast Guard beacon were used to compute positions with sub–meter accuracy. The GPS data were used as tiepoints to register the classified NDVI image to map coordinates. The image was then converted to TIFF format, with a "world file" for geo–referencing, and loaded onto a laptop computer with an integrated GPS receiver.

The NDVI image was taken to the field in early August 1997 to physically navigate and subdivide the study block into three management zones representing high, moderate– and low–vigor. Aspen software (Trimble Navigation, Sunnyvale, Calif.) was used to display the grower's position with respect to the image. Seven groups of five consecutive (within–row) vines from throughout the field were selected and flagged: two groups in the high– vigor zone, two groups (moderate), and three groups (low). Subsequent revision of zone boundaries based on *in situ* measurements resulted in the following distribution of sample vine groups: two (high), one (moderate), and four (low). Values reported herein are with respect to this revised configuration (fig. 1).

Canopy Transmittance

A Sunfleck Ceptometer (Decagon Devices, Inc., Pullman, Wash.) was used in the field to estimate the percent of photosynthetically active solar irradiance (400–700 nm) transmitted from top–of–canopy to mid–canopy per sample vine. This instrument has 80 light sensors placed at 1–cm intervals along a linear wand. The wand was exposed to direct sunlight to record ambient insolation (AMB) and inserted into the canopy of the sample vine to record canopy light levels (CAN). For CAN, the wand was positioned parallel to and midway between the first and second catch wires of the trellis, centered between the stakes. A bubble–level was used to maintain the wand level for all AMB and CAN readings. All recorded AMB and CAN values were the mean of five replicates taken within 10–15 sec. A maximum of ten minutes elapsed between AMB and CAN. Percent canopy transmittance (CT) was calculated for each sample vine as: CT(%) = (CAN/AMB) × 100. An inverse relationship was expected between canopy density (vigor) and CT. All measurements were made under clear skies on 25–26 August 1997, 10:00–11:30 A.M. local time.

Leaf Water Potential

A pressure chamber (PMS Instrument Co., Corvallis, Ore.) was used to measure mid–day leaf water potential (LWP), an indicator of water status, after the procedure of

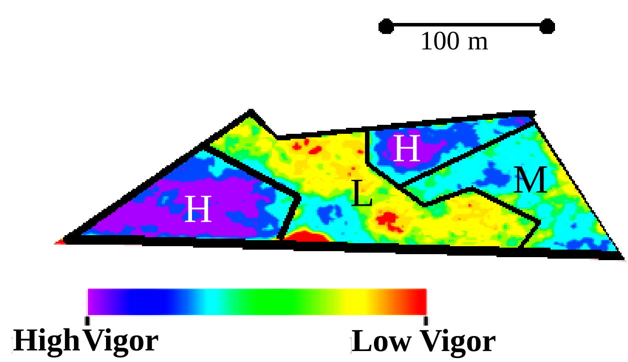

Figure 1. Study block with management zones defined by remote sensing and field measurements. Zones are low (L), moderate (M), and high (H) vigor.

Grimes and Williams (1990). LWP measurements were made on the center three vines from each sample group. Three leaves were sampled per vine. A sun–exposed leaf was detached and immediately inserted into the chamber with the petiole protruding. The chamber was pressurized with CO_2; the amount of pressure required to visibly force sap through the end of the petiole was recorded. Higher pressures (expressed as –Mpa) indicate greater water bonding and greater vine water stress. An inverse relationship was therefore expected between LWP (absolute values) and vigor. Measurements were made under clear skies on 25–26 August 1997 within 1 h of solar noon.

Leaf Chlorophyll

A SPAD–502 Chlorophyll Meter (Minolta Corp., Ramsey, N.J.) was used for *in vivo* measurement of the ratio of light transmittance through the leaf at two wavelengths: 650 nm (red) and 940 nm (near infrared). The instrument is a self–contained unit including illumination source and detectors. Instrument readings have been shown to be strongly related ($r^2 = 0.91$) to laboratory measurement of chlorophyll concentration in grape leaves (Baldy et al., 1996) and in several other species (Yadava, 1986). Measurements were made from the inter–vein portions of fully expanded leaves at top–of–canopy. Each leaf was characterized by the mean of six replicate measurements. Measurements were made under cloudy skies on 20 August 1997. A manila folder was placed in the solar path to provide further shielding from diffuse illumination.

Fruit Biochemistry

Measurements of brix (sugar), titratable acidity (TA), pH, and malic acid (MA) were made periodically by industry–standard procedures from early August until harvest. These measurements were made from juice samples of 150–200 grapes collected from 30–40 vines throughout each zone. Data reported here were collected on 5 September, 8 September, and 10 September 1997 for the moderate, low, and high zones, respectively, one day pre–harvest in each case.

Harvest

Harvest occurred 6 September, 9 September, and 11 September 1997 for the moderate–, low–, and high–vigor zones respectively. Grapes from each management zone were allocated to separate wine lots for barrel fermentation.

Biomass

Pruning weights (PW) were recorded for the sample vines in mid–December 1997, during the dormant season and after completion of leaf drop. All shoots produced during the growing season were counted, removed and immediately weighed with a field–portable scale. A short length of each shoot, containing two to three buds, was retained on the vine to support the following season's growth. Many growers find that PW gives a good, albeit retrospective, approximation of overall vine vigor.

Wine Evaluation

In February 1998, a panel of 15 enologists performed an industry standard blind taste test to evaluate differences among the study block wine lots. Three samples were involved: a known "reference" wine and two blind samples (hence the test name: "duo–trio"). Under the rules of this test, one of the blind samples was drawn from the same lot as the reference, and the other from a different lot. The evaluators were simply asked whether each blind sample was the same as the reference, or different. Statistical significance was associated with test results as a function of the number of evaluators participating.

In addition, the wine lots were evaluated with respect to overall quality according to the summary judgment of a single expert, the chief winemaker. Three general designations are used in this geographic region. Ranging from high to low in terms of quality and value, these are "reserve," "district," and "varietal."

Results

The vine measurements are summarized in table 1. Pruning weights, which are relied upon extensively in the wine industry, confirmed the vigor level zonation established with remote sensing. That is, pruning weights were was positively related to vigor level. A second biomass measure, canopy transmittance, also tended to confirm the zonation. As expected, canopy transmittance was greatest in the low–vigor zone; the moderate– and high–vigor zones were much lower and statistically inseparable. The number of shoots per vine was similar among zones, indicating that biomass differences were driven mainly by vigor of individual shoots. Leaf water potential measurements indicated that water stress was inversely proportional to vigor level. No significant differences were seen in foliar chlorophyll concentration, as inferred by measurement of leaf optical properties in the red and near infrared, indicating that the remotely sensed NDVI was responding primarily to differences in foliar biomass rather than leaf color.

The immediate pre–harvest fruit measurements are summarized in table 2. The only notable trend was in malic acid, levels of which in the high–vigor zone were some of the

Table 1. Vine measurements by management zone.

Variable	Vigor[a]	Mean (std. dev.)[b]	Sample Size
Pruning wt (kg)	L	0.65 (0.40)*	20
	M	0.79 (0.21)	5
	H	1.13 (0.48)*	10
Number of shoots	L	13.5 (2.5) **	20
	M	14.4 (1.7)	5
	H	14.3 (2.1)	10
Canopy transmittance (%)	L	39.9 (26.7)**	20
	M	11.5 (13.4)	5
	H	12.1 (11.3)	10
Leaf water potential (Mpa)	L	–1.2 (0.15)**	36
	M	–1.0 (0.1)*	9
	H	–0.9 (0.12)**	18
Chlorophyll conc. (unitless)	L	40.8 (2.8)	20
	M	39.3 (4.1)	5
	H	42.5 (3.8)	10

[a] L = low; m = moderate; H = high.
[b] *mean significantly different at .05 level,
**mean significantly different at .01 level, according to *a posteriori* F–test (Sokal and Rohlf, 1973).

Table 2. Fruit biochemistry by management zone, based on random samples of 150–200 grapes collected from 30–40 vines per zone.

	Low	Moderate	High
Brix (g/L)	24.2	24.0	23.8
TA (g/L)[a]	7.2	7.3	7.9
pH (unitless)	3.51	3.51	3.6
MA (g/L)[b]	3.94	4.60	5.51

[a] TA = titratable acidity.
[b] MA = malic acid. Note excessive level of MA in high–vigor zone.

Table 4. Programs to which wines produced from each management zone were assigned, as determined by a single enological expert, the chief winemaker.

Zone	Program[a]
Low	Reserve
Moderate	Reserve
High	District

[a] "Reserve" is the highest quality and value designation.

highest the winery had ever seen. Probably this resulted from excess canopy density and self–shading (Smart and Robinson, 1991). Elevated malic acid can result in immature–tasting grapes and a flat tasting, lower quality wine.

Results of the wine evaluations are shown in table 3. The duo–trio panel judged that the low and moderate wine lots were different ($p < .05$) as were the low and high lots ($p < .10$); the moderate and high lots were not shown to be significantly different. In a separate evaluation for quality (table 4), the low and moderate lots were judged to be of reserve quality and the high–vigor lot of lower, district quality.

Conclusions

Remotely sensed vegetation index imagery was used to establish sub–block management zones in a 3–ha commercial vineyard of Chardonnay wine–grapes. Subsequent ground–based measurements revealed a clear differentiation between low– and high–vigor zones with respect to biomass (primarily shoot vigor), vine water status, and most importantly, fruit and wine character. The relationship of the moderate–vigor zone with respect to the remainder of the block was ambiguous, with some measurements indicating greater similarity to low–vigor and some to high–vigor. These results suggested that the boundaries of the moderate–vigor zone either need adjustment, or the entire zone be dissolved and incorporated into the remaining zones. In fact, the latter is exactly what has occurred over the 1998–2000 timeframe.

Harvesting by vigor zones allowed for the extraction of unique wine lots from a block that was historically treated as a single management unit. This aspect alone has value in that the winemaker was provided with greater flexibility in the final blending process. More significantly, however, zonation allowed the production of reserve quality, highest value wines from the study block for the first time ever.

These results were achieved on a clean cultivated vineyard block. It is expected that the presence of green understory vegetation, in the form of a cover crop or extensive weeds, would complicate image interpretation. Due to typical summer drought conditions and widespread use of drip irrigation, however, understory is generally senescent by mid–to–late season in Napa vineyards. Thus, understory should not pose a problem for making relative, sub–block determinations in Napa Valley and similar wine-growing regions.

The winery, in concert with a commercial value–added remote sensing vendor, has continued to use annual late–season imagery for decision support over the 1998–2000 growing seasons. The technology is used primarily to establish and adjust sub–block management zone boundaries across ~500 ha of vineyard (both clean cultivated and otherwise) at Carneros and two other Napa Valley properties. Zone vigor is then influenced by various viticultural practices, such as adjusting the number of buds left at pruning, cultivating a cover crop, or adjusting the irrigation start–date. In addition to harvest management, other Napa Valley growers are evaluating the use of imagery to monitor irrigation, nutrient status, disease, pest infestation, and also to support new vineyard development (Carothers, 2000).

Table 3. Duo–trio blind taste test for differences among wines produced from management zones, as determined by panel composed of 15 enologists.

Zone Comparison	Different?	Significance Level[a]
Low vs. Moderate	yes	$p < .05$
Low vs. High	yes	$p < .10$
Moderate vs. High	no	

[a] Significance level gives probability, based on panel size, that wines from different zones are the same.

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