A 4D HIGH RESOLUTION VINEYARD SOIL ASSESSMENT FOR SOIL-HYDROLOGICAL INTERPRETATION IN COMBINATION WITH AUTOMATED DATA ANALYSIS AND VISUALIZATION TO MANAGE SITE-SPECIFIC GRAPE AND WINE QUALITY

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Abstract

A Visual Information eNvironment for Effective agricultural management and Sustainability (VINES) is under development, which can provide significant competitive advantages to winegrowers by sustaining their appellation-specific grape and wine qualities and yields while measurably conserving water resources. The system has been designed to validate, refine, and improve the Automatic Landform Inference Mapping (ALIM) soil modeling/ sampling method, and to define the key components for perennial crop production, in general, and wine grapes in particular. The feasibility of this novel technology has been validated through analysis of data collected to date through sensor deployment in West Coast vineyards and the development of highly resolved 4D soil maps that can visualize vine water availability. A comparison of predicted map-based water flow at several depths and locations vs. in-field sensor sampled values was conducted. The accuracy of predicted soil characteristics across vineyard blocks at several locations has been validated based on physical and chemical analyses and statistical comparisons. The first completed real-time spatial soil functional maps have been used to design visual analytics to create an effective decision-making environment applicable in commercial vineyards. Working directly with vineyard managers and winemakers, this integrated research and extension project has collaboratively developed an interactive, user-driven decision making environment that harnesses visual analytics to organize all the inputs from deployed soil sensors, high-resolution spatial soil function and water dynamic responses, while integrating all available historic and current data flows. VINES is designed to integrate future soil, plant, viticulture, and enological models into its decision support system to help respond to changing climatic and especially to drought conditions, and to improve general vineyard management, harvest scheduling, and long-term sustainability and life-cycle decisions.

Keywords: soil mapping, terroir, wine quality, plant water availability, visualization, decision-support

1 INTRODUCTION

"At last, and maybe above all, terroir is a state of mind, a humbler attitude in front of Nature …", a quote by Burgundian winegrower Jean-Yves Bizot of Vosne-Romanée from the 2nd Joint Burgundy-California-Oregon Winemaking Symposium, we organized in the winter of 1998/99 (Bizot, 1999). Those were the days just before global awareness of acute climate change, and its impact on wine grapes as the crop whose value is the most sensitive to minute differences in temperature profiles throughout the growing season, and the diurnal differences between night and day temperatures. It was a time when those who had grown grapes for generations already knew that the winds of change were blowing hard, from the warming caves of Rioja to the 360-year old vineyards of the Cape of Good Hope. Farmers knew that historic geographical distinctions by coordinates and quality-rankings from the mid-19th century might not be sufficient to address the changing composition of musts and wines, and the unprecedented physiological phenomena now observed throughout recent growing seasons. Appellation-based *typicité* had started to be over-powered by climate-driven vintage-to-vintage variation. The current prevalence of robust, indistinct, non-traditional blends marketed through an ever-multiplying array of generic brands in the industrial wine market, is a reflection of these changes. It is also a consequence of the rather small genetic differences within the *Vitis vinifera* varieties, the surprisingly close relationship between assumingly distinct varieties like Pinot and Syrah (Vouillamoz and Grando 2006), or Aligoté and Chardonnay (Myles et al, 2010).

Compressed growing seasons diminish the compositionally-relevant differences between early- and late-ripening varieties, and their more distinct varietal aromas. These changes explain the increasing inability of even the most experienced and thus least consumer-representative wine critics to confidentially identify varietal wines, not to speak of vintages or villages. Yet for the regions whose artisan wines and reputations have always been appreciated for their distinct sense of place, wine remains not a commodity but a piece of local art that has always eluded a scientific definition of quality.

While the "art and science" of wine is often mentioned together, today there still is no comprehensive scientific method to objectively define wine quality even just based on a total analysis of compounds and their relative concentrations and interactions (Boulton 1999, Jackson 2014). Even if it were possible, chemical and physical analysis would still have to be intertwined with our mental associations with an appellation or an appellation-necessitated style of wine. Artificial intelligence derived from big data analysis of wine production and consumption is making small steps to solving the problem; enlightenment that sadly would take away from the deliberate myth and magic that makes wine as a beverage so unique. Terroir today is both a mental attitude as well as a qualitative continuum that acknowledges a changing climate with its early harvests, its dropping water tables, increasing soil salinity and new pest pressures. Terroir cannot necessarily be seen any longer as a solely location-based concept. This static idea has always attracted critics to point out the difficulty to distinguish between turf-protecting marketing and true uniqueness of wine styles, aromas and textures.

We have to come to terms with the possibility that terroir may be a *temporal, moving target* that creates a certain type of wine in a certain location in a certain year. The now urgent need to use our remaining natural resources more conservatively and wisely is giving us the opportunity to explore and define the differences that geographical location, latitude and continental position, vintage degree days, topographical features such as vineyard slope, row orientation, aspect, altitude, corresponding sun and UV light exposure, soil pH and water holding capacity, soil compaction and water flow, drainage and plant water availability, soil depth, fertility and microbiome, nutrient distribution and flow, root and air temperatures, etc., may or may not make on the overall quality of the resulting local wine (Keller 2015).The holy grail of winemaking may be to understand the inherent difference between the $3 and $3,000 bottle of wine, grown just miles apart from each other (Butzke 2010).

However, the ability to measure and correlate alone is not enough to allow both grower and winemaker to maximize the potential of their terroir. The “big data” generated by sensors, and airplanes and drones, written down in notebooks and archived in spreadsheets and limbic systems, is too overwhelming to be useful during a busy harvest when decisions needs to be made fast and confidently. Running a vineyard and making wine on intuition, instinct, experience, and gut feeling alone is no doubt possible but requires higher risk-taking and may ultimately not be sustainable. As the intuitive mind is indeed a sacred gift, this project attempts to combine the vast knowledge that generations of winegrowers have acquired, with the most advanced sensing techniques available to create a visual interface that provides user-friendly real-time decision-support. Understanding what goes on deep underground below a vineyard, how water, nutrients, and pests move based on fundamental interpretations of soil profiles and climate data, can help validate the concept of terroir with unprecedented accuracy and predictive power. After all, it is what eventually is in the glass that will allow us to make the ultimate judgment about a unique appellation, or vintage, and the distinct typicity of an individual wine.

To address the current and future needs of winegrowers, a Visual Information eNvironment for Effective agricultural management and Sustainability (VINES) is under development, which can provide significant competitive advantages to winegrowers by sustaining their appellation-specific grape and wine qualities and yields while measurably conserving resources. The system has been designed to validate, refine, and improve the Automatic Landform Inference Mapping (ALIM) soil modeling/ sampling method (Frank *et al.*2014, Goodman *et al* 2013, Zhu 2010), and to define the key components for perennial crop production, in general, and wine grapes in particular. The feasibility of this novel technology has been validated through analysis of data collected to date through sensor deployment in West Coast vineyards and the development of highly resolved deep soil maps that can visualize vine water availability in real-time. VINES’ decision support software system is based on the latest sensing technology (*in-situ*) to enable producers, field managers, and winemakers to manage soil moisture, pruning, irrigation, canopy management, and water conservation to increase production efficiency quality and crop sustainability, while reducing variability in production within a field and across seasons. This sensor network combines moisture and temperature sensors to remotely track the availability and characteristics of soil moisture and temperature at a high level of data resolution throughout the crop root zone and soil profile. The network makes possible to provide a 3-dimensional assessment of water movement through the soil and across the vineyard making it possible to respond to spatial and temporal variations in real time. This information can help producers plan and minimize the costs of cover crop decisions, irrigation and other management practices. The resulting large volume of environmental sensor data were analyzed and transformed using visual analytics (Thomas and Cook 2005) into a useful interactive software decision making environment using easily understood visual metrics and graphics. Growers, vintners and vineyard managers have been directly involved in the identification of their information needs and critical crop management decision points. The testbeds have been located in California within the Napa Valley American Viticultural Area, California, at Robert Biale Vineyards (Napa, CA) and Tres Sabores Winery (Rutherford, CA).

2 MATERIALS AND METHODS

SOIL MOISTURE AND TEMPERATURE SENSORS: We have used commercially available time domain reflectometry soil moisture and temperature sensors (Decagon 5TM) to obtain accurate soil moisture and temperature readings for each soil horizon. Three to five depths are selected based on the site, root stock, top depth of anaerobic zone, and the horizon depths to accurately capture moisture and temperature characteristics in the primary root zone. This has typically been down to at most 9 feet in Napa valley. These sensors are connected to data loggers that record readings every 15 minutes and upload the data multiple times per day via cellular transmission.

WEATHER STATIONS: We collect wind, solar radiation, temperature, humidity, vapor pressure, and precipitation information at each weather station again at 15 minute intervals.

SOIL MAPPING ALGORITHMS: VINES utilizes Owens' proprietary ALIM algorithm that is based on pattern recognition from terrain algorithms and legacy data from the USDA Soil Survey (See Figure 1A upper left for an example of a USDA Soil Survey map for a 10 acre vineyard). This process is used with no point data input and relies on statistically derived terrain patterns and legacy information to create the Version 1 map (See Figure 1A upper right for an example). This can then be used to interpolate soil moisture (see Figure 1A lower-right) and grape composition properties. A comparison of spatial interpolation vs. soil property-based interpolation can be seen in Figure 1B. The soil mapping method combines automatic landform classification with fuzzy logic inference mapping (Zhu 2010). With a limited number of point data, the model can be refined and improved with a minimum number of samples to create improved versions of the soil map, generating soil class, composition, and topographic wetness index maps (See Figure 1A lower left for an example). Additionally, based on the selected patterns in the landscape, a minimum number of point samples and best possible locations for additional sensors can be determined (the most representative areas of determined soil classes).

This ALIM approach is based on fundamental soil knowledge and concepts as background assumptions in the modeling process. The method uses DEM derived terrain attributes, such as slope, topographic wetness index and geomorphons in combination with algorithm classified landform delineations to define membership rules used in the fuzzy logic modeling process to generate the functional soil map used for data interpolation.

DATA VISUALIZATION APPROACH: Working directly with producers, field managers, and winemakers, we collaboratively developed an interactive user-driven decision making environment that harnesses visual analytics to organize all the input from the deployed soil sensors, high-resolution soil maps and transport models, available data flows, and new soil and enological models into a the decision support system to help them improve crop management, production scheduling, and multi-year sustainability decisions. The current software prototype is built upon our spatiotemporal visual analytic suite of tools (e.g., Afzal *et al.* 2011) with patented predictive temporal analytical techniques. The software is written in C++, Java, and OpenGL and is being transitioned to a web-based platform based on WebGL, HTML5, D3, and associated libraries.

GRAPE ANALYSES:
The following conventional grape and wine analyses and calculations were performed by ETS Laboratory (St. Helena, CA): Titratable acidity, pH, L-malic acid, Brix, glucose + fructose, ammonia, alpha-amino compounds, yeast assimilable nitrogen, catechin, quercetin glycosides, tannin, polymeric anthocyanins, total anthocyanins, catechin/tannin index, polymeric anthocyanins/tannin index, berry weight, sugar per berry.

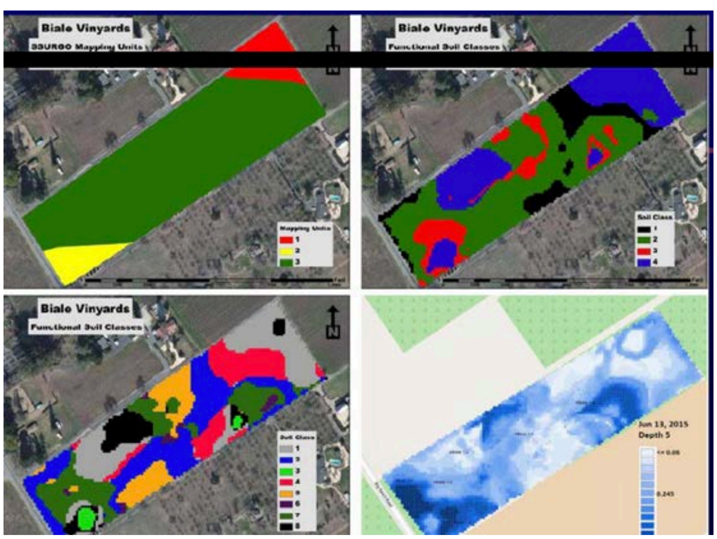
WINE SENSORY ANALYSIS:
Wines made from the respective vineyard blocks were evaluated by descriptive sensory analysis typical in commercial winery settings. All wines were assessed by the winemaker, winegrower, enologist and collaborators in respect to color, phenolic structure, acidity, and other flavors by mouth, perceived mouthfeel, and volatile aromas by nose and retronasal olfaction. In global absence of either scientifically valid yet commercially practical descriptive analysis techniques, or comprehensive, quantitative chemical analysis methods for wine, this subjective yet ultimately deciding wine quality assessment remains the only empirically feasible way to connect grape quality with wine quality and value in the market place. In the future, when a full flavoromics/chemiomics approach has been developed, its integration into VINES will be implemented.

3 RESULTS AND DISCUSSION

As mentioned above, we have deployed our technology and software at two wineries and three vineyards in Napa Valley. Our first deployment was in two vineyards owned by Robert Biale Vineyards and Winery in 2014 and we have collected data and worked with the Biale team for two seasons giving insights into deep available soil moisture, effectiveness of irrigation strategies, and within block soil, moisture, and grape composition variability. One vineyard is dry-farmed (head-pruned Zinfandel field blend planted in 1938) and the other is mainly dry-farmed (deficit irrigation) – trellised Zinfandel planted in the 1990's. Both are in the Oak Knoll AVA. Our second partner winery was added in Spring 2016 and is a hillside to valley dry-farmed Zinfandel and Cabernet vineyard in the Rutherford AVA that is the estate vineyard of Tres Sabores Winery. We have worked with the Tres Sabores team giving insights into deep available soil moisture, canopy management within block soil, moisture, and grape composition variability. With both partners we have done cluster collection and analysis (see above) near the sensor locations at veraison and on the day of harvest. At Tres Sabores, they have additionally done small lot fermentation of the grapes near each sensor location that has then undergone both sensory and chemical analysis after the wine was through malolactic fermentation. We did similar chemical and sensory wine evaluation of larger lots at Biale where the lots were mainly comprised of grapes (over 80%) from different blocks where we had available sensor data.

As a reference for the terroir characteristics of this particular vintage, below is an example of the compounded tasting notes for five of the blocks we monitored to illustrate the diversity of the sites. Two separate blocks were tracked for this sensory and analytical analysis. Both of these blocks are located at the Robert Biale estate vineyard which is located in the Oak Knoll District AVA of Napa Valley. Block A was located at a specific soil sensor and Block B at another soil sensor. Sensors are located within a few hundred meters of each other but in different soil profiles. After tracking each block throughout the growing season and using the soil moisture data to determine best irrigation practices, we decided to run specific analysis on each individual block. Full cluster samples were taken from both blocks from a single vine located directly next to the soil sensors. These samples were taken at full ripeness just prior to harvesting the blocks on August 7th, 2015. The chemical analyses showed very similar numbers for both blocks. On December 7th, 2015 another set of analyses were run on the same two lots of wine. The results of these analyses showed different numbers due to chemical changes in the wines through maturity. However, the numbers from each block showed little to no variance from one another. Sensory analysis of the wines showed that there was a commercially significant difference in the aromas, flavors and mouthfeel of each of the wines. Note that the processing of these two wines were exactly the same from fermentation vessel, fermentation temperature, yeast stain used, pressing and cooperage selection. These are descriptions for young and unfinished, unblended wines, and thus must be compared as such:

- Block A: Medium purplish color with light tannins, great mid-structure with a long finish that was a little bit drying at the very end, fresh acidity, balanced alcohol, fine overall balance. Fruit aromas of candied black cherries, cooked strawberry compote. Savory notes of smoked speck, raw bacon, glazed ham. Spicy notes of tar and licorice.
- Block B: Slightly darker than Block A. Less drying tannins than Block A. Stronger alcohol. Very good balance. Fruit aromas aromas of blueberry as well as bright red fruits: pomegranate, rhubarb, and bing cherries. Spicy, savory notes of rosemary, sage, crème brulee, dill pickle potato chips, cloves, celery salt, baking spices, and cola. “Juicy, racy, attractive”, aka “süffig” (German), “coulant, gouleyant, glissant” (French), “passante” (Italian).

(A) 

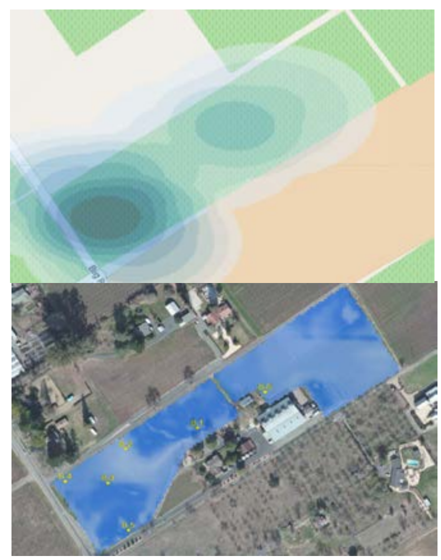
(B) 

Figure 1 (a): Algorithm-Improved ALIM Soil Moisture Map. Top-left is the USDA SSURGO soil map. Top-right is the version 1 soil map created using the ALIM algorithm. Lower-left is the refined soil map based on in-field soil analysis data. Bottom-right is 5 ft soil moisture map based on the final functional soil map (right image).
Figure 1(b): Top is moisture interpolated using traditional spatial interpolation (kernel density estimation) and the bottom is the result of using our soil property-based functional soil maps.

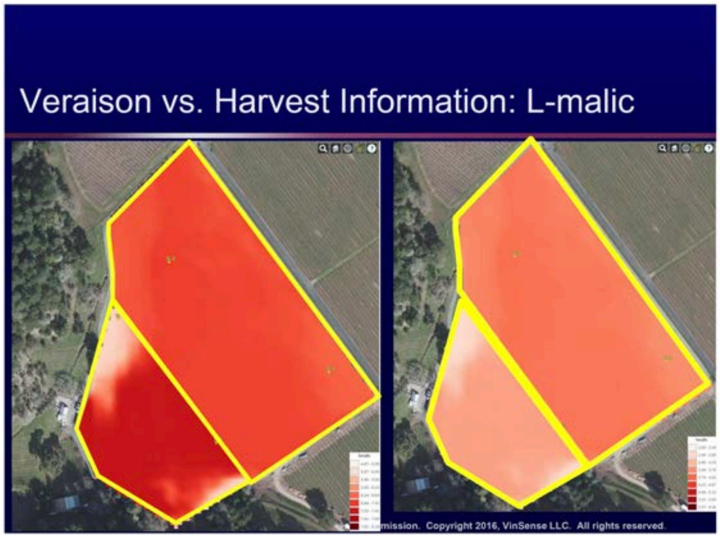


Figure 2: Grape Berry Malic Acid Concentration at Veraison (Left) vs. Harvest (Right) at Tres Sabores Vineyard in 2016. The right-most block in each image is cabernet and the left is Zinfandel. Notice the more uniform malic acid readings at harvest after canopy management practices based on precise deep soil moisture information was utilized.

Figure 3: 4D water flow map at Tres Sabores Vineyard.

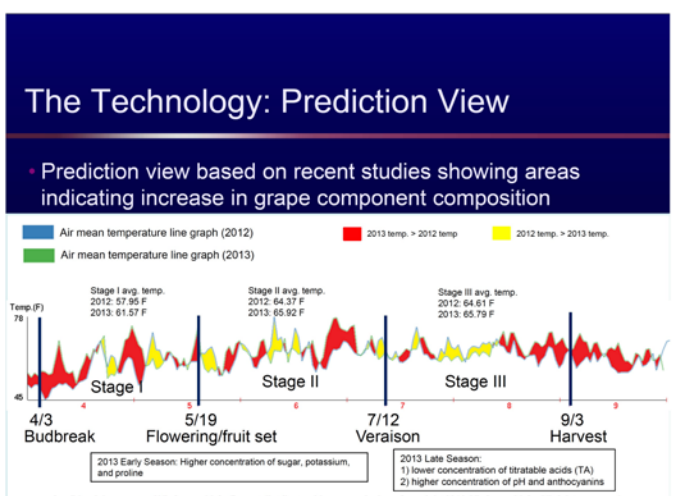


Figure 4: Predictive modeling of seasonal winegrape composition.

4 CONCLUSION

Our approach to visualize complex sensor and mapping data in a clean, intuitive user interface has let to several competitive advantages for commercial grape growers who collaborated in this project:

1. Early harvest date predictions within two days of actual harvest.
2. Deep soil water availability awareness unrelated to traditional surface moisture observations (Figures 1 and 3).
3. Vintage-to-vintage grape composition predictions allowing for stylistic and blending winemaking decision-support (Figure 4).

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