Experiment 5 Conclusions

- EM data correlated to Ksats in areas where drainage rates were influenced by clay content
- Macropore flow is a common phenomenon in vineyard soil hydrology, and appears to impact Ksat results at some of our test sites
- Low ground conductivity does not necessarily indicate fast drainage
- High ground conductivity does not always indicate slow drainage
- Multiple Ksats measurements should be made to assess for representative results
- Ground-truth data is critical for understanding subsurface variability as it relates to geophysical data

Experiment 6: Electromagnetic Induction in All-Steel Vineyards

The primary limitation of mapping soil EC with electromagnetic induction for viticultural applications is that steel posts distort readings. Throughout data collection, metal trellis wires alone were not observed to negatively interfere with conductivity data as long as the vineyard had wooden posts. EM data collected in all steel vineyards produced distorted conductivity maps with a distinct overprint pattern seen in each dataset (low conductivity on the ends of the rows, grading to high conductivity in the center as seen in **Figures 18-22**). Steel posts in combination with metal trellis wire and soil with substantial amounts of clay and/or moisture create conductivity loops, amplifying apparent conductivity values measured by EMI (Lamb 2009). Wooden posts are insulators and help prevent this phenomenon from occurring.

Experiment 6 Results

Some EM maps from steel vineyards did accurately depict important soil variations (although they still have the distinct overprint pattern on the maps); others were completely dominated by the electromagnetic noise. Based on conversations with growers, the amount of electromagnetic noise present in all-steel vineyards depends on a number of factors including vineyard size, row spacing, and amount of wire utilized in the trellis system.

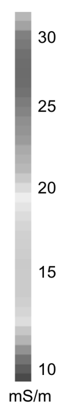


Figure 18 - EM conductivity map from Chester Gap Cellars, Rappahannock County. Classic steel vineyard overprint (low on the north and south ends, high in the middle) masking variations in soil EC.

Figure 19 - EM38 Conductivity Map from Chester Gap Cellars, Rappahannock County. Smaller vineyard with about half as much trellis wire used compared to Figure 19, according to grower. Here, the hot colors represent groundwater seepage from the toe of a large slope, with the exception of the highest conductivity anomaly near the eastern edge of the survey, which represents an area with high clay content (based on field observations). This steel vineyard was successfully imaged with EMI, but as with all other datasets collected in steel vineyards, the familiar overprint can be seen here and may mask important soil variations.

Figure 20 - Familiar overprint from steel trellising seen on EM conductivity map from an all-steel vineyard at Early Mountain Vineyards in Madison County. Any variations in subsurface conditions are masked by the noise created from the all-steel trellising.

Figure 21 - EM conductivity map from an all-steel block at Linden Vineyards in Fauquier County. Overprint seen to mask soil EC variations here as well. A wide range of conductivity values is noted.

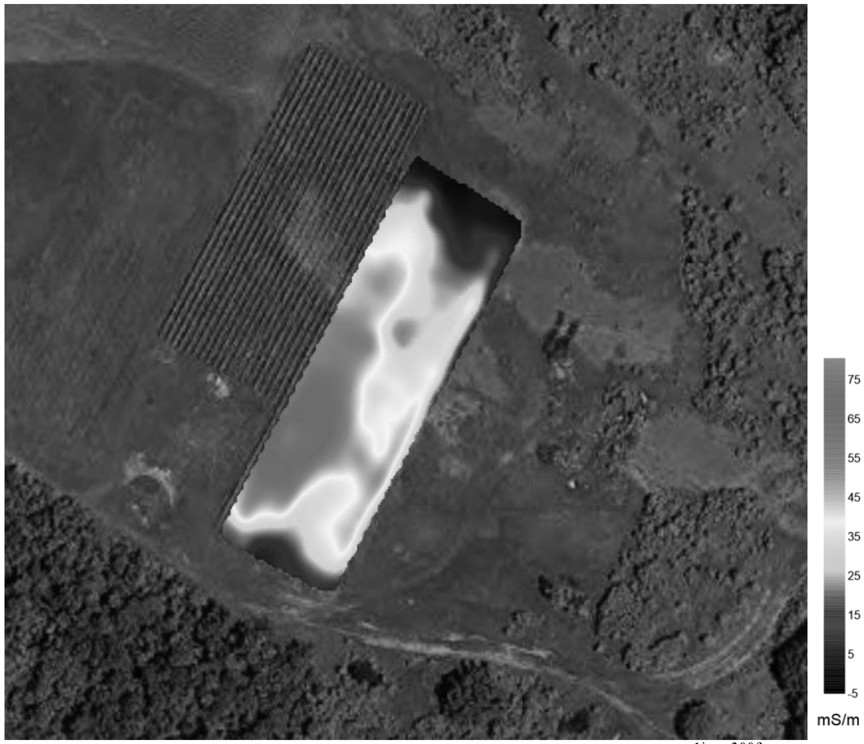


Figure 22 – EM conductivity map from an all-steel vineyard in Albemarle County, Virginia. A wider row spacing makes for a more useful EM38 dataset in this steel vineyard block as correlations to soil properties were noted; however, the overprint of the steel noise is still apparent on the map and may mask important soil EC variations. A wide range of conductivity values is seen here as well.

The presence of electromagnetic noise in all-steel vineyards is the primary limitation of EM mapping for viticulture. **Experiment 7** (p.21) discusses an alternate soil EC data collection method (Direct Contact, or DC) that measures current between two electrodes in the soil. Although DC soil conductivity mapping has its own limitations, it shows potential as a substitute for EM in all-steel vineyards.

Experiment 6 Conclusions:

- Steel posts distort EM data
- Amount of electromagnetic noise in all-steel vineyards depends on the amount and height of trellis wire, density of metal posts and row spacing
- Wooden posts act as insulators and prevent (or at least significantly dampen) electromagnetic noise
- EM data can still be useful in all-steel vineyards if a low level of noise is encountered
- Development of a different method to collect soil EC data in steel vineyards is warranted

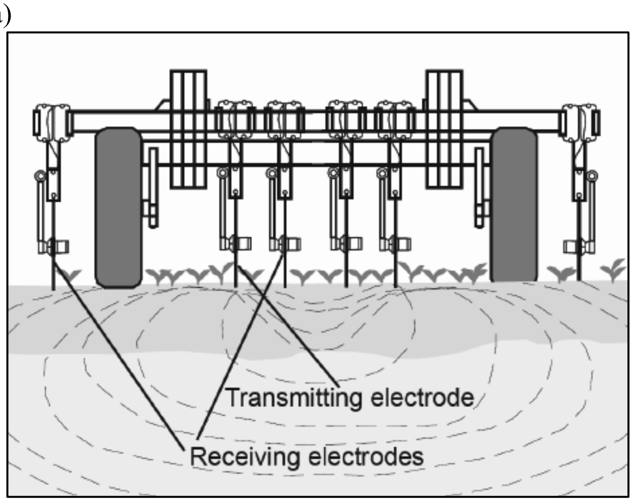
Experiment 7: Direct Contact Conductivity Mapping

This experiment implements unique testing methodology, so additional background and methods are discussed herein.

Direct Contact (DC) conductivity mapping is an emerging technology in the field of precision agriculture and is perhaps more common among agronomists than EM. It uses the same subsurface electrical properties to give indications of soil type, but implements a different principle of operation to measure soil EC (**Figure 23a**). This experiment investigates the use of DC vs. EM mapping for viticultural applications in Virginia.

DC data were collected with the Veris EC Surveyor 3150 and EM data were collected with the Geonics EM38-MKII. Our findings suggest that while each method does have limitations (**Table 6),** strong ground conductivity datasets can be collected with both the EM and DC methods under good conditions and DC may be the preferred method in all-steel vineyards. However, much of the DC conductivity mapping currently available commercially threatens to result in poor site characterization for viticulture. It is the depth of measurement, conceptual interpretation, and methods of processing the raw soil EC data (not the conductivity sensor itself) that can lead to potentially flawed vineyard site interpretations.

a)



b)

Figure 23 – a) Principle of operation for the direct contact (DC) conductivity mapping sensor. Coulters act as transmitting and receiving electrodes. (Veris Technologies, Salina, Kansas and Grisso 2009) The soil EC data are continuously logged along with geographic coordinates throughout the survey. b) Veris Soil EC Surveyor 3150 towed behind tractor at a Central Virginia vineyard.

Automated Processing vs. Gridding and Contouring Soil EC Data

The use of geophysical methods for agricultural applications is a relatively new concept, having only been widely adopted by the agriculture industry for the past couple of decades (Taylor and Whelan, 2010). In recent years, direct contact soil EC surveys have become quite popular among agronomists who use the maps to guide soil sampling and nutrient management programs. Most agronomic software packages designed for EC data processing were developed for row crops and appear to be effective for corn and soybean farming, but lack the level of detail and finesse desired for quality winegrowing.

The typical agronomic approach to soil EC mapping falls short for viticultural applications for three main reasons:

- First, processing of soil EC data by many of the standard agronomic software packages is entirely automated. The raw data are loaded into the program, which automatically produces a map representing conductivity zones. The program selects zone boundaries based on statistical analyses of the raw data. No site observations such as topography, vegetation, soil texture, landscape position, depth, parent material, hydrology, soil color changes, etc., are incorporated into the zoning interpretations.

- Second, the DC mapping methods employed by many agronomists were developed for shallow-rooted crops and many of the machines implemented for soil conductivity surveys only have the capability to measure EC down to about 12". The goal in quality winegrowing is for the vines to be deeply rooted; if a winegrower is considering mapping his or her soil EC, depth of measurement of the instrument should be strongly considered. For winegrowing, EC maps should be produced for both shallow and deeper horizons (down 5 or more feet) to investigate for significant variability as a function of depth. Soil samples and subsurface analysis should reflect the depths of interest (and deeper, if possible) to formulate robust interpretations.

- Third, soil EC maps are too often based on generalized assumptions that the variability in conductivity values is caused by the same factors at each site. The numerous trials presented in this work illustrate that each dataset should be interpreted individually and with an open mind as a number of geologic scenarios can lead to similar conductivity readings (and similar geologic scenarios can have different geophysical signatures, too for that matter).

The geoscientist's approach to geophysical data processing and interpretation originated with spontaneous potential surveys for copper prospecting by Robert Fox in England in the 1830s. Modern approaches to geophysical data collection, processing and interpretation have been developing among the mainstream geophysics and geology community since the 1920s (Reynolds 1997). The geoscientist typically displays gridded soil EC data as color contour maps, often viewing the data under many different color schemes and displays to visually assess for any areas that may stand out. Analysis of mapped raw data is an important step to assess for misleading gridding artifacts. This approach allows the professional to define soil zones (if appropriate) and make site interpretations based on a large number of factors other than statistically selected boundaries. The geoscientist relies heavily on ground-truth data for map interpretations because a number of factors is known to influence soil EC values.

a) b) c)

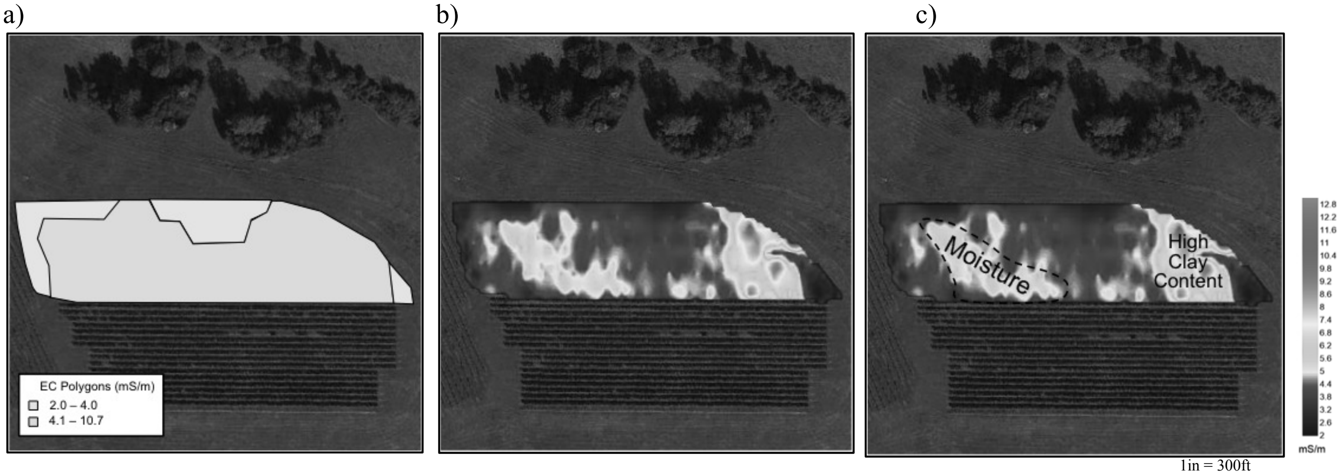


Figure 24 – a) Example of soil EC zone map collected with a DC sensor and processed with automated software. Note that each EC zone (automatically selected by the program) contains a range of EC values, masking variability that may occur with each zone. b) Soil EC data collected with a DC sensor and processed with gridding and contouring software designed by geologists. The geoscientist has the control to adjust color contouring to visually draw out features of interest on the map, resulting in an EC map that is more representative of subsurface conditions. c) The same map as 25b with interpretations based on ground-truth data.

Figure 24 compares DC datasets from a Virginia vineyard processed with common automated methods (**Figure 24a**) to DC data from the same vineyard processed by gridding and contouring methods controlled manually by a geoscience professional (**Figure 24b and c**). **Figure 24b** shows much more detail in subsurface variability than does **Figure 24a**. Backhoe pits were used in this study area to ground-truth the geophysical data and interpretations of the dataset are shown on **Figure 24c**.

The grower at this site has experienced poor vine performance in the area delineated with a dotted line on **Figure 24c**. Use of the automated EC zoning methods shown in **Figure 24a** would not have revealed the potential cause of the grower's problem. The contoured dataset in **Figures 24b and c** shows a distinct med-high conductivity feature in the area of concern, which was confirmed to represent an area of high soil moisture based on backhoe pit observations and soil sample analysis. The geologist's approach to soil EC data processing and interpretation shed light on a likely cause of this grower's vine performance issue.

Trial 1: EM vs. DC Soil EC Mapping

We compared EM mapping to DC conductivity mapping in two different vineyard blocks at Pollak Vineyards in Greenwood, Virginia. The study vineyards have wooden posts with metal trellis wire and a 10-foot row spacing. The objective was to determine whether the two methods would produce similar results when the data were processed using the same gridding software and contoured using identical color schemes. EM data were collected in September 2013 and DC data were collected in early June 2014, so some variability between surveys due to seasonal moisture changes is expected. Quantification of the moisture changes between surveys was beyond the scope of this project; however, as **Figures 25 and 26** illustrate, repeatability in soil EC measurements was achieved using the two methods.

Figure 25 a) EM conductivity map. b) DC soil conductivity map.

As seen in **Figure 25**, both methods imaged the significant high conductivity anomaly in the southwestern portion of the survey area and the NE-SW trending med-high conductivity area extending northeast from it. Both methods show the southeast corner of the survey as lower conductivity relative to the aforementioned high conductivity features. EM data show the area along the northern edge of the survey as high conductivity, while the DC dataset shows the same area as low conductivity. Ground-truthing would be required to determine actual site subsurface characteristics at this specific location.

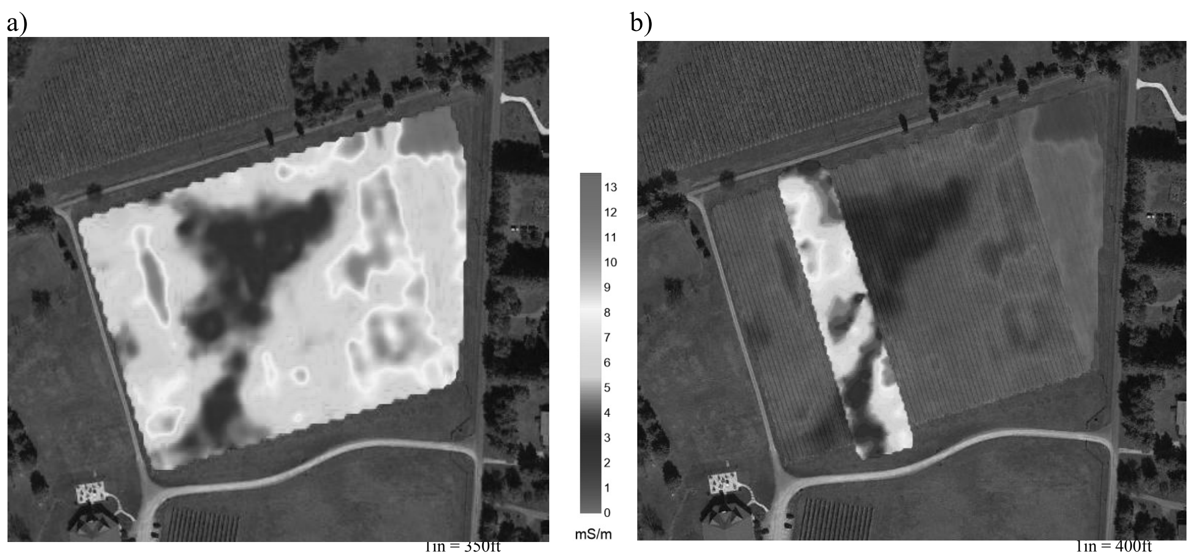


Figure 26 – a) EM conductivity map of 10-acre research block at Pollak. b) EM map faded with DC conductivity survey data overlain on top. DC data collection did not cover the entire EM survey area because of width restrictions.

Figure 26 shows that both methods produced similar results in the second area tested. DC data were not collected across the entire EM survey area because of width restrictions and the concern of damaging the canopy.

Trial 2: EM vs. DC in an All-Steel Vineyard
Australian researchers have reported that steel posts in combination with trellis wire and site soils create conductivity loops that amplify EM conductivity readings, masking important soil EC variations (Lamb 2009). As discussed in **Experiment 6**, we had similar results in Virginia at research vineyards with steel posts. The purpose of this trial is to compare DC and EM conductivity maps in an all-steel vineyard to assess for the most reliable soil EC data collection method in established vineyards with steel posts.

EM data were collected in September 2013 and DC data were collected in June 2014. The vineyard block consists of steel posts with metal trellis wire and a 12-foot row spacing.

When processed with identical gridding parameters (ordinary kriging) and color-contouring scheme, the DC conductivity sensor appears to collect more representative soil EC data than EM in this all-steel vineyard in Albemarle County. The familiar overprint pattern seen in other EM maps from all-steel vineyards appears in the EM map from this Albemarle County site, but is absent in the DC conductivity map of the same vineyard block (**Figure 27**).

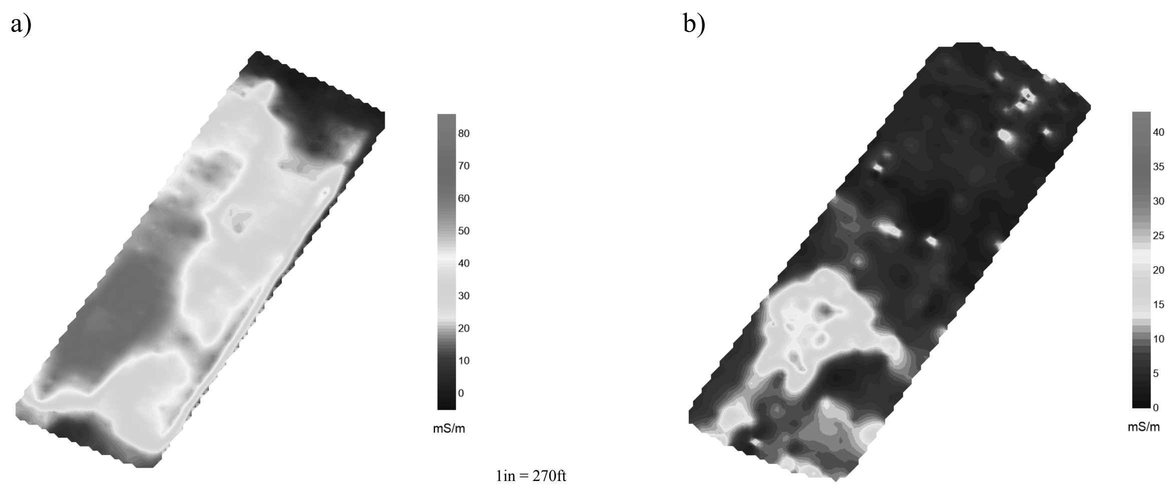
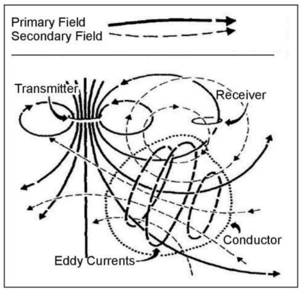
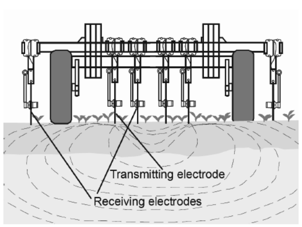


Figure 27 – a) Noisy EM conductivity map from an all-steel vineyard with a 12-foot row spacing. b) DC conductivity map from the same vineyard.

While the results of this sub-experiment suggest that DC collected more representative soil EC data in this all-steel vineyard, more work is needed in vineyards with closer row spacings. The wide 12-foot row spacings seen in this block are becoming less common in Virginia vineyards, so results of this experiment may not apply directly to other sites with closer row spacing. DC data from all-steel vineyards with closer row spacings should be analyzed before any conclusions are made about its applicability to all vineyards in Virginia with metal posts.

Experiment 7 Conclusions
- Soil EC data processing approach is important and should be tailored to the objectives of the survey
- DC and EM produced similar results at research vineyards with wooden posts
- DC produced a more representative soil EC dataset than EM in an all-steel vineyard with 12-foot row spacing
- The DC method should be tested in all-steel vineyards with closer row spacings to assess its suitability as a substitute for EM in all-steel vineyards

Table 6: Electromagnetic Induction vs. Direct Contact Conductivity Sensors – Pros and Cons

	Pros	Cons
Electromagnetic Induction  	• Rapid data collection • Snow or wet ground surface does not interfere with readings • Does not require ground contact • Data collection at multiple depths • Ability to easily maneuver around cluttered, recently clear cut, or very steep sites • Repeatable results • Instrument may be carried by field worker or towed	• Noisy data in all-steel vineyards • Results can be affected by electromagnetic noise • Instrument must be calibrated often
Direct Contact Sensors  	• Rapid data collection • Repeatable results • Data collection at multiple depths (depending on instrument model) • Useful data in all-steel vineyard	• Coulters must be replaced often • Requires ground contact • Instrument must be towed • Inability to maneuver around cluttered or steep sites • Snow or wet ground distorts data (based on conversations with industry professionals) • Data collection at single depth (depending on instrument model)

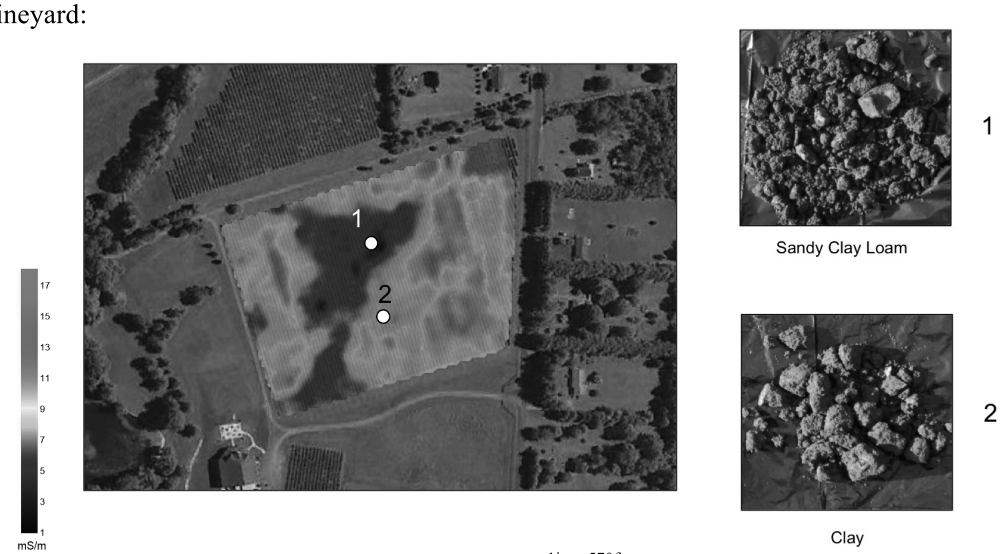
The pros and cons of the two different soil EC data collection methods in Table 6 are based on the author's experience through this research project, his consulting work, and conversations with other professionals who work with soil EC surveys.

Experiment 8: Geophysics and Wine Quality – An Ongoing Study at Pollak Vineyards

In an initial experiment at Pollak Vineyards, we implemented a differential Cabernet Franc harvest guided by EM conductivity mapping in Fall 2013. Preliminary results showed significant differences in wine quality from two soil zones within the same vineyard block, delineated with EM. I am continuing to work with Pollak Vineyards to turn this into a multi-vintage experiment, the results of which we intend to share with the international wine industry.

Methods

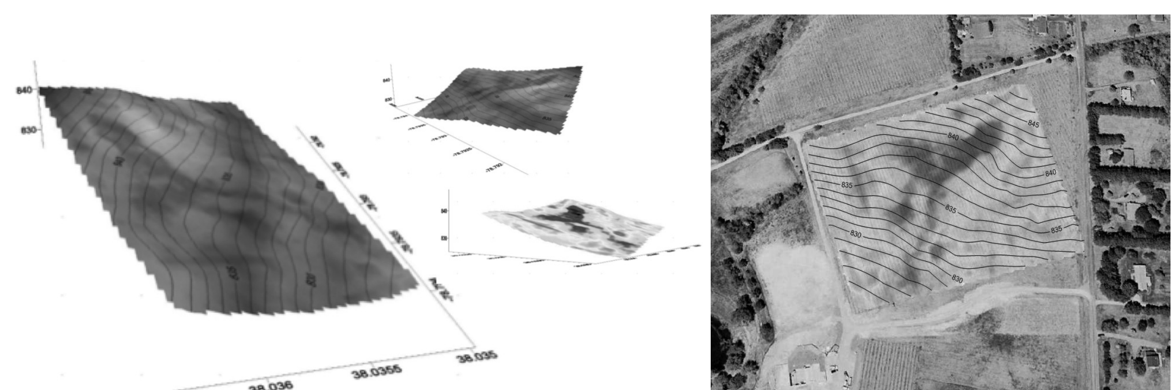
EM mapping of a 10-acre vineyard block at Pollak Vineyards was conducted in September 2013; soil samples were collected via hand auger for analysis. This experiment focuses on a particular 2-acre Cabernet Franc planting within the larger block. The vines in the study area are reported by the grower to be CF004 clone on 101-14 rootstock with no variability in trellising or viticultural practices. Interpretation of EM mapping suggested that two different soil types underlie this vineyard:



1in = 570ft

Figure 28 – Soil variations in Pollak Vineyards Block B represented by EM conductivity map. Both samples were collected from a depth of approximately 24 inches below ground surface. Sample 1 is a sandy clay loam with gravels and sample 2 is a clay soil with no rock fragments.

Precise soil zone boundary locations were identified based on statistical analysis of the EM data, field observations, and topographic mapping. Boundaries were field-delineated with survey flagging tape utilizing a Differential GPS unit, satellite photos, and a tape measure for boundary placement in the vineyard.



1in = 650ft

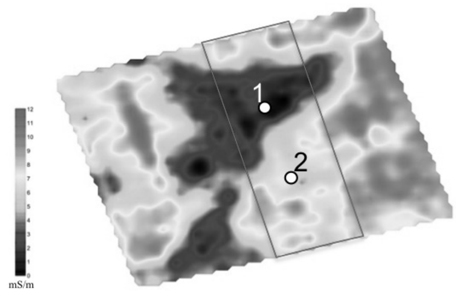
Figure 29 – Topography is one of the five main factors controlling soil formation (Jenny,1941) and should be closely analyzed in any work involving mapping of soils and geomorphology. Topographic data were used in conjunction with EM data and site observations to help locate the experimental soil zone boundaries.

The grapes were harvested separately from the two soil zones on October 6, 2013 and separate lots of wine were made. Pollak used the same oenological treatments with each lot of experimental Cabernet Franc, recording analytical parameters throughout the winemaking process.

Figure 30 – a) Workers loaded grapes from each zone into separate bins during harvest. b and c) Field workers harvest Cabernet Franc from the experimental block at Pollak, taking care not to mix fruit form the two zones. c) Bins of "high conductivity" (closest to tractor) and "low conductivity" (foreground) Cabernet Franc en route from the vineyard to the winery onsite.

Experiment 8 Preliminary Results and Discussion
The preliminary findings of this experiment (shown below in **Figure 31**) suggest a direct relationship between measurable differences in fruit and wine quality and distinct soil zones within a single vineyard block, mapped with EMI:

a)



b)

	1	2
Apparent Conductivity:	0-3 mS/m	6-8 mS/m
Soil:	Sandy clay loam w/ gravels	Clay
Color Intensity: 420, 520, 620 nm	5.9	4.8
pH:	3.83	3.93
Sugar:	23.7° Bx	24.0° Bx
Yield:	4.0 tons/ac	3.28 tons/ac
Average panel dry pruning weight:	9.4 lb	11.4 lb

Figure 31 – a) The red box marks the 2-acre study area within the larger vineyard block. Distinct soil zones within study area are clearly seen on the EC map (blue "low conductivity" area around borehole 1 and green/yellow/orange "high conductivity" area around borehole 2). b) Data from 2013 harvest show measurable differences in wine quality characteristics.

The experimental wines were bottled separately and tastings were conducted by winemakers and wine industry personnel at approximate three month intervals throughout 2014. Based on tasting results, there is no question that the differences measured in the fruit and wine during experimental winemaking process carried into the bottle and thus the final end product wine. The high conductivity Cabernet Franc is lighter in color (a bit tawny, almost bricklike in color) and lighter in flavor with a soft mouthfeel; the low conductivity Cab Franc is unmistakably darker in color (and is ruby colored) with more intense flavors and more pronounced tannic structure.

We intend to continue this work in future vintages at Pollak Vineyards in an effort to fully understand all factors contributing to the differences in wine quality. I hope that experimental data from multiple vintages with different weather and precipitation patterns will provide a better understanding of the complex relationship between soil, hydrology, weather, vintage, EM mapping and wine quality.

Experimental wines from the 2014 vintage are currently undergoing malolactic fermentation in the cellar. Tasting of the 2014 experimental Cab Franc wines will begin this winter, but preliminary measurements and observations suggest similar results to those seen in 2013.

Experiment 8 Conclusions to Date

- We successfully detected and delineated different wine quality zones in the same vineyard block with EM
- EM is a valuable tool for improving wine quality by guiding management zoning in existing vineyards
- This approach could be applied to new plantings to tailor vineyard layout to soil variability

Summary

In this work, geophysical surveys consistently imaged a number of important factors for vine growth and wine quality in vineyards of the Valley and Ridge, Blue Ridge, and Piedmont Provinces of Virginia. For use in vineyards similar to our research sites, soil conductivity mapping via EM appears to be more widely applicable than GPR. High quality maps of subsurface electrical properties can be produced with strong repeatability, but it is critical to base interpretations on site soils and geology with laboratory and borehole data. Additionally, the appropriate map scale for robust data analysis not only varies, but is open-ended and should be determined by the geoscientist during the analytical phase of data interpretation. Many agronomic soil EC mapping methods were developed for row crops; soil EC mapping for viticulture requires more detail, a solid understanding of site geology and soils, and as much ground-truth data as practicable. In this work, frequent correlations between conductivity measurements and clay content, moisture, CEC, internal drainage and shallow rock were noted. The EM results in steel vineyards presented herein support David Lamb's 2009 findings that steel posts distort EM data. The DC method of conductivity data collection was tested in an all-steel vineyard and shows potential as a method suitable for existing vineyards with metal posts; however, more work is needed in vineyards with closer spacings. This work demonstrates that electromagnetic soil conductivity mapping is an extremely valuable tool for viticulture in Virginia, but that it does not provide an absolute indication of what lies beneath the ground surface; ground-truthing of geophysical data is critical.

Conclusions

Soil Texture

- EM data can give indications of spatially variable soil texture
- Conductivity variations on a map do not always indicate relative soil texture as many believe
- Increased soil conductivity can indicate increased clay content
- Increased soil conductivity has also been correlated to decreased clay content
- EM data can be used to locate soil series boundaries
- Ground-truth data is critical to assess for correlations to soil texture

Soil Salinity and CEC

- EM data can give indications of spatially variable soil salinity and CEC
- EM data can be used to locate soil series boundaries
- Ground-truth data is critical to assess for correlations to CEC and salinity

Shallow Rock

- Shallow rock at one site may not have the same geophysical signature as shallow rock at another site in a different geologic setting
- A deep understanding of site geology, mineralogy, geomorphology, soils, and geophysical principles employed is critical for producing robust interpretations of geophysical data
- Ground-truth data is critical to determine whether or not geophysical data represent shallow rock

Soil Drainage (Ksats)

- EM data can correlate to Ksats in areas where drainage is controlled by clay content
- Macropore flow is a common phenomenon in soil hydrology, and appears to influence Ksat results at some of our test sites
- Low ground conductivity does not necessarily indicate fast soil drainage
- High ground conductivity does not always indicate slow soil drainage
- Multiple Ksats measurements should be made in one soil type to assess for representative results
- Ground-truth data is critical for physical indications of soil drainage, which may or may not relate to EC

Seasonal Moisture Variations

- Seasonal moisture variations can affect EM data
- The extent of their effects on EM data in Virginia vineyards is still unknown
- More work should be conducted in this area as we hypothesize that seasonally variable soil moisture has a profound effect on EM data at some sites, a phenomenon which is not well demonstrated by the Figures in Section 4
- Ground-truth data can provide valuable information regarding soil moisture and ground conductivity

All-Steel Vineyards

- Steel posts distort EM data
- Amount of electromagnetic noise in all-steel vineyards depends on the amount and height of trellis wire, density of metal posts and row spacing
- Wooden posts act as insulators and prevent (or at least significantly dampen) electromagnetic noise
- EM data can still be useful in all-steel vineyards if a low level of noise is encountered
- DC produced a more representative soil EC dataset than EM in a steel vineyard with a 12-foot row spacing
- The DC method should be tested in a all-steel vineyards with closer row spacings to test for its suitability as a substitute for EM in all-steel vineyards

Soil EC Data Processing

- Soil EC data processing approach (automated zoning vs. contouring and visually analyzing data) is important and should be tailored to the objectives of the survey
- Contouring data appears to meet the objectives of geophysical surveys for viticulture better than automated soil zoning based on the level of map detail desired for viticulture

EM vs. DC Sensors

- DC and EM are capable of producing similar results at research vineyards with wooden posts and 10-foot row spacings
- Based on our results in an all-steel vineyard, DC may be the preferred data collection method in vineyards with steel posts, but more data is needed from sites with closer spacings
- Depth of measurement is important and should be strongly considered in geophysical surveys for viticulture

Wine Quality

- EM is capable of detecting and mapping wine quality zones within a vineyard block
- EM is a valuable tool for improving wine quality by guiding management zoning in existing vineyards
- Ground-truth data is critical for understanding subsurface variability as it relates to wine quality

Technology Transfer

The results of this work have been (or will be) discussed in the following presentations:

- “Wine Board Research Update” - Virginia Wineries Association Annual Conference (November 2013)
- “Geophysical Investigations for Viticulture” - Virginia Vineyards Association 2014 Winter Technical Meeting (January 2014)
- “Geophysical Surveys for Viticulture” - Wineries Unlimited (March 2014)
- “Geology and Wine Quality” - Guest Interview Series at Dodon Vineyards, Anne Arundel County, Maryland
- “Soils, Geology, and Wine Quality” - Maryland Grape Growers’ Association Winter Technical Meeting (March 2015)

I am preparing articles to publish the results of this work in peer-reviewed journals and trade magazines. I am also in communication with university geology departments scheduling speaking engagements to share the results of this work with college students majoring in geology, environmental, and agricultural sciences.

Acknowledgements

Many thanks to the following individuals and entities for project support, access to vineyard sites for this work, contributing expertise in soils, geology, and viticulture, inspiring conversation, and field work assistance:

- Virginia Wine Board
- Tony Wolf
- Benoit Pineau
- Scott Dwyer
- Jake Busching
- Nick Dovel
- Dave and Margo Pollak
- Vincent Day
- NAEVA Geophysics
- Bernd Jung
- Lucie Morton
- Chris Hill
- Alex Blackburn
- Jonas Mueller
- Kirsty Harmon
- Jim Law
- Tremain Hatch
- Pauric McGroary and A&L Eastern Labs
- Michael Gay
- Cole Peale-Grody
- Brycen Hill
- Bynon Connor
- Early Mountain Vineyards
- Stone Tower Estate

Photo Credits

- Vincent Day (Figure 3a)
- Lucie Morton (Figures 3b and 3d)
- NAEVA Geophysics (Figures 4, 5, 10, 14, 18 and 19; Appendix A: GPR photo and GPR maps)

References

Andre, Frederic, et al. 2012. “High-resolution imaging of a vineyard in south of France using ground penetrating radar, electromagnetic induction and electrical resistivity tomography.” Journal of Applied Geophysics. Volume 78, March 2012. 113-122.

Beasley, E. 2013. Virginia Wine Board Grant Proposal for RFP # 301-13-028. Non-Invasive High-Resolution Vineyard Soils Mapping Techniques. February 2013.

Beven, K. and Germann, P. 1982. “Macropores and Water Flow in Soils.” Water Resources Research, Volume 18, Number 5, October 1982. 1311-1325.

Bouma, J., C. F. Belmann, et al. (1982). "Water Infiltration and Redistribution in a Silt Loam Subsoil with Vertical Worm Channels." Soil Science Society of America Journal 46: 917-921.

Cailleux, A. Plaisance G. (1981). Dictionary of Soils. New Delhi and Springfield, Va. Amerind Pub. Co

Fisher, James 2010. “Scaling of terroir and geospatial mapping of vineyard soils via electromagnetic induction.” Proceedings from the 19th World Congress of Soil Science, Brisbane, Australia, August 2010. 43-46.

Hamilton, D. 2002. “Mafic and Felsic Derived Soils in the Georgia Piedmont: Parent Material Uniformity, Reconstruction, and Trace Metal Contents.” Masters Thesis under the direction of Larry West. University of Georgia. Athens, Georgia.

Hezarjaribi, A. et al. Year unknown. “Soil conductivity sensing using non-invasive electromagnetic induction-based and electrode-based methods.” A publication by the Institute of production Engineering and Building Research, Federal Agricultural Research Centre, Braunschweig, Germany. Text available at: http://literatur.vti.bund.de/digbib_extern/dk039996.pdf.

Hubbard, S. and Rubin, Y. 2004. “The Quest for Better Wine Using Geophysics.” Geotimes. August 2004.

Jenny, H. 1941. Factors of Soil Formation. McGraw-Hill, New York.

Klein, J. and Lajoie, J. 1980. Practical Geophysics for the Mining Geologist: Northwest Mining Association, Spokane, WA.

Lamb, D. 2009. “EM38 in All-Steel Vineyards – a Cautionary Tale.” Precision Agriculture and Viticulture Expo. 2009. 19-22.

McNeill, J. 1980. “Electrical Conductivity of Soils and Rocks.” Technical Note TN-5. Geonics Limited, Ontario, Canada.

McNeill, J. 1996. “Why doesn’t Geonics Limited build a multi-frequency EM-31 or EM-38?” Technical Note TN-30. Geonics Limited, Ontario, Canada.

Meyles, E., A. Williams, et al. (2003). "Runoff generation in relation to soil moisture patterns in a small Dartmoor catchment, Southwest England." Hydrological Processes 17(2): 251-264.

Moore, D.M. and Reynolds R.C. 1997. X-Ray Diffraction and the Identification and Analysis of Clay Minerals, 2nd ed. Oxford University Press, New York, New York.

NRCS Web Soil Survey: http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

Phillips, R., V. Quisenberry, et al. (1989). "Mechanism of Water Entry into Simulated Macropores." Soil Science Society of America Journal 53: 1629-1635.

Priori, S. et al. 2010. “Three proximal sensors for mapping skeletal soils in vineyards.” Proceedings from the 19th World Congress of Soil Science, Brisbane, Australia, August 2010. 121-124.

Priori, S. et al. 2012. "Improving Wine Quality Through Harvest Zoning and Combined Use of Remote and Soil Proximal Sensing ." Soil Science Society of America Journal. Volume 77. November 2012. 1338-1348.

Reynolds, J. M. 1997. An Introduction to Applied and Environmental Geophysics. John Wiley and Sons, West Sussex.

Rhoades, J.D., F. Chanduvi, and S.M. Lesch. 1999. Soil salinity assessment: Methods and interpretation of electrical conductivity measurements. FAO Irrigation and Drainage Paper #57. FAO, Rome, Italy.

Saidi, D. 2012. " Relationship between cation exchange capacity and the saline phase of Cheliff soil." *Agricultural Sciences,* 2012*,* Vol.3, No.3, 434-443

Sherwood, W. C. 2003. "Soils for the Earth and Environmental Sciences" James Madison University Academic Coursepack Service. Geology 340: Soils and Land Use, Fall 2003, #76.

Stephens, D.B. 1996. Vadose Zone Hydrology. CRC Press: Boca Raton, FL.

Taylor, J., Whelan, B. 2010. A General Introduction to Precision Agriculture. Australian Centre for Precision Agriculture/Grains Research and Development Corporation. PDF can be found at: http://www.agriprecisione.it/wp-content/uploads/2010/11/general_introduction_to_precision_agriculture.pdf

Tisseyre, B., Taylor, J. 2005. "An overview of methodologies and technologies for implementing precision agriculture in viticulture." Proceedings from XII Congresso Brasileiro de Viticultura e Enologia – Anais. 45-54.

U. S. Geological Survey Virginia Geologic Map Data: http://mrdata.usgs.gov/geology/state/state.php?state=VA

US Patent: US 6938461 B1. Johnson Permeameter

Wolf, T. and Boyer, J. 2009. "Vineyard Site Selection." Virginia Cooperative Extension Publication 463-020, May 2009.

Wollenhaupt, N.C., Richardson, J.E., Foss, J.E., Doll, E.C. 1986. "A Rapid Method For Estimating Weighted Soil Salinity From Apparent Soil Electrical Conductivity Measured with and Aboveground Electromagnetic Induction Meter." *Canadian Journal of Soil Science*, 1986, 66(2): 315-321

Appendix A – Ground Penetrating Radar

The GPR system consists of four major parts: a 4-wheeled chassis with an integrated odometer, a transmitter/receiver antenna, a battery unit, and a display monitor with built-in data storage capabilities. During operation, the GPR's transmitter radiates a short pulse of electromagnetic energy into the ground. When this pulse strikes an interface between layers of material having different electrical properties, a portion of the energy is reflected back to the surface and detected by the GPR antenna, while the remaining energy continues on to the next interface. In addition to providing information about lateral soil variations, GPR is an effective tool for interpretation of soil stratigraphy, or layering.

Like EMI, the GPR method provides a means of non-intrusive data collection. The system is most commonly moved along the ground surface at a consistent pace as data are collected continuously along profiles. For this work, multiple parallel profiles were executed with an unshielded 400 mHz GPR antenna along vineyard rows and were then integrated using specialized software to produce plan view graphics, depicting lateral variations in subsurface dielectric constant, which is closely related to electrical properties (Reynolds 1997).

Because of the substantial amount of clay in the soils at our research sites, our GPR surveys produced noisy datasets that did not depict lateral subsurface properties as effectively as the EM and DC conductivity data. Additionally, GPR data collection took more time than conductivity data collection because the antennas that drag the ground had to repeatedly be cleared of debris during surveys. Thus the GPR datasets collected for this work do not cover as much area as the EM and DC datasets.

The field worker pushes the GPR cart along parallel profile lines during data collection; the lines are later integrated to produce plan view maps of the GPR data.

1in = 300ft

GPR data from Chester Gap Cellars in Rappahannock County. Map reflects an average of subsurface properties down to about 5 feet bgs. Red represents areas with a high dielectric constant, blue represents areas with a low dielectric constant. Red areas may represent subsurface "reflectors" of the GPR signal (e.g. rocks or clay pockets.)

1in = 190ft

GPR data from Mt. Juliet Farm in Albemarle County. Red colors represent areas with a high dielectric constant, blue represents areas with a low dielectric constant. This map represents subsurface properties down to about 5 feet bgs. Red areas may represent subsurface "reflectors" of the GPR signal here as well (e.g. rocks or clay pockets).

Correlations to site conditions were weak, if at all present. Geophysicists at NAEVA Geophysics (the firm that provided GPR services for this project) reported that the GPR datasets were noisy and difficult to glean meaning from during processing. We did not note significant correlations to conductivity data collected at the same sites. GPR investigations were halted after our initial findings indicated that EM was the more pertinent geophysical method for addressing our research questions related to viticulture at the study sites. GPR data may be useful in more uniform alluvial or Coastal Plain soils; however, data collection in such settings was beyond the scope of this project.