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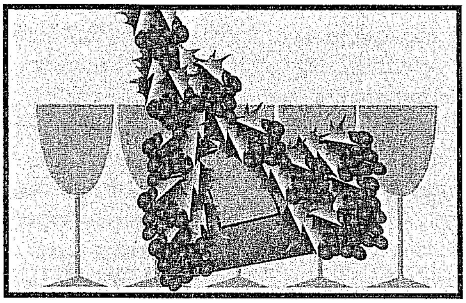

Vineyard Soil Water Content: Mapping Small-scale Variability using Ground Penetrating Radar

Susan Hubbard[1,2], Ian Lunt[3], Katherine Grote[4] and Yoram Rubin[1]
[1]*University of California at Berkeley, Department of Civil and Environmental Engineering, Berkeley, California 94720 USA*
[2]*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Mail Stop 90-1116, Berkeley, California 94720 USA*
[3]*Department of Earth Sciences, University of Leeds, Leeds LS2 9JT, United Kingdom.*
[4]*University of Wisconsin Eau-Claire, Department of Geology, 105 Garfield Avenue, Eau Claire, Wisconsin 54702 USA*

SUMMARY
Development of precision viticulture strategies, focused on promoting uniformly high wine quality throughout vineyard blocks, necessitates an ability to assess the factors that influence winegrape quality over various spatial and temporal scales. Although micrometeorological factors are often considered when developing an irrigation approach or assessing fruit quality, the influence of small-scale soil variations and their control on water use and associated fruit quality is poorly understood. We have investigated the use of surface GPR (Ground Penetrating Radar) data, using both 900 MHz groundwave and 100 MHz reflected wave techniques, to map shallow soil water content in high resolution with acceptable accuracy and in a non-invasive manner. By combining the different GPR techniques and by using different frequency antennas, it is possible to construct a 3-D soil water content cube and to monitor moisture distribution over time. Techniques such as these open the way for development of precision viticulture approaches that account for natural soil variabilities, such as precision irrigation. Additionally, the high resolution characterization methods could be very helpful for guiding vineyard development. For example, such detailed soil information can be used to lay out vineyards according to the natural geologic variations or to develop variable vine spacing in an attempt to encourage uniform development across a vineyard block.

RÉSUMÉ
L'élaboration de stratégies viticoles de précision, visant à produire de façon uniforme des vins de haute qualité par parcellisation des vignobles, impliquent que l'on puisse évaluer les facteurs qui déterminent les qualités vinifères du raisin à diverses échelles spatiales et temporelles. Bien que des facteurs micrométéorologiques soient souvent pris en compte au moment de déterminer une stratégie d'irrigation ou lors de l'évaluation de la qualité du fruit, l'influence des variations à petites échelles des sols et leur influence sur la disponibilité de l'eau et sa relation sur la qualité du fruit sont encore mal connues. Nous avons étudié des données de levés par géoradar de surface, à partir de techniques utilisant à des ondes de sol à 900 MHz et des ondes réfléchis à 100 MHz, afin d'obtenir une cartographie à haute résolution de la teneur des sols en eau à faible profondeur, avec une précision suffisante et cela de façon non-invasive. En combinant les différentes techniques de levé par géoradar et en ayant recours à des antennes à différentes fréquences, il est possible d'en arriver à un cube unitaire de la teneur hydrique du sol et ainsi à pouvoir suivre la distribution de la teneur hydrique en fonction du temps. De telles techniques ouvrent la voie à la mise au point d'approches viticoles de précision qui tiendront comptes de la variabilité des sols, comme l'irrigation de précision. Par ailleurs, les méthodes de caractérisation à haute résolution pourraient être fort utiles pour orienter le développement des vignobles. Ainsi, de telles informations pédologiques détaillées pourraient permettre d'établir les vignobles en fonction des variations géologiques des sols, ou encore, d'adapter l'espacement des vignes de manière à favoriser un développement uniforme sur toute la parcelle.

INTRODUCTION
Enhancing wine quality is critical to the financial success of the wine industry. Quality in turn is linked to the physiological status of grapevines, and specifically to the plant's water status. Through trial and error over hundreds of years, European winemakers have recognized that certain soils, and their associated water holding capacity, produce finer wines than do others, and that soils play a role in '*terroir*' (Wilson, 1998). Due to natural geological processes, soil properties can vary laterally over distances as small as several metres to tens of metres. Recognition and incorporation of information about small scale soil variability into crop management practices could lead to winegrapes that better

reflect the microterroir of the area. However, because viticulture within areas such as California and Australia is relatively new and human intervention there tends to play a significant role (e.g., Bohmrich, 2006), the perspective that has helped to define terroir in older winegrape growing areas is still evolving in newer winegrape growing regions. Geospatial information about properties that influence grape quality could be useful in these newer areas for guiding precision viticulture.

Soil parameters (such as soil texture, volume of rock fragments, and soil moisture) play an important role in winegrape growing. Soil texture, or the proportion of sand, silt, and clay, influences the depth to which the roots grow, the amount of water that is available for the roots, water movement through soil (hydraulic conductivity), the extent of soil compaction, and the amount of aeration (e.g., Wright, 2001; Rice, 2002; White, 2003). Sandy soils generally have a low water-holding capacity, and thus require frequent irrigation in regions that do not receive sufficient rainfall. Loams and clay loams have finer soil particles and a higher plant-available water-holding capacity, and therefore generally require less irrigation. Large-scale soil surveys, such as those provided by the United States Department of Agriculture (USDA) Soil Conservation Service, provide general information about the spatial variations in soil properties but do not provide the level of detail required to make management decisions at the vineyard scale. The "industry standard" approach to vineyard soil characterization is to dig backhoe pits for soil sample collection at points located on a 75 m grid. Measurement spacings such as this are also typical for collection of conventional 'point' soil water content measurements. A number of studies have shown, however, that soil properties may vary significantly *over lateral distances of less than a metre to tens of metres* (e.g., Saddiq *et al.*, 1985; Hendrickx *et al.*, 1990; Loague and Gardner, 1990; Or and Rubin, 1993; Western and Grayson, 1998; Huisman *et al.*, 2003; Grote *et al.*, 2003). Under these natural conditions, conventional approaches for characterizing soil properties using point sampling techniques may not be sufficient for capturing the variations in soil properties needed to guide precision agriculture (e.g., Lamb and Bramley, 2001).

A considerable amount of viticultural research has identified strategies that can be used to optimize winegrape quality, including canopy management cropping levels, and irrigation (e.g., Kennedy, 2002). Although the impact on microclimate is often considered when developing large-scale irrigation strategies or when assessing vintage quality, a clear and consistent message emerging from many viticulture workshops is that the wine industry has an inadequate understanding of the influence of small- and intermediate-scale soil variabilities on winegrape variability and irrigation needs. Below we briefly describe different approaches that are often used to guide winegrape irrigation. We then present two studies that describe how we have used a surface geophysical method to map soil moisture in very high spatial resolution, and suggest that such data can be used to guide precision viticulture strategies.

WINEGRAPE IRRIGATION APPROACHES

Because water is a key control on the physiological status of grapevines, good water management can be used to optimize crop quality. It is generally accepted that moderate water stress on grapevines at early stages in the growing season controls canopy density and has a positive impact on the fruit characteristics (e.g., Hardie and Considine, 1976; Freeman and Kliewer, 1983; Matthews *et al.*, 1987; Wample *et al.*, 1989; Loveys *et al.*, 1998; Dry *et al.*, 2000; Williams, 2001). In areas where there is little rainfall during this time period, such as in the Napa Valley of California, water management typically entails irrigation.

To optimize water stress, it is critical to understand how much irrigation water to apply and when to apply it. Because the amount of irrigation water that a plant requires is a function of the plant and soil characteristics as well as the microclimate, irrigation approaches are guided by measurements of those properties. Plant-based irrigation approaches often include using visual indicators or measurements at one location in the vineyard. Visual indicators of plant stress include assessing shoot-tip growth and leaf colour (e.g., Caldwell-Ewart, 2003). Plant based measurement techniques include collecting measurements, such as leaf water potential (LWP), stem water potential (SWP) (e.g., Matthews *et al.*, 1987; Naor 1998; Chone *et al.*, 2001), and canopy temperature (Van Zyl, 1986). Typically these measurements are collected at single plant locations within a subset of vineyard blocks during times when the vineyard manager suspects that water stress is critical.

Popular climate-based methods for guiding irrigation rely on weather data, empirical crop coefficients, and meteorological models to calculate the evapotranspiration (ETo) and irrigation requirements (e.g., Snyder *et al.*, 1989; Grattan *et al.*, 1998, White, 2003). Because moderate water stress in the early growing season is desirable, deficit irrigation strategies have been developed that strive to give the plant some fraction of the full ET_0, where $ETc = ETo * k_c$, where k_c is the crop coefficient. The crop coefficient is a function of canopy density and winegrape variety and is spatially and temporally variable (e.g., Williams, 2001). Deficit irrigation approaches require accurate monitoring of leaf water status or soil moisture content (Stamp, 2003) to ensure that the plant does not reach a critical state of water stress. Such monitoring can be challenging, given the natural variations that can occur over small scales.

Soil-based characterization methods often involve taking soil water content measurements at single locations within a vineyard by retrieving a soil sample and assessing the moisture, or by using an indirect geophysical probe or borehole approach. These 'point' soil measurement techniques often include gravimetric, time-domain reflectometry, and neutron probe approaches. Because soil properties can vary laterally on the order of metres, however, conventional sampling at a location or two within a vineyard block is commonly insufficient to assess the soil moisture distribution throughout a vineyard. Additionally, without destructive analysis of the soil system, it is often difficult to assess the vertical soil moisture variations. In some cases, such as under irrigated conditions, roots may be concentrated in the very shallow wetted zones. In other cases, 'feeder roots' may penetrate many metres below the ground surface in search of moist soil layers or groundwater. Because of the uncertainty associated with the root zone depth range, it is commonly difficult to determine at which depth or over which depth range conventional soil moisture measurements should be collected.

HIGH RESOLUTION CHARACTERIZATION OF SOIL WATER CONTENT USING GROUND-PENETRATING RADAR

Because surface geophysical tools can probe the subsurface with high spatial resolution and in a non-invasive manner, they offer great potential as a shallow soil investigation tool. Electrical methods have been used in recent years to guide precision agricultural studies (e.g., Lund *et al.*, 2001; Johnson, C.K. *et al.*, 2003; Bramley, 2005). The ability to conduct electrical current through the soil is a function of a variety of factors, such as the soil clay content, temperature, water content, and soil water salinity. As such, unique interpretation of electrical conductivity (or its inverse, electrical resistivity) data in terms of a single soil property can be challenging (e.g., Rhoades *et al.*, 1976; Harstock *et al.*, 2000), although it has been successfully performed using site-specific controls (e.g., Sheets and Hendrickx, 1995; Michot *et al.*, 2003; Reedy and Scanlon, 2003). Typically, electrical measurements are used to provide spatial patterns of electrical conductivity, rather than to provide unique estimates of soil properties.

Ground Penetrating Radar Background

Surface Ground Penetrating Radar (GPR) approaches have been used recently to map the dielectric properties of the soil and subsequently to estimate soil water content within vineyard sites in a non-invasive manner and with high spatial resolution (Hubbard *et al.*, 2002; Grote *et al.*, 2003; Lunt *et al.*, 2005). GPR uses high frequency electromagnetic waves (~50MHz to 1200 MHz) to probe the subsurface. Radar signal penetration varies as a function of several parameters, including the GPR system performance, the attenuation of the media, and the antenna frequency (Davis and Annan, 1989). GPR signal attenuation increases with both increasing frequency and increasing electrical conductivity of the subsurface material. For example, using a conventional radar system with lower frequency (50 or 100 MHz) antennas, signal penetration depths of ten to twenty metres below ground surface have been realized (e.g., Fisher *et al.*, 1992; van Overmeeren *et al.*, 1997; Hubbard *et al.*, 2001), especially in sandy areas or when using common midpoint (CMP) acquisition geometries to collect the data (which increases the signal to noise ratio; Annan, 2005). However, acquisition using higher frequency signals (such as 900 MHz) in clay rich sediments may permit GPR imaging of reflections located only a metre or less below the ground surface. Resolution refers to the ability to distinguish two signals that arrive very close in time. Because the maximum vertical resolution is generally considered to be a quarter of the predominant wavelength of the system, and wavelength decreases with frequency, higher resolution can be obtained using higher frequency signals. For example, resolutions on the order of 0.25 m are common using 100MHz data, whereas resolutions on the order of 0.05-0.1 m are possible using 900MHz data. There is a trade-off between achievable spatial resolution and penetration depth: higher frequency signals tend to yield higher resolution information than lower frequency signals, but because they attenuate more rapidly they cannot be used for probing deeper soil layers. In practice, the antenna frequency is chosen depending on target depth of the investigation and considerations of the electrical characteristics of the study site. In general, GPR methods work best in soils that have a low electrical conductivity, such as coarser grained soils with low-salinity soil water, as soils having a high electrical conductivity tend to attenuate the GPR signal rapidly.

The GPR concept of estimating water content is similar to that of the Time Domain Reflectometry (TDR) method, which is commonly used in agricultural applications to measure water content at a single location. With TDR applications, metal prongs are inserted into the ground, and a high frequency (~1-3GHz) electromagnetic pulse is sent out, which travels through the soil along the probes. The travel time (or the velocity, v) of the electromagnetic wave is used to estimate the dielectric constant (k) of the soils through which the wave travels using the approximate relationship $k=(c/v)^2$, where c is the electromagnetic speed of light in a vacuum ($3x10^8$ m/s). With the GPR technique, the instrument is pulled along the ground surface as is illustrated in Figure 1 or is attached to farm equipment, and an electromagnetic pulse is sent from the transmitting antenna (Tx) into the soil. Energy from the pulse travels directly through the air (A in Figure 1) to the receiving antenna (Rx), along the ground surface (the groundwave; G in Figure 1), and through the soil. Energy penetrating the soil is reflected at soil interfaces having differing dielectric constants (R in Figure 1). The travel-time of the wave is measured, and if the length of the travel path is known, the electromagnetic wave velocity can be estimated and converted into dielectric constant values. A detailed discussion of the use of GPR for hydrogeological investigations is given by Annan (2005).

The dielectric constant of soils is most sensitive to soil water content, which renders both TDR and GPR useful tools for measuring vineyard soil water content. The dielectric constant of air is 1, of water is 80; these two values represent the approximate end members of the dielectric constant range. The dielectric constant of dry soils is ~4-8, and as the pore spaces become filled with soil water, the effective dielectric constant increases. A relationship commonly used to relate dielectric constant measurements to volumetric soil water content was developed empirically by Topp *et al.* (1980) using TDR laboratory estimates of dielectric constant and various soil samples. Other researchers have used dielectric mixing models, where the effective dielectric constant is represented as a function of the volume fractions and the dielectric constant of each soil constituent, such as soil grains, air, and water (e.g. Roth *et al.*, 1990; Friedman, 1998). To obtain quantitative and accurate estimates of water content using TDR or GPR methods, other researchers have developed site- and frequency-specific calibration equations. Further discussion of these relationships, as well as the use of GPR methods to estimate water content, is given in Huisman *et al.*, (2003).

We have used both GPR groundwave and reflection techniques to provide spatially extensive estimates of soil water content distribution over time within two different California vineyards. Different GPR antenna frequencies (100 MHz and 900 MHz) were used so that we could map soil moisture in shallow as well as in deeper soil layers. The results of a vineyard GPR groundwave and a vineyard GPR reflection wave study are briefly described below.

GPR Groundwave Study at the Robert Mondavi Vineyard

We tested the concept of using the GPR groundwave technique to estimate water content within a Robert Mondavi Vineyard, located in Napa Valley, California. This study vineyard is located in Oakville, which is about 9 miles northwest of the city of Napa. Sediments at the Robert Mondavi study site were deposited within alluvial fans, flood plains, and low terrace settings during the Holocene Epoch. Soils at the study site are generally categorized as USDA Bale Loams. The water table is approximately 3 to 4 m below ground surface, and the topography is fairly level. The approximately 4 acre study site is planted with Cabernet Sauvignon grapes having row and vine spacing of 1.2 m. The mean annual precipitation in this valley is from 64 to 89 cm. Summers are hot and dry, and the winters are cool and moist with a mean annual air temperature of ~60 degrees F. All vines in the study area are subject to the same volume and frequency of irrigation water via a drip system, with an average of 0.02m^3/vine/week during the warmest months (typically May through October).

Soil texture, soil moisture, remote sensing, and GPR data were collected at the study site. Approximately 30 soil texture measurements were obtained by hand-auguring soil samples and assessing the gravel, sand, silt, and clay content. Water content measurements were obtained using conventional sampling techniques (TDR, gravimetric, and neutron probe techniques) to compare with estimates of volumetric water content obtained from the GPR data. Remote sensing data sets were acquired using the airborne ADAR Multispectral System 5500 (Positive Systems) in the blue, green, red and near-infrared portions of the spectrum from a flight altitude of 4300 m above ground level and with a high spatial resolution of 2m x 2m (Johnson *et al.*, 2001, 2003). These data were used to estimate canopy vegetation density variations within the block; Figure 2a illustrates the normalized density vegetation index (NDVI) map created from the multispectral data for the site, where the brown tones illustrate areas of low vegetation density and the green tones illustrate areas of higher vegetation density, or higher vigor (Johnson, L.F. *et al.*, 2003). Note that although this vineyard block is planted with the same grape variety, has been subject the same farming practices, irrigation, and microclimate, and has relatively uniform topography, there are variations in the vegetation that likely reflect soil property variations.

GPR data were collected several times over a period of 18 months within the area shown in Figure 2a using a 900 MHz PulseEKKO 1000 System. The GPR data were collected with measurement spacing in the lateral direction of 0.1-0.2 m along the middle of every 5th row with a fixed antenna separation distance of 0.17 m (see Fig. 1). Because the high frequency groundwave only travels a short distance from the transmitting to the receiving antenna, the strength of the groundwave signal was significant enough to be detected at all locations, despite the presence of some finer textured soils that tend to attenuate the GPR signals. Using the GPR groundwave arrival travel time and the distance between the transmitting and receiving antenna, we estimated the electromagnetic velocity and subsequently the dielectric constant at each sampled location. As described by Grote *et al.* (2003), we used a site-specific relationship to portray the GPR-obtained dielectric constant values in the form of maps of estimated water content. Figures 2b and 2c illustrate the estimated water content obtained at two different times during the year using the GPR groundwave technique. Independent comparison with conventional 'point' soil moisture measurements, obtained using time domain reflectometry (TDR) and gravimetric techniques at the locations indicated in Figure 2a, revealed that the estimates of

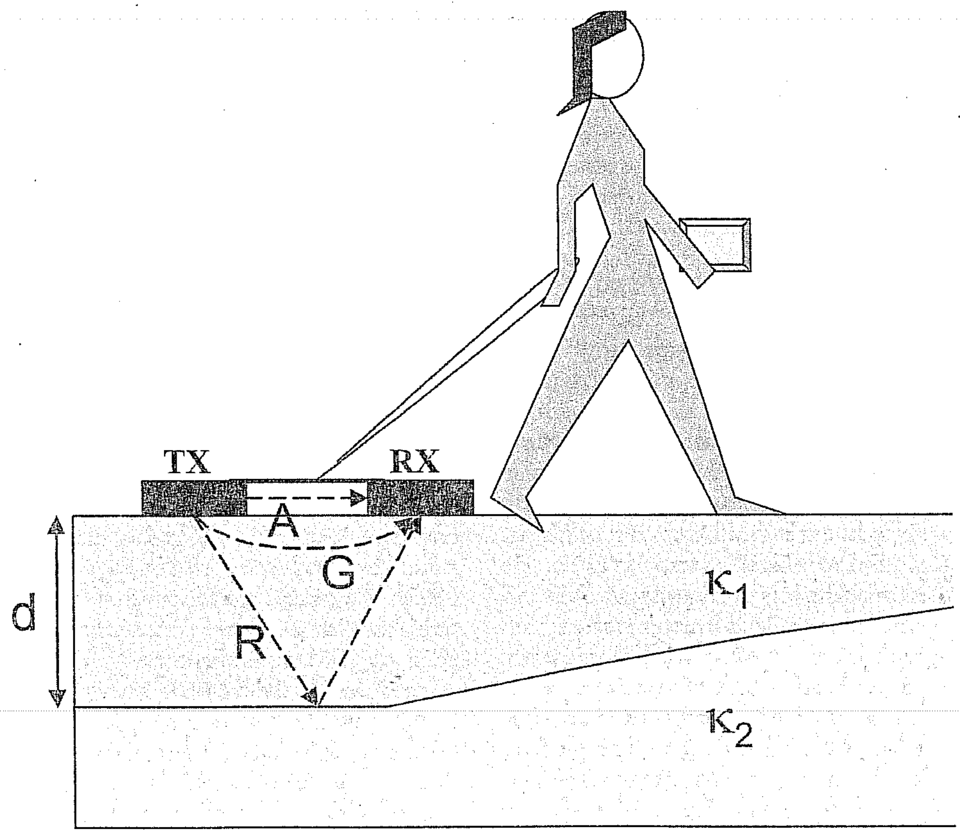

Figure 1. Surface GPR acquisition geometry. Waves travel from the transmitting antenna (TX) to the receiving antenna (RX) through the air (A), and through the soil as groundwaves (G) and as reflected waves (R). The signal is reflected at boundaries that have different dielectric constants (κ).

volumetric water content obtained using the 900 MHz GPR groundwave data were accurate to within 1% by volume, and that the 900 MHz groundwave sampled approximately the upper 15 cm of the soil layer. The spacing of the GPR-obtained water content estimates was extremely dense; each dataset in Figures 2b and 2c contains over 20,000 measurements, which is perhaps the highest density of shallow moisture measurements obtained to date in vineyards. We found that although the mean value of the water content estimates throughout the study block changed during the year, the spatial pattern remained fairly consistent. A detailed discussion of the GPR Mondavi groundwave study is given by Grote *et al.* (2003).

Figure 2d shows the spatial variations in sand content obtained from interpolating between shallow soil samples at the same study site. Comparison of the GPR-obtained water content estimates (Figs. 2b, 2c), and the soil textures (Fig. 2d) reveal the control of soil texture on shallow soil moisture; the sandy areas are consistently dryer while the finer textured soils, which retain moisture better, are consistently wetter. Comparison of these figures with the remote sensing vigor estimates (Fig. 2a) suggest that at this location, the sandy,

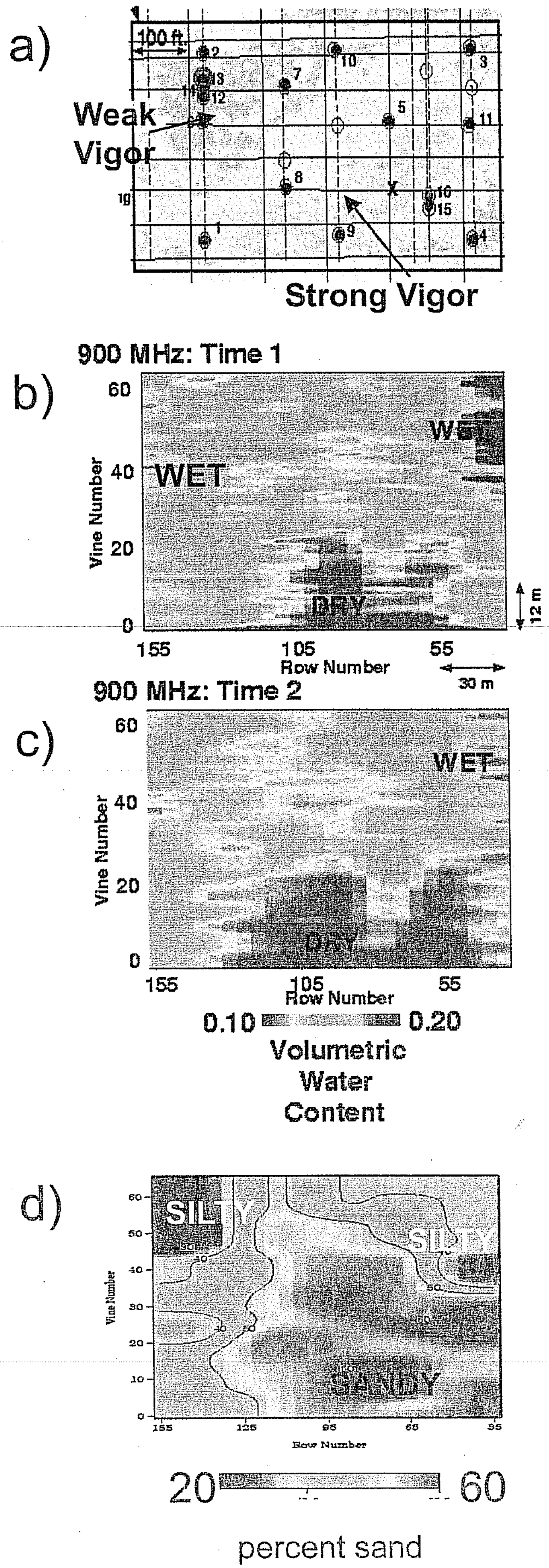

Figure 2. Datasets at the Mondavi Study Site. a) NDVI map obtained from multispectral data (e.g., Johnson, L.D. et al., 2003) indicating areas of weaker vegetation (brown) and stronger vegetation, or vigor (green). Solid black circles indicate locations of neutron probe access tubes; red circles indicate detailed 'study areas' where validation of the GPR moisture content estimates was performed; note 100 ft scale, top left corner; b) Estimates of volumetric water content (m^3/m^3) in the top ~0.15 m obtained using surface 900 MHz GPR groundwave data at one point in time. This map encompasses ~20,000 data points; note 12 and 30 m scales, lower right; c) estimates of volumetric water content (m^3/m^3) during another point in time obtained using surface GPR groundwave data; scale as in (b); d) soil texture maps obtained from interpolation of soil texture data collected in the near surface soil layer throughout the site.

dryer areas have a higher vegetation vigor than the more silt-rich, wet soils. A similar but better correlation was found by comparing soil textures over a thicker depth interval with NDVI responses (Hubbard *et al.*, 2003). The relationships between soil texture, soil moisture, and NDVI suggests that at this site, the silt-rich soils may be too compacted for proper root functioning, or that the uniform water that is applied to the block through irrigation, which is designed to satisfy the needs in the more sand-rich soils, results in over-watering of the finer textured soils. The consistent moisture patterns over time and the apparent linkages between the soil water content, soil texture, and vegetation density are in line with the findings of Bramley (2001), who found that, although annual winegrape yields per acre could vary as much as by a factor of ten within a vineyard, the patterns of spatial variation in yield typically were constant over time. Bramley (2001) found that the variations remained consistent, regardless of year-to-year variations in winegrape yield, which were driven largely by climate.

GPR Reflection Study at the Dehlinger Vineyard

Although the GPR groundwave approach provided high resolution and accurate information about water content at the Mondavi site, the zone of influence of the high frequency groundwave was quite shallow. In this section, we describe the use of GPR reflected waves (refer to Fig. 1) to obtain information about moisture content variations in deeper soil layers. We tested the concept of using GPR reflection arrivals to map deeper water content at the Dehlinger vineyard in Sonoma County. As illustrated in Figure 1, a GPR reflection occurs where there is a dielectric contrast between two subsurface units, such as between a soil layer and bedrock, unsaturated and saturated soils, or possibly between two different soil layers. However, in some soils, GPR reflections may be difficult to detect because soil properties can vary gradually with depth rather than as a series of distinct layers with detectable interfaces. Also, in-row tilling of vineyard soils may disrupt the natural geological variations that can create GPR reflections. Additionally, if the electrical conductivity of the soils is high, i.e. if significant volumes of clay or saline pore fluids are present, the signal attenuation may be too large to permit the GPR signal to travel down to the reflecting interface and back up to the receiving antenna (see Fig. 1). Importantly for GPR reflection methods, the difference in dielectric constant between different soil types alone typically is not large enough to give rise to a strong GPR reflection. However, different soil layers commonly retain different amounts of soil moisture, and these differences in soil moisture content may give rise to a GPR reflection (Martinez and Byrnes, 2001).

In order to estimate the velocity of the reflected event from the recorded two-way travel time of the signal, information about the depth of the reflector ('d' in Fig. 1) must be independently determined, for example, from borehole measurements. If the subsurface horizon that causes the GPR reflection varies greatly in depth over short distances, it may be difficult to determine the depth of the reflecting horizon in all locations. The absence of reasonably accurate depth information will reduce the accuracy of water content estimates. In spite of these difficulties, when a smoothly varying reflecting subsurface horizon can be identified using GPR and borehole data, estimates of water content can be made over time using the GPR reflection method.

We investigated the use of GPR reflection data for providing information about deeper soil layer water content at the Dehlinger Winery in Sonoma County, California. This vineyard is located on Guerneville Road of Sebastopol, a town situated about 8 miles southwest of the city of Santa Rosa. Vineyard soils at this site are composed of a 1.5 to 1.8 m thick red, fine-loamy soil (Sebastopol series) and a buff-coloured, clayey soil (Goldridge series) (Miller, 1972). We used conventional soil textural analysis techniques to assess soil variations within this 80 by 180 m study area. We found that the soil textures vary between sandy loam and clay loam, but are generally composed of sandy clay loam. Up to 30 weight percent gravel is present in the Sebastopol series soil, but gravel is absent in the Goldridge series soil. Topography varies by up to 3.5 m over the study area, with the highest elevations located in the north-western corner of the study site. The water table is approximately 4 m below the ground surface, as measured in nearby wells. Average air temperatures vary between 7°C between November and March and 16°C for the remainder of the year. Mean annual precipitation is around 100 cm, with the majority of the rain falling between November and March. Vines are spaced at 2.44 m (8 feet) intervals and are arranged in rows that are 3.48 m (10 feet) apart. Metal trellises are located at every fourth vine. The crops in this study area are 20 year-old Chardonnay vines, all of which are derived from the same rootstock. No in-row tilling has been performed at this site, and thus the natural soil horizons are 'intact'. An above-trellis spray system is used occasionally to irrigate the winegrapes during hot weather.

GPR reflection travel time data were used to estimate changes in soil water content under a range of soil saturation conditions throughout the growing season at the Dehlinger site. Data were collected during several data acquisition campaigns using 100 MHz and 900 MHz surface GPR antennas. GPR reflections, imaged using 100 MHz antennas, were associated with a thin (~0.1 m thick), low permeability clay layer located 0.8 to 1.3 m below the ground surface and identified from borehole information. GPR profiles indicated that the subsurface reflection is channel-shaped. Field infiltration tests and neutron probe logs suggested that the thin clay layer inhibited vertical water flow, and was coincident with high volumetric water content values. The GPR reflection two-way travel time and the depth of the reflector at the borehole locations were used to calculate an average dielectric constant for soils above the reflector. A site-specific relationship between the dielectric constant and volumetric water content was then used to estimate the depth-averaged volumetric water content of the soils above the reflector. Compared to average water content measurements from calibrated neutron probe logs over the same depth interval, the estimates obtained from GPR reflections at the borehole locations had an error of 1.8%. Details of the Dehlinger GPR reflection study are provided by Lunt *et al.* (2005).

Measurements of travel time to the GPR reflector (obtained using the

100 MHz antennas) and estimates of the depth of the reflecting clay layer (obtained using borehole measurements) were used within a Bayesian estimation approach (following Chen *et al.*, 2001) to estimate deeper, depth-averaged volumetric water content. Figure 3 illustrates the estimated volumetric water content for the zone located above the reflecting clay layer (i.e., at depths less than 1.5m below ground surface) at different times during the year. As was observed at the Mondavi study site, there is a consistent spatial pattern of water content variation over time at the Dehlinger site that might be difficult to detect using conventional measurement approaches. Figure 3 shows that a channel-shaped feature trends NE to SW through the study site, and that this feature influences water content distribution: within this area, the soils are consistently wetter than the surrounding soils. The Dehlinger Winery vineyard manager has recognized that the area outlined by this channel-shaped feature consistently has lower grapevine vegetative growth (= lower vigor) than that of the surrounding area, based on annual measurements of fruit yield and pruning weight. The close correspondence of the soil moisture distribution and the vegetation variations at the Dehlinger Winery site indicate how soil variations may influence grapevine characteristics.

These results suggest that the two-way travel time to a GPR reflection associated with a geological surface can be used under some natural conditions to obtain estimates of average water content when GPR reflectors are present and detectable over time, and when borehole control is available. By using different GPR arrivals and different frequency GPR events, we can sample different effective soil layers and thus resolve soil water content variations vertically as well as laterally. Figure 4 illustrates water content estimates obtained from 900 MHz groundwave data, 100 MHz groundwave data, and 100 MHz reflection data over the Dehlinger site during a single acquisition campaign, which are interpreted to have sampled approximately the top 0.15m, 0.8m, and 1.2m of the subsurface soil, respectively. This example indicates the potential of developing 3D "moisture cubes", using different GPR signal components and frequencies.

SUMMARY AND OUTLOOK

Development of targeted wine grape irrigation strategies, focused on promoting uniformly high wine quality throughout vineyard blocks, necessitates an ability to assess the soil water content across a range of spatial and temporal scales. Although micrometeorological factors are often considered when developing an irrigation approach or assessing fruit quality, the influence of small-scale soil variations and their control on water use and associated fruit quality is poorly understood within the industry. However, ground-based geophysical methods now make it possible to characterize variations in soil properties.

We have investigated the use of surface GPR data, using both groundwave and reflected wave techniques, to map shallow soil water content in high resolution, with acceptable accuracy, and in a non-invasive manner. We found that GPR groundwave techniques provide rapid and accurate estimates of soil water content in shallow soil layers. We found that the GPR reflection technique is less straightforward to perform, as it requires a-priori information about the depth of a reflector, and the application is limited to areas that have good GPR reflectors and low electrical conductivity environments. However, in areas such as the Dehlinger vineyard, which satisfied those criteria, the GPR reflection approach can be used to map water content in deeper soil layers. Use of multiple GPR methods and frequencies offers the potential to characterize the soil in 3-D space. The depth of penetration of the GPR energy is a function of the site-specific conditions. Our GPR reflection example at the Dehlinger site extended to only 1.5 m below the ground surface. However, in areas that are less electrically conductive and that have a deeper GPR reflector, such as a deeper water table or a deep interface between soils and bedrock, the same technique could be used to map soil water content at deeper levels. Both studies suggest that soil water content, soil texture, and vegetation vigor are correlated. Our experience suggests that there is often a temporal persistence of soil moisture patterns within vineyard blocks. This suggests that once soil patterns are identified, point measurements at 'hot spots' within a block may suffice

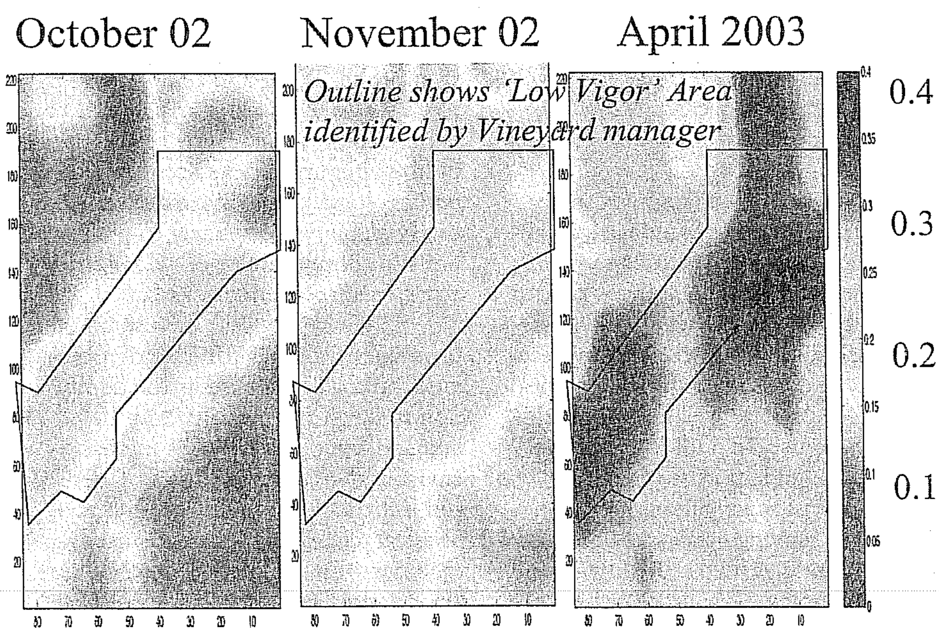

Figure 3 Average volumetric water content of the top soil layer (<1.5m below ground surface), estimated using 100 MHz GPR reflection travel time data at the Dehlinger Vineyards. Black line indicates the boundary of a low vigor area identified by the vineyard manager, which is coincident with the consistently wetter area identified using GPR reflection data. Color key at right indicates relative volumetric water content in units of m^3/m^3, from red (drier) to blue (wetter).

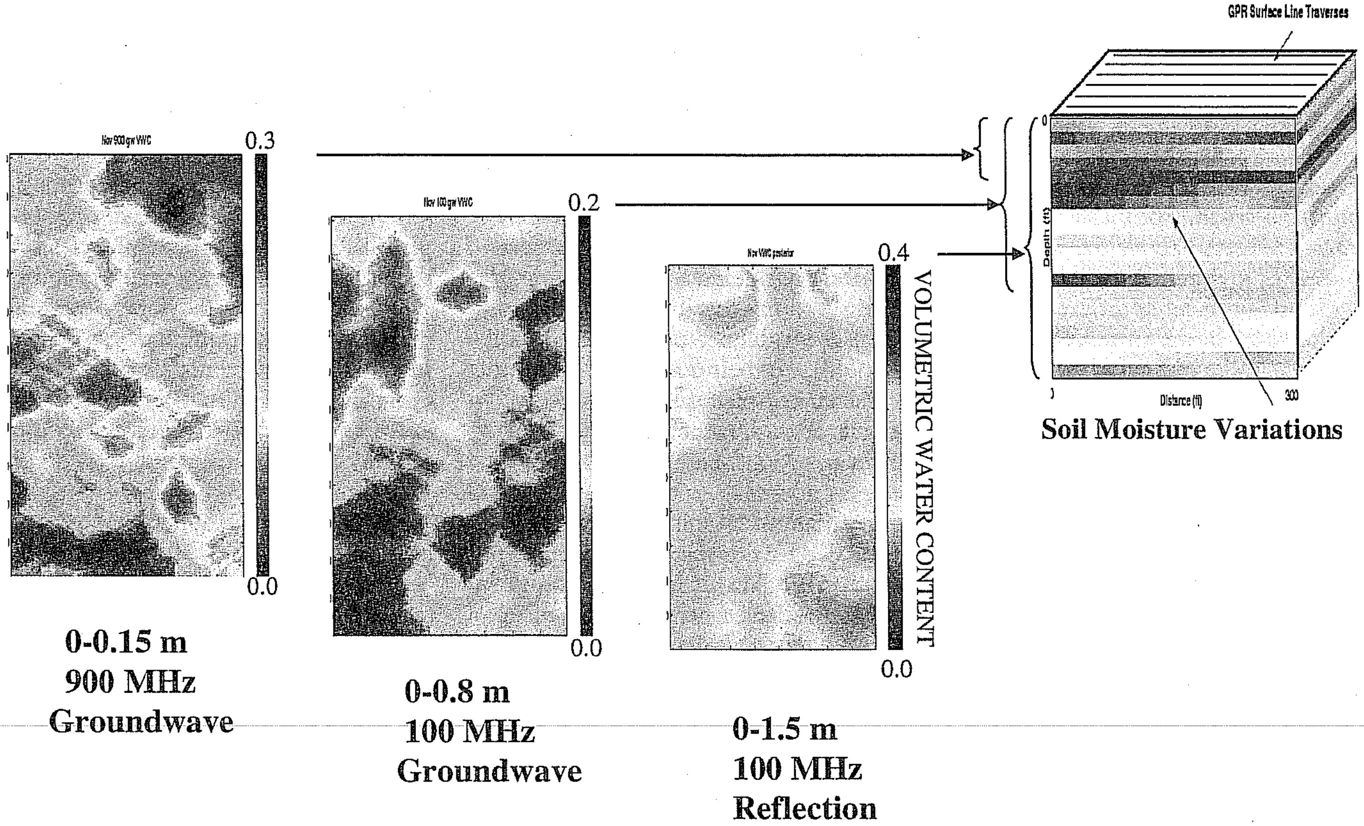

Figure 4. Estimates of volumetric water content (m^3/m^3) obtained over different soil layers using different GPR arrivals and antenna frequencies at the Dehlinger vineyard site, illustrating how different components of the GPR signal and different frequency antennas can potentially be used to construct a 3D soil water content cube. Color keys indicate relative moisture contents.

for management purposes. Geophysical techniques, such as the GPR method presented here, open the way for development of precision viticulture approaches that account for natural soil variabilities.

Because of the high gross revenue per acre and large financial premiums associated with improving wine quality, developing such abilities to map soil properties and use these as a guide for precision irrigation could prove economically feasible for optimizing winegrape production as well as reducing overall water use. In addition to using such data to guide precision farming (such as precision irrigation), the high resolution characterization methods could be very helpful for guiding vineyard development. We are currently in the process of working with Dr. Phillip Freese of WineGrow on development of the Dichiro Vineyards, located approximately five miles north of Healdsburg in Alexander Valley of Sonoma County, California. At this 20 acre site, we are using a variety of measurement methods, including GPR, electrical resistivity, cone penetrometer, neutron probe, TDR, and remote sensing, to delineate vineyard management zones. We are using the maps to guide lay-out of the vineyard blocks according to natural geologic variations and to choose the (variable) vine spacing to promote uniform development of winegrapes across management zones.

We expect that the use of geophysical techniques for guiding precision viticulture will increase as the competition for high fruit quality and the demand for water supplies increases. We envision that a combination of dense soil information, obtained using geophysical techniques, could be used together with remotely-sensed canopy information and microclimate climate data to develop a better understanding of the relationships between soil, vegetation, meteorological variables, and winegrape quality, or of the micro-terroir.

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