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Soil Water Monitoring Using Geophysical Techniques: Development and Applications in Agriculture and Water Resources Management
Technical Completion Report
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Technical Completion Report W-929
Soil water monitoring using geophysical techniques: Development and applications in agriculture and water resources management

ABSTRACT

Monitoring of soil water content is a vital component for agricultural and ecological programs, and the key component for rational water resources management. The information obtained from monitoring is critical for optimizing crop yields, achieving high irrigation efficiencies, planning irrigation scheduling, and minimizing lost yield due to waterlogging and salinization. Such water content monitoring is also important for addressing issues of water quantity and quality, both relevant for managing the environmental impacts of irrigated agriculture and for protecting functional ecosystems. Water content information is also needed for a variety of other scientific investigations, such as climate change, environmental remediation, and engineering investigations.

There are currently no techniques available to yield information about soil heterogeneities and water content at both the resolution and spatial coverage needed to assist in many subsurface problems, and in particular, vineyard management. We investigated the applicability of a surface based geophysical tool, Ground-Penetrating Radar (GPR), for estimating soil water content under both controlled and natural field conditions. Our studies focused on use of travel time data obtained from both the ground wave and from the reflected wave of the GPR signal. Our research shows that GPR groundwave techniques offer an accurate, quick, and reliable approach for estimating shallow (top 20 cm of soil surface) soil water content in very high resolution and in a non-invasive manner, and we recommend further development of this approach for use as a field tool (i.e., technology transfer). Investigations using the reflected component of the GPR signal suggests that accurate estimates of water content can be obtained using this approach when the depth to the reflector is known. More work is necessary to assess the accuracy and feasibility of the GPR reflection approach under natural field conditions.

1. Introduction and Problem Statement

Monitoring of soil water content is a vital component for agricultural and ecological programs, and the key component for rational water resources management. The information obtained from monitoring is critical for optimizing crop yields, achieving high irrigation efficiencies, planning irrigation scheduling, and minimizing lost yield due to waterlogging and salinization. Such water content monitoring is also important for addressing issues of water quantity and quality, both relevant for managing the environmental impacts of irrigated agriculture and for protecting functional ecosystems. Leaching of agrochemicals and salts into the groundwater and downstream ecosystems, for example, can be minimized if irrigation water infiltrates only to the bottom of the root zone. High resolution, continuous water content distributions allow one to design optimal irrigation and chemical application programs that make possible such "prevention at the source." No current technique can provide such information quickly, reliably, and at low cost. Our funded proposal focused on investigating the applicability a surface geophysical method, ground penetrating radar (GPR), for use as a water content estimation tool; development of such a tool could lead to increased water savings and better control on the ecology of natural vegetation.

Our proposal called for careful development and application of GPR data acquisition and inversion techniques under a variety of hydrological/geological conditions. Preliminary experiments that we had conducted at the Richmond Field Station using surface GPR proved very promising; these results are briefly reviewed in Section 3.1. Using funding from this project, we have continued to explore the potential and limitations of GPR methods for water content estimation under both controlled and natural heterogeneity conditions. These studies have illuminated the potential of using GPR to estimate moisture content or changes in moisture content as well as the obstacles that need to be overcome in order for this method to be developed into a reliable field tool. Section 3.2 presents results from extended investigation at the Richmond Field Station test pits, where we have tested the GPR methods under varied but controlled hydrological conditions. Analysis of these data suggested that GPR methods can provide reliable soil moisture content estimates under a variety of saturation conditions. We have also developed a field site at the Robert Mondavi Winery in Napa, CA, as discussed in Section 3.2. At this site, we investigated the potential and limitation of GPR groundwave methods under natural conditions. We chose to initially develop this technique for use in the vineyards because these grapes are high-cash crops, and because precision vineyard management is emerging as a realistic and beneficial approach for the California vineyards. Successful development of GPR methods for vineyard management will naturally encourage experimentation of the technology within other crops as well.

2. Objectives

Our research objectives can be described by the following tasks:

1) *Acquisition:* Investigation of optimal acquisition and inversion methods for ground wave and reflected GPR travel time information under different field moisture conditions.
2) *Survey Analysis and Development of Interpretation Methods*: This task entailed field data calibration, development of the petrophysical relationships needed to transfer the geophysical measurements into water content or soil type, and development to the geophysical data analysis procedures. This task was the key component in the research, and analysis is focused on travel time and amplitude of both ground wave and reflected wave events.
3) *Validation*: Comparison of soil water content point estimates obtained from GPR data with co-located measurements from available from conventional tools such as gravimetric, neutron probe, time-domain reflectometry, and soil textural analysis techniques indicated the viability of this method as a reliable and efficient water-content field tool.
4) *Geostatistical Analysis*: Comparison of water content spatial correlation structure obtained from GPR data with correlation structure obtained from conventional moisture content/soil texture measurement techniques as well as remote sensing over space and season.
5) *Comparisons between GPR-, plant- and airborne-based measurements; assessing the utility for GPR within precision farming practices:* This task entailed comparison of

point and spatial correlation estimates of water content/soil texture, obtained from GPR, with plant and remote sensing information (collected by our NASA collaborators) that are currently being used to guide vineyard farming operations.

3. Procedures and Research Results

Investigations of the use of GPR reflected and groundwaves for near subsurface water content estimation were performed under both controlled and natural conditions. We investigated the use of GPR travel time data by analyzing both GPR ground and reflected wave events. Figure 1 provides a simplified illustration of the typical energy arrivals recorded by the GPR receiving antenna (RX) from a transmitting antenna (TX), including the path that the energy takes in air between the transmitter and receiver, the path of the ground wave travelling in the near subsurface along the air-ground interface, and the path of the reflected event from an interface between materials having different dielectric constant (κ) values. The most rapid acquisition mode of GPR data is the common offset mode. With this mode, the transmitter and receiver are kept a fixed distance apart, as shown by the 'S' in Figure 1, and the entire unit is pulled along the ground surface. By analyzing the travel time of the GPR signal and by knowing the length of the travel path, estimates of velocity and subsequently dielectric constant can be obtained, which can then be translated into estimates of water content. Below we describe experiments performed to assess the accuracy and feasibility of GPR approaches for water content estimation under both controlled and natural conditions.

3.1 Controlled Pit Experiment at the Richmond Field Station: A Review.

We performed a study at the Richmond Field Station in Richmond, California during 1998 to test the feasibility of using surface GPR to estimate sub-asphalt moisture content under controlled conditions (Grote et al., 1999; Grote et al., 2002). As this experiment served as an impetus for current research, we briefly review the experiment and results here. At this site, a 1.5m deep pit was built and filled with clean, compacted sand. During filling, gravimetric moisture content, TDR, and nuclear density gauge measurements were acquired at selected pit locations. Four aluminum plates were buried during at different depths to serve as reflectors during radar acquisition, and neutron probe access tubes were also installed during pit filling. After completing the pit, we collected common offset surface GPR surveys over the buried plates using 450, 900 and 1200 MHz antennas; the locations of the GPR survey lines relative to the buried reflectors and neutron probes are shown in Figure 2. Standard data processing procedures (such as amplitude balancing and low cut filtering) were applied to the surface GPR data. When the GPR apparatus is directly above the plate, the electromagnetic signal travel time is a minimum, and as the transmitter and receiver move farther away from the plates in the pit, the travel time increases. This traverse of GPR transmitter and receiver antenna pair over the buried object yields a “reflection hyperbola” centered at the plate location. This phenomenon is shown by GPR Line 2 in Figure 3, which was collected using a frequency of 450 MHz and which traverses two plates located at depths of 0.6 m and 0.85 m below the ground surface (BGS). By analyzing the travel time between the buried plates and knowing the plate separation distance, we calculated the velocity and dielectric constant as a function of depth within the pit. Petrophysical relationships between dielectric constant and moisture content were both developed in the laboratory using pit material and TDR/gravimetric measurements. This site-specific relationship, together with the published petrophysical relationships given by Topp et al. (*Water Resources Res. 16(3),* 1980) and Roth (*Water Resources Res. 26(10)*, 1990), was used to convert the GPR-obtained dielectric constant values into water content estimates. Figure 4 shows a comparison of water content estimates at a single pit location obtained using surface GPR travel time measurements with the site specific and the Roth relationship. Compared to these estimates are moisture content measurements taken at the same depths using gravimetric techniques. This figure reveals that the surface GPR-obtained estimates are within 1% of those obtained gravimetrically under controlled and optimal conditions.

3.2 Extended Investigations under controlled conditions: Richmond Field Station Phase 2

A second controlled experiment was carried out at the Richmond Field Station during 1999 using constructed test pits. These studies were carried out to test the potential of GPR methods under different moisture conditions and with different reflecting plate geometries, and to compare the GPR results with measurements collected using a benchmark electromagnetic conductivity meter method. During this experiment, two test pits were constructed in a similar style to the test pit described in Section 2.1. To test the method under different yet controlled moisture conditions, the moisture content in Pit #1 was designed to be 6% by volume, and in Pit #2 to be 12% by volume. In comparison to the first pit experiment, the type and location of the buried plates were altered in these experimental pits to determine if there was an optimal plate configuration that would give the best GPR signal-to-noise ratio with the least amount of soil disturbance. Figures 5a and 5b illustrate the plan views of test pits #1 and #2, respectively, and show the different plate configurations. GPR data with central frequencies of 450,900 and 1200 MHz were used to sample the pit material. In addition to collecting GPR data over the test pits, we also collected electromagnetic conductivity data using an EM38 tool, which has previously been used as a non-destructive water content estimation tool. We collected the EM data so that we could compare our GPR soil moisture estimate results with results obtained from a previously developed geophysical tool.

The data collected during Phase 2 suggest the following:

1) Petrophysical relationships between dielectric constant and moisture content developed from co-located measurements in the two new test pits appear to be equally accurate at both the lower and higher saturation values, suggesting that the method should work equally well under both dryer and wetter conditions.
2) The measurement support volume sampled by the EM tool was large compared to the pit dimensions. This suggests that the EM tool is likely not capable of providing the accurate and high-resolution soil moisture changes that are needed in both the lateral and vertical directions and that we are estimating using GPR methods.
3) The data associated with the stacked plate configurations were complicated to interpret, and would probably be even more so under non-ideal natural conditions. If plates are to be stacked the plate thickness should be negligible compared to the

intraplate distance, or it should be thick enough relative to the wavelength to clearly image the top and base of the plate.

4) The orientation of the reflectors was an important variable that can influence the accuracy of the water content estimate.
5) In order to estimate the electromagnetic velocity, we must measure the travel time of the signal from the time it enters the subsurface to the reflectors. In order to do this, we must be able to distinguish the signal onset (or "zero-time") precisely in the recorded signal. Unfortunately, for the near-surface studies, the offset between the transmitting and receiving antennas is close, which causes interference between the air and the ground wave. The superposition of the two arrivals renders determination of a precise zero-time difficult. We find that picking the arrival time of the air wave and compensating for the (known) travel distance by the air wave yields a good "zero time" for the high frequency data. The zero-time issue is also a concern when dealing with GPR groundwaves, which is discussed in Section 3.3.

Testing at the constructed test pits, summarized by Grote et al., 2002, *showed that surface GPR reflection data can be used to estimate volumetric water content to within 1%,* if the depth to the reflecting horizon is known. Using reflected arrival travel times associated with soil layer interfaces, information about water content distribution in deeper layers may also be obtainable (Hubbard et al.; 2003).

3.3 Investigations under Natural Field Conditions.

An important component of our investigation is the testing of GPR water content estimation approaches under natural field conditions, where soil texture and moisture vary spatially, and where soil moisture varies temporally. To investigate the accuracy and feasibility of the GPR groundwave technique, we performed both detailed studies and full field-scale grid studies at the Robert Mondavi Winery, near Napa, California, below.

Below, we briefly describe our results in the following three categories.

1) Near surface soil water content estimation using GPR groundwave travel time data
2) Spatial Correlation analysis using GPR groundwave travel time and other data
3) Relationship between 3-D subsurface data cube and remote sensing information at the Robert Mondavi Study Site

3.3.1 Water Content Information using GPR Groundwaves. We investigated the accuracy and resolution of GPR groundwaves for providing non-invasive and high-resolution estimates of near surface soil moisture content under naturally heterogeneous conditions. This research has been quite fruitful in terms of publications and presentations, and has attracted interest in the scientific as well as the precision agricultural community. The GPR groundwave is a wave that is tied to the air-ground interface as shown in Figure 1. Thus, by nature, it samples only the shallow near-subsurface soil zone. The depth of influence is a function of many factors including the electrical conductivity of the soil, the soil moisture, and the GPR antenna frequency. Given the parameters at our site and for our system, the GPR groundwave data sample approximately the upper 20cm of the subsurface.

The groundwave study was performed at a vineyard within the Robert Mondavi Winery near Napa, California. Figure 6 shows the location of the study site and indicates some of the different types of subsurface data that were collected at the site. In this study, densely spaced GPR measurements were collected using two different frequency antennas (900 and 450 MHz), and following the analysis procedure developed during the first year of the project, estimates of near surface (upper 20 cm) soil water content were obtained from these data at the Mondavi Study site several times during the year. Comparison of the water content values estimated using GPR groundwave data with gravimetric water content measurements showed that the GPR estimates were accurate and that the vertical distribution of water content could be inferred using multi-frequency GPR data. The pattern of spatial variability of water content across the vineyard obtained from GPR estimates did not change significantly with time, although the absolute water content values varied seasonally and with irrigation. We interpret the spatial patterns of soil moisture content to be controlled by soil texture.

Figure 7 shows the variation in moisture content estimated using 900 MHz GPR groundwave data collected at four times during the year. The May survey (upper left) occurred at the beginning of the dry season, one week after a light precipitation event, while the August survey was taken during the dry season, three weeks after the most recent irrigation. The September data were also collected during the dry season, but only two days after irrigation, and the January data were taken one day after light precipitation during the rainy season. Please note that the January survey (lower right) has a different range of water content values than the other images in Figure 7. The GPR data sampling for these figures is extremely dense; each display in Figure 6 was created using over 20,000 data points from the surface GPR data collected over the 5 acre study area. Comparison of these figures reveals the persistent spatial pattern of water content as was mentioned above, but shows that the mean water content varies with season and irrigation (Hubbard et al., 2002). A comparison of 450 MHz and 900 MHz data collected during the same acquisition campaign is given in Figure 8. This figure reveals that the lower and higher frequency data sets also have similar, although not exact spatial patterns of near surface water content. As the lower frequency data are expected to sample deeper soil depths than the shallower near-surface soils, it is not surprising that the mean water content of the lower frequency data set in this comparison is higher than the mean water content associated with the higher frequency data set. Figures 7 and 8 display how GPR can yield information about moisture content and its variations over 3-D space and time. 9 displays the percent sand content in the near surface (upper 20cm) soil samples (with the other components being silt and clay). Comparisons of Figures 6 and 7 with Figure 8 suggest the textural control on water content: the sandy areas are consistently dryer than the more silt- and clay-rich areas at the Mondavi Site. The comparisons of GPR-derived estimates of water content to gravimetric and TDR measurements throughout the field site show that *GPR groundwave techniques can be used to provide quick, spatially dense and non-invasive estimates of shallow water content in large-scale field applications that are accurate to within 1.5%* (Grote et al., 2003). This information is potentially very useful to a variety of subsurface problems where the near-surface moisture distribution or flux across the air and ground interface is important.

3.3.2 Spatial Correlation Summary

Information about the spatial correlation function of water content, or the persistence of correlation of this parameter in space (and time), is important as input to stochastic vadose zone modeling and climatic modeling. Additionally, general information about agricultural soil spatial correlation functions could help to ensure that field data are collected using a spacing that will capture the expected spatial variability of the site. We have used the exhaustive near-surface soil moisture content estimates obtained from GPR groundwave data to investigate the spatial variability of water content at the Mondavi Site as a function of season and irrigation, to test how sensitive the model is to data density, and to investigate the role of farming practices on the water content spatial variability.

Estimation of the spatial correlation function obtained using GPR data show that the relevant correlation length (effective range) of near-surface water content over time is on the order of ~5 m, and that samples taken at distances greater than ~5 m away add little value when using estimation techniques based upon spatial correlation. As it is rare that conventional "point" measurements in agricultural settings (i.e., using TDR, gravimetric or neutron probe techniques) are obtained using spacing smaller than 5m, this suggests a limited use of conventional measurement for obtaining reliable soil water content spatial correlation models.

Geostatistical evaluation of the near-surface GPR-obtained water content data has also shown that crop cover, precipitation and irrigation, and depth beneath the ground surface dramatically influence the spatial correlation function. Analysis of GPR data that measures the soil water content at different depths has shown that the highest water content variability is at the near surface, and variability decreases with increasing depth. Additionally, our study revealed that the GPR method is sensitive enough to detect systematic spatial correlation variations in moisture content associated with ground cover conditions. Rows associated with crop cover (a California grass) show both lower average water content and lower water content variability during the growing season (spring, summer, and fall) than rows without crop cover. During the wet winter season when the ground is fairly uniformly saturated, we observe similar average water contents and water content variability in rows with and without crop cover. Rows with crop cover show the greatest variability when the soil water content is high (winter), while rows without crop cover show the greatest variability when the soil water content is relatively low but soon after irrigation has occurred. Figure 10 shows a variogram of volumetric water content obtained using 900MH GPR groundwave data collected at the same Mondavi Field site that is categorized according to the presence or absence of a typical California grass ground cover. This figure reveals that there are systematic differences between the two different conditions within the same field site, and highlights the sensitivity of the GPR system for detecting factors that control water infiltration and distribution in the near subsurface.

3.3.3 Comparison of Subsurface Soil and Remote Sensing Information

An exploratory analysis was performed to investigate the relationships between airborne remote sensing data and VWC and soil texture within the Robert Mondavi Study Site shown in Figure 6. The study was undertaken to understand the relationships between the vegetation vigor (obtained from remote sensing of the plant canopy) and subsurface soil properties such as volumetric water content and soil texture (obtained using geophysical and conventional measurements). This relationship may be important for accurate prediction of vegetation growth given subsurface soil information, for improved precision vineyard layout and farming practices, and for understanding the control of subsurface soil properties on water and nutrient fluxes across the air-ground interface.

In this exploratory analysis, we compared the variations in subsurface soil moisture and soil texture over space and time with remote sensing data collected using multi-spectral airborne data over the same site. NDVI (Normalized Difference Vegetation Index) estimates were obtained from the remote sensing data. In theory and in observation at our site, higher NDVI data correspond to more vigorous vegetation, while lower NDVI values correspond to sparser vegetation. Thus, the remote sensing data reveal information about the density of the vine grape canopy, which we suspect, is controlled by subsurface variations in soil texture and soil moisture. Our analysis consisted of constructing a 3-D data cube of soil properties over the area shown in Figure 6 from a depth range from the ground surface to the water table (about 3 m below ground surface). This data cube was constructed using water content information obtained in the near surface from GPR data, as described above, along with soil moisture and soil texture obtained from interpolated borehole data whose locations are also shown in Figure 6.

Comparison of the subsurface data and the NDVI canopy data suggested that the higher values of NDVI (more vigorous vegetation) were highly correlated with higher sand content and lower water content in this unsaturated zone. An example of the good comparison between remote sensing NDVI responses and the average sand content over the first 2.5 m of soil is shown in Figure 11. The data also suggested that the subsurface zone that appeared to exert the most influence on the vegetation response be between 0.5 and 1.5 m below ground surface, which may represent the primary root zone. Our dense GPR, conventional subsurface data, and remote sensing data sets at the Mondavi Site have allowed us to perform this exploratory analysis to investigate the static controls of subsurface soil properties on vegetation responses. However, continued systematic investigation is necessary to understand the processes involved in the moisture uptake, to quantify the fluxes across the air-ground boundary, and to understand the temporal relationships between the soil and plant responses. Improved understanding and quantification of the fluxes and processes across the air-ground boundary is valuable for a variety of systems investigations. As described by Hubbard et al. (2003), use of high resolution estimates soil parameter estimates, obtained from GPR, has great potential for improving water balance predictions, which is important to a variety of research areas such as precision agriculture and climatic studies.

5.CONCLUSIONS

Our investigations have focused on the use of surface GPR data for estimating shallow soil water content. We have explored the use of both groundwave and reflected GPR wave travel time data for estimating soil water content, and have assessed the feasibility and accuracy of the method, as well as the limitations. Based on our studies, we conclude the following:

1) Soil water content in the upper 10-20 cm can be accurately estimated (within ~1.5%) using 900 MHz GPR groundwave travel time data. Difficulties may arise in very dry times due to the superposition of the air and groundwave, although alternate event picking procedures have been successfully developed to deal with this obstacle (Grote

et al. 2003). As the shallow soil water content is closely linked to soil texture, potential exists to exploit this information for estimating soil texture. Finally, use of multiple frequency GPR groundwave data sets may permit investigation of the average soil water content over thicker soil packages. GPR groundwave data in our studies were shown to be very useful for investing water distribution over space and time for both agricultural and transportation studies.

2) Soil water content using surface GPR reflection data can be used to accurately (within ~1%) estimate the average water content associated with a soil package located above the reflecting horizon (Grote et al., 2002) when the depth to the reflector is accurately known. In natural systems, where more uncertainty exists about the nature and depth of reflecting horizons, the error in water content estimates associated with surface GPR reflection travel time data increases. Assessing the accuracy of GPR reflection travel time data for estimating water content under natural conditions is a continuing topic of research (i.e., Hubbard et al., 2003).
3) The water content estimates obtained from GPR data provide an unparalleled density of information, which can be extremely useful for a variety of subsurface investigations. In our studies, we used the dense data for a variety of investigations, including: assessing the differences between estimated water content correlation length scales obtained using conventional vs. GPR data, the influence of cover crops on water content distribution, investigating the link between the soil and plant parameters, and for use as input for improving vineyard water balance numerical predictions.

In summary, our research has assessed the utility of GPR groundwave data for shallow water content estimation. Our research has shown that GPR groundwave methods offer a good, reliable, and relatively easy to use geophysical approach for field-scale estimation of shallow water content. Although the GPR reflection approach yielded accurate estimates of water content at greater depths than the groundwave approach, this approach has limitations as a field tool, as the interpretation is more time consuming and expertise is needed to identify the source and depth of the reflector. Both GPR groundwave and reflection information can be used for a variety of subsurface investigations where understanding water infiltration and distribution over space and time is important. Additional work is necessary to transfer the GPR-groundwave technology to a more user-friendly interface for use in the field by non-experts, and to fully assess the GPR reflection method accuracy under natural conditions and away from borehole control.

6. PUBLICATIONS

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Figure 1 Illustration conceptually showing the travel paths of the ground wave and the reflected wave from the transmitting antenna (TX) to the receiving antenna (RX). The dielectric constant of the upper soil layer (κ_1) influences the velocity of both the groundwave and the reflected wave.

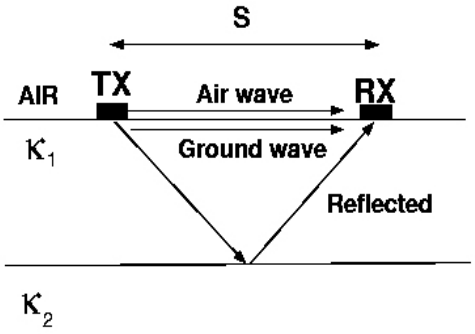


Figure 2

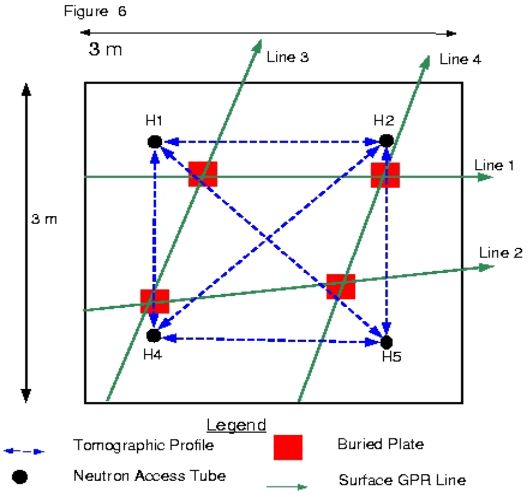


Figure 3

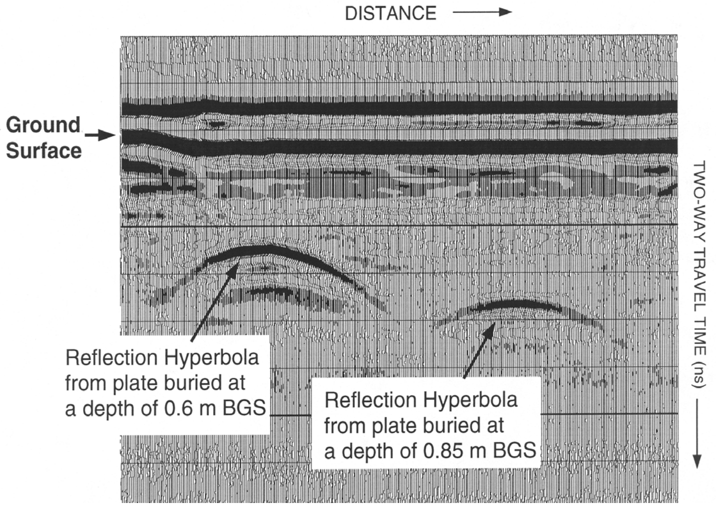
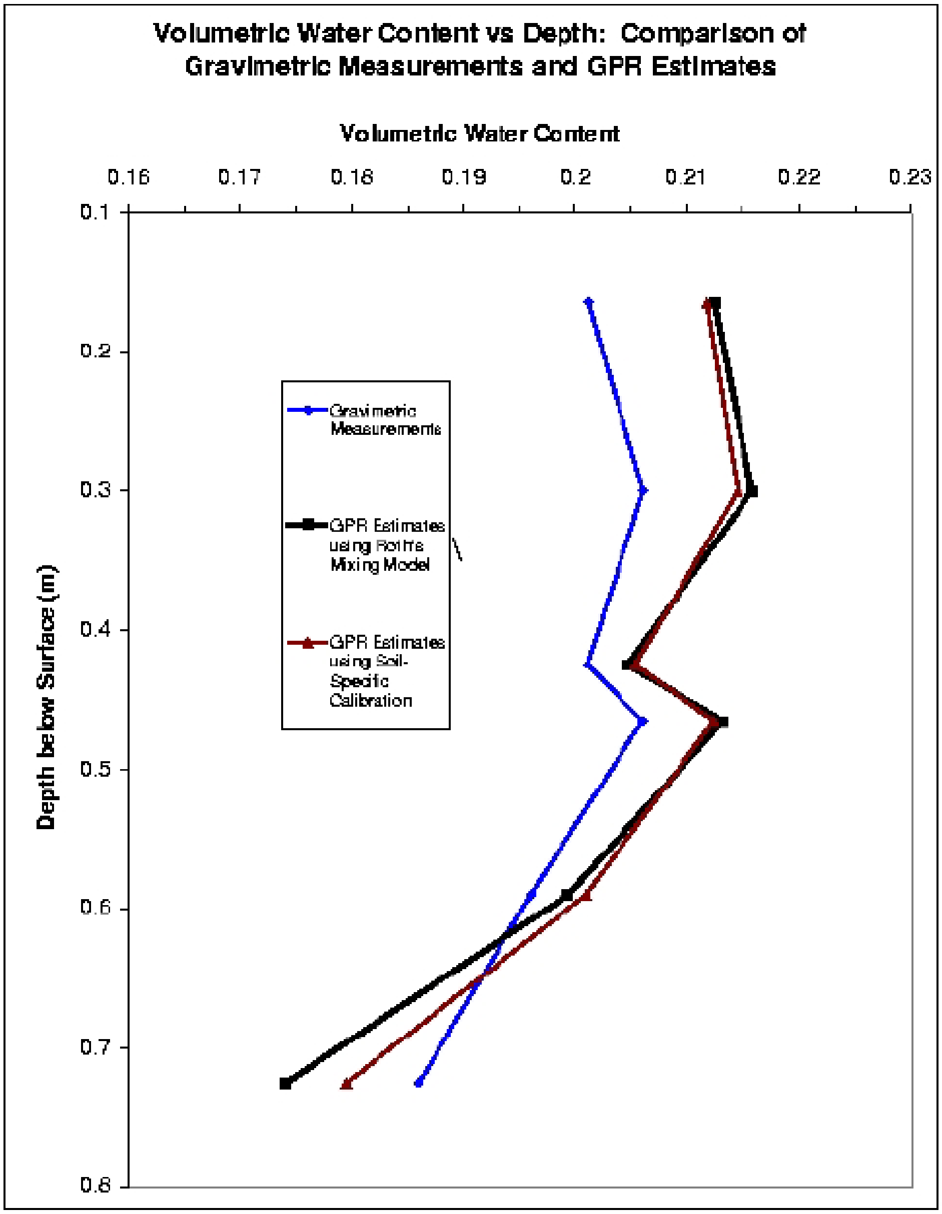


Figure 4



Volumetric Water Content vs Depth: Comparison of Gravimetric Measurements and GPR Estimates
Volumetric Water Content
0.16
0.17
0.18
0.19
0.2
0.21
0.22
0.23
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Depth below Surface (m)
Gravimetric Measurements
GPR Estimates using Roth's Mixing Model
GPR Estimates using Soil-Specific Calibration

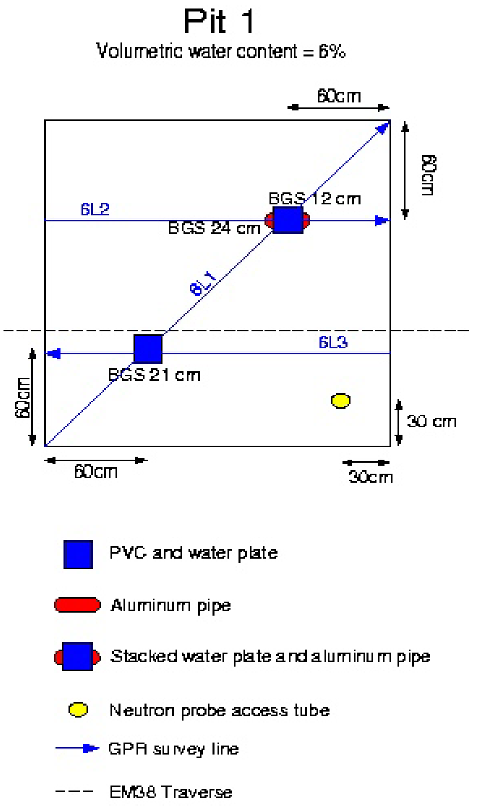


Figure 5a

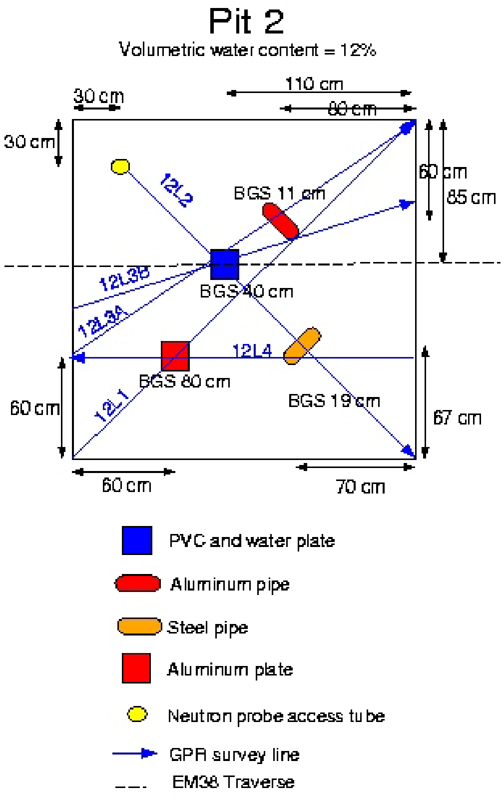


Figure 5b

Figure 6 Field Site location and acquired data.

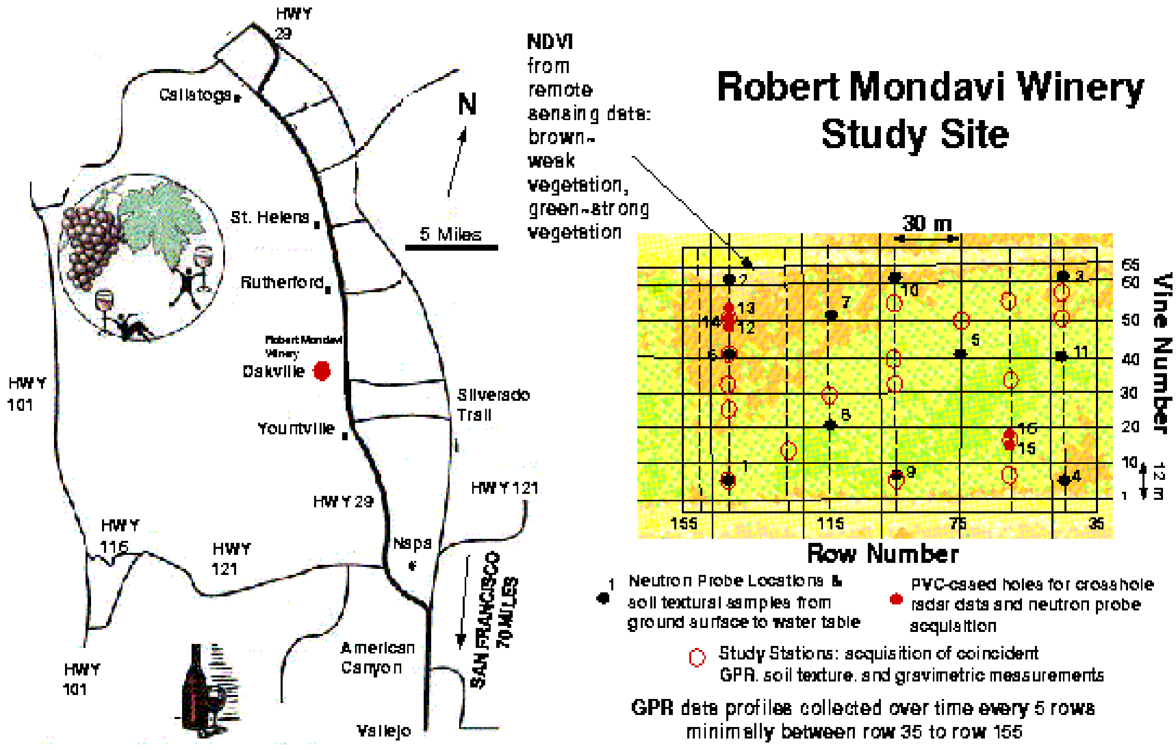
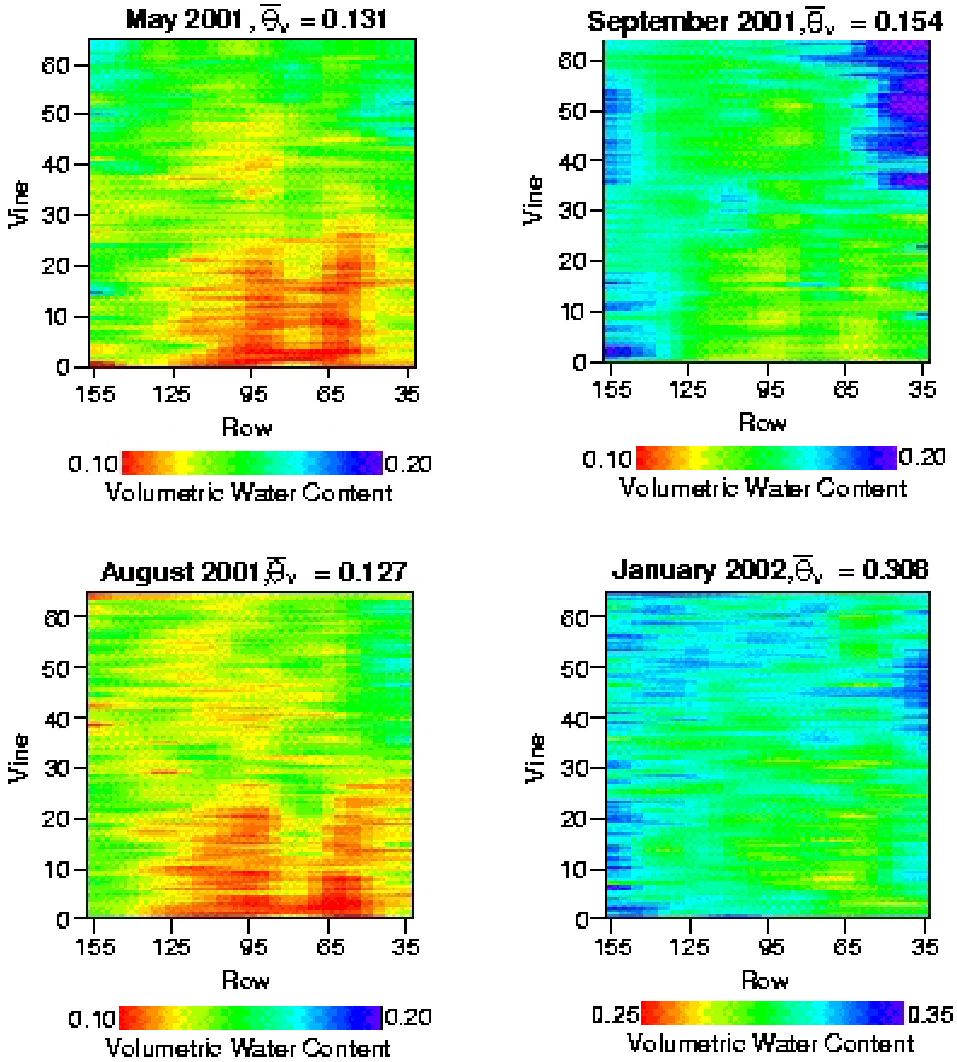


Figure 7

Estimated volumetric water content obtained from GPR data collected over the entire site shown in Figure 1 during different times of the year.



May 2001 , $\overline{\theta}_v$ = 0.131

September 2001, $\overline{\theta}_v$ = 0.154

August 2001, $\overline{\theta}_v$ = 0.127

January 2002, $\overline{\theta}_v$ = 0.308

Figure 8 Water content estimated over the field site using high frequency 900 MHz GPR data (that sample shallower) and lower frequency 450 MHz GPR data (that sample deeper). This figure reveals the potential of multi-frequency GPR data for estimation of water content over 3-D space.

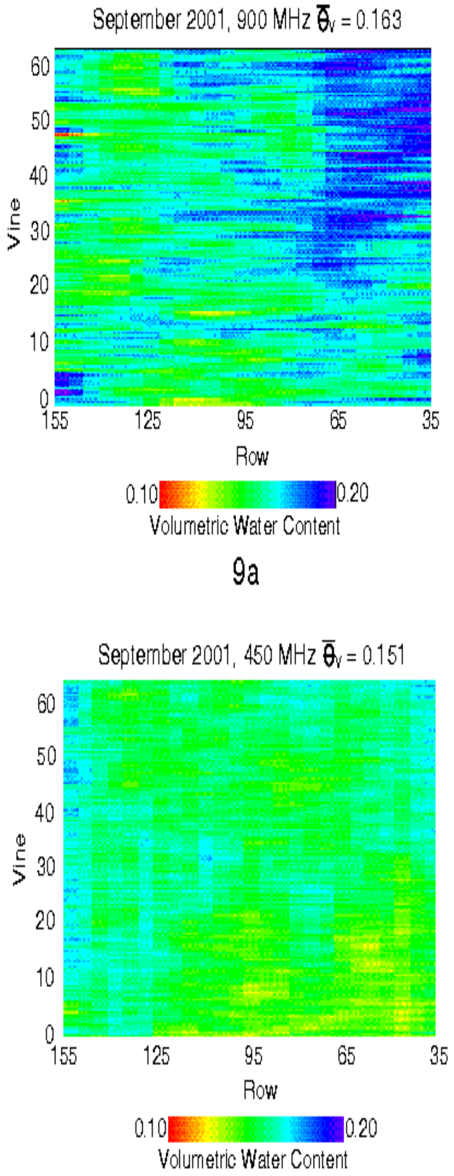


Figure 9 Near-surface soil texture over the site shown in Figure 6.

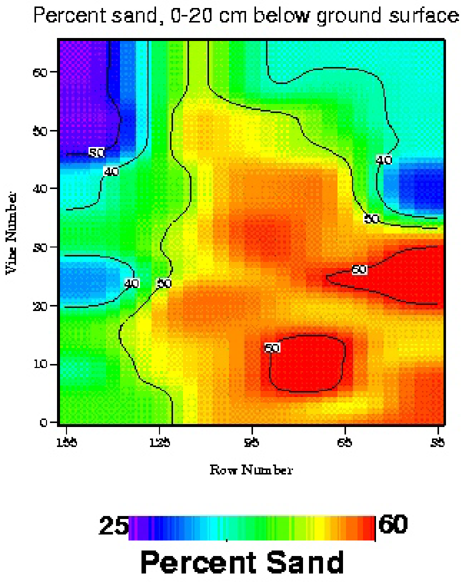


Figure 10 Variograms showing differences in spatial correlation patterns as a function of ground cover.

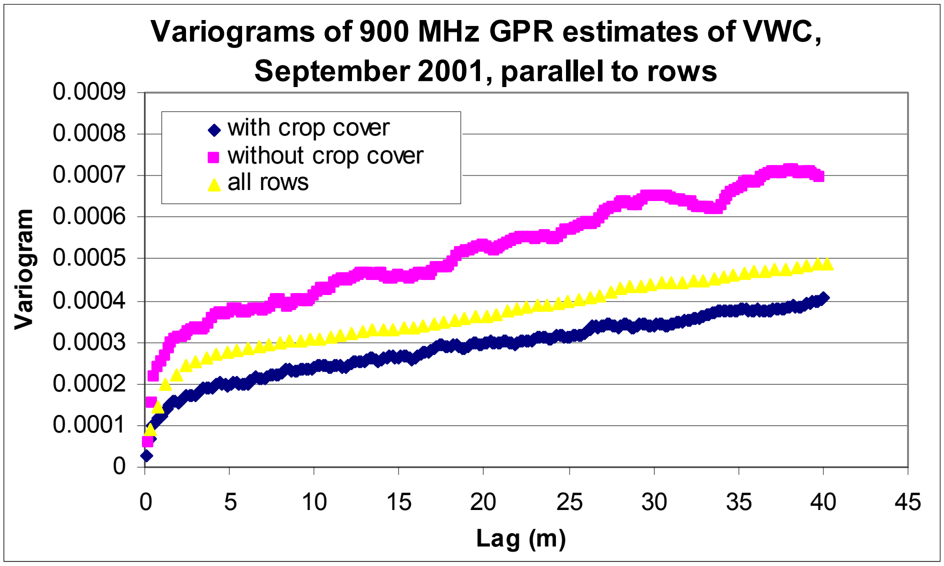
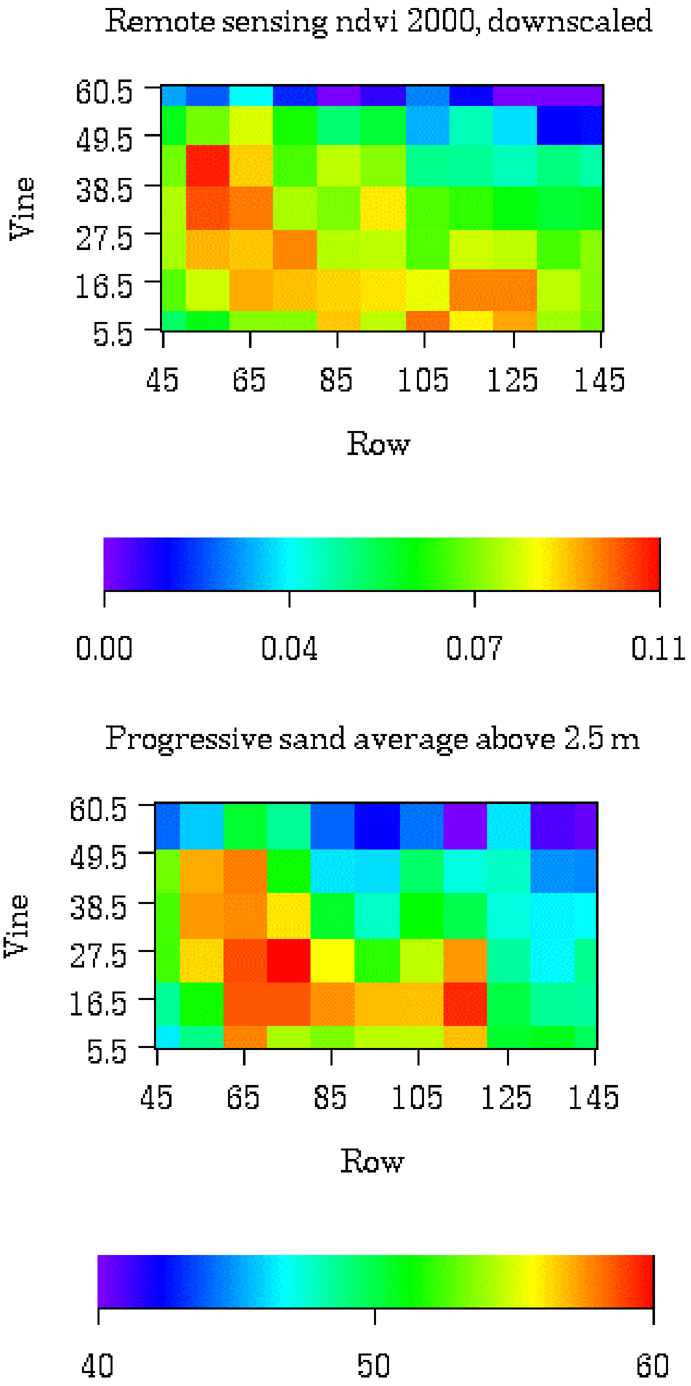


Figure 11 Comparison of remote sensing NDVI data, which indicates plant vigor, and average sand content to a depth of 2.5m over the site shown in Figure 6.



Remote sensing ndvi 2000, downscaled

Progressive sand average above 2.5 m