DETERMINING THE INFLUENCE OF TRANSPIRATION ON SOIL MOISTURE PATHWAYS USING ELECTRICAL RESISTIVITY IMAGING

by
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ABSTRACT

Many hydrologic models assume the vegetation and streamflow are fed by the same source of water, but isotopic studies have shown this is not always the case, especially in semi-arid climates. We investigate how soil moisture pathways are affected by daily transpiration using time-lapse electrical resistivity imaging (ERI) on a ponderosa pine and the surrounding soil during the growing season. By comparing sapflow measurements to the ERI data, we find that high periods of sapflow within the diel cycle are aligned with decreases in ground conductivity and soil moisture due to drying out of the soil during uptake. As the sapflow slows during the night, the ground conductivity increases as the soil is replenished. The mean and variance of the ground conductivity decreases into the summer dry season, describing drier soil and smaller diel fluctuations as the summer progresses. Sapflow does not significantly decrease through the summer, however, suggesting use of a deeper water source to maintain sapflow in a time of soil moisture depletion. ERI successfully captured spatiotemporal variability of soil moisture on daily and seasonal timescales, and with further research could be used to monitor temporal changes in tree water content.
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Dedicated to my loving and supportive fiancé.
CHAPTER 1
GENERAL INTRODUCTION

Understanding how watersheds gain, transport, and lose water is vital to water management. Transpiration, the process by which trees lose water to the atmosphere during photosynthesis, contributes to a large portion of the water cycle in forested semi-arid climates. Due to the significant role that vegetation plays in forested watersheds, questions arise regarding the change in hydrologic response to natural events such as wildfire and pine beetle infestation. What happens to the quantity and quality of the subsurface water when vegetation is drastically decreased? Before investigating possible hydrologic responses in the absence of transpiration, it is important to first understand hydrologic patterns due to its presence.

In hydrologic modeling, it is currently assumed that the water used by vegetation during daily transpiration essentially comes from the same “pool” of water by which groundwater and streams are fed. In climates that are fairly wet during all times of the year, this assumption may be appropriate due to vegetation having relatively consistent access to water. However, in semi-arid regions, where summers are typically dry and soil moisture is significantly lower than in other times of the year, this assumption does not hold true. Isotopic analyses have shown a clear separation between vegetation and stream source water during periods of low soil moisture (Dawson and Ehleringer, 1991; Brooks et al., 2010). During wet seasons, the soil is saturated and the streams are fed by water traveling through relatively larger soil pores via gravity. Vegetation also extracts water from these larger soil pores during the wet season. However, during dry seasons, the soil water content is much lower, and most of the water remaining in the soil is held in small pores between soil grains. This water cannot be drained by gravity but can be extracted by plant roots (Figure 1.1). Although transpiration is strongly coupled to stream flow patterns, the water flowing in the stream and the water used by the vegetation during these times of year is not from the same source.

To further understand how vegetation processes modify hydrologic flow, it is essential to unpack what is inside the current “black box” model, starting with the shallow subsurface in direct contact with vegetation. Feedbacks between soil moisture and transpiration exist in seasonally dry climates. Moore et al. (2011) found that seasonal soil moisture levels controlled
the correlation between transpiration and streamflow. Sapflow and thus transpiration in a mixed stand of pine and spruce trees was found to decrease when 80% of the extractable water in the rooting zone had been depleted (Lagergren and Lindroth, 2002).

Figure 1.1: Conceptual model of separation between source water of vegetation and streams during dry seasons in semi-arid climates.

It is difficult to quantify the connections between transpiration and soil moisture with standard point measurements due to spatial and temporal variability. It is important to capture the size and shape of root distributions, soil moisture changes in space and time, and transpiration patterns to investigate how each of these pieces interact with one another. Soil moisture is typically monitored with highly accurate point measurements such as time-domain reflectometry (TDR), gravimetric methods, direct-push based sensor probes, neutron probes. Transpiration at the tree scale is typically quantified using a point measurement known as sapflux velocity, which also has spatial resolution limitations. However, these methods cannot capture spatial changes, even with a dense distribution of point measurements.

The goal of this research is to use electrical resistivity imaging (ERI), a geophysical method, to explore the connection between transpiration and soil moisture on a single tree and the surrounding soil plot in conjunction with standard point measurements. By using ERI, we are able to capture changes within the soil-plant-atmosphere system with high spatial resolution without sacrificing temporal resolution.
In this study we found spatial and temporal variability of the uptake of water due to transpiration. During the day, transpiration is high, and much of the soil water is taken up by the tree. The decrease in the soil water content causes a decrease in the bulk conductivity of the soil plot shown in our results. During the night, transpiration is very low and no the tree is no longer drawing water from the subsurface (Figure 1.2). This allows the water to be replenished, increasing the soil water content. The mechanism behind the re-wetting process is likely hydraulic redistribution, where water in wet soil areas is moved to areas of dry soil via the root system. The results from this research have been compiled into the following manuscript for submission to the Journal of Hydrology. After the paper, the reader will find a closing statement regarding future research directions.

Figure 1.2: Conceptual model of the soil-plant system. A decrease in soil moisture during the day occurs during high transpiration periods. An increase in soil moisture then occurs during the night, partially refilling the soil plot for the next day of transpiration.
CHAPTER 2
DETERMINING THE INFLUENCE OF TRANSPIRATION ON SOIL MOISTURE PATHWAYS USING ELECTRICAL RESISTIVITY IMAGING

A paper to be submitted to the *Journal of Hydrology*
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2.1 Abstract

Many hydrologic models assume the vegetation and streamflow are fed by the same source of water, but isotopic studies have shown this is not always the case, especially in semi-arid climates. We investigate how soil moisture pathways are affected by daily transpiration using time-lapse electrical resistivity imaging (ERI) on a ponderosa pine and the surrounding soil during the growing season. By comparing sapflow measurements to the ERI data, we find that high periods of sapflow within the diel cycle are aligned with decreases in ground conductivity and soil moisture due to drying out of the soil during uptake. As the sapflow slows during the night, the ground conductivity increases as the soil is replenished. The mean and variance of the ground conductivity decreases into the summer dry season, describing drier soil and smaller diel fluctuations as the summer progresses. Sapflow does not significantly decrease through the summer, however, suggesting use of a deeper water source to maintain sapflow in a time of soil moisture depletion. ERI successfully captured spatiotemporal variability of soil moisture on daily and seasonal timescales, and with further research could be used to monitor temporal changes in tree water content.

2.2 Introduction

A unifying assumption in how forest ecosystems interact with the hydrologic cycle is transitory flow. It is assumed that when precipitation infiltrates, the water that is currently in the subsurface is pushed deeper and replaced by the infiltrating water. This implies that the water used by vegetation for transpiration is essentially the same water that contributes to baseflow and runoff (Hewlett and Hibbert, 1967; McDonnell et al., 2007). However, isotopic studies have

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indicated differences between water that is extracted by forested riparian and hillslope areas and water in the streams (e.g., Brooks et al., 2010; Dawson and Ehleringer, 1991). Despite the observation of a clear connection between transpiration and streamflow in watersheds of varying sizes and locations via correlating diel (24-hour) cycles in transpiration and streamflow (Bond et al., 2002; Boronina et al., 2005; Butler et al., 2007; Loheide et al., 2008; Reigner, 1966; Wondzell et al., 2010), how the transpiration signal is propagated to the stream is poorly understood.

Quantifying these subsurface connections has been difficult due to complexities in measuring the dynamic nature of plant root distribution, uptake patterns, transpiration, and soil-water inputs, which create highly heterogeneous systems that are difficult to capture with standard point measurements. For example, hydraulic redistribution, the process of passive water movement from relatively wet to dry soil areas via root systems (Blebly et al., 2010; Burgess et al., 2000; Richards and Caldwell, 1987), largely depends on the size and shape of root systems, and influences the interactions between the subsurface and vegetation (Schwinning, 2010; Stone and Kalisz, 1991). However, current measurement techniques exploring root systems and soil moisture prove to be time-consuming, technically demanding, and disruptive to the soil plot (Maeght et al., 2013). Another common limitation of using point measurements to monitor soil moisture and transpiration is limited spatial resolution, which leads to uncertainties when applying results from a single point across a heterogeneous area. Geophysical methods can be used to overcome some of the limitations of point measurements. Time-lapse electrical resistivity imaging (ERI) allows for non-invasive 3D monitoring of the subsurface at broad spatial scales without sacrificing temporal resolution. ERI has also been applied to tree ecology in a limited number of studies, successfully imaging cavities and fungus within tree trunks due to infestation and decay (e.g. al Hagrey, 2006; Nicolotti et al., 2003; Skutt et al., 1972) and delineating sapwood from heartwood (al Hagrey, 2006; Bieker and Rust, 2010; Guyot et al., 2013; Wang et al., 2015).

Here, we explore the connection between soil moisture and tree transpiration using traditional point-scale measurements, but couple these with ERI to monitor spatially exhaustive moisture content changes within the soil and tree. While time-lapse ERI is an established method for the non-invasive 3D monitoring of soil moisture movement (e.g., Beff et al., 2013; Brunet et al., 2010; Chambers et al., 2014; Schwartz et al., 2008; Zhou et al., 2001), this is the first known
application to monitor tree transpiration and its connections to soil moisture through time. We aim to a) evaluate the application of ERI as a minimally invasive method with high spatial resolution to monitor spatial and temporal changes in soil and tree water content and b) relate these water content patterns to the seasonal variation in transpiration and explore their feedbacks.

2.3 **Field Site Description**

The study site is located in the Gordon Gulch catchment within the Arapahoe National Forest in the Boulder Creek Critical Zone Observatory (BCCZO) in Boulder, Colorado (Figure 2.1). Gordon Gulch is approximately 2.7 kilometers in area and ranges from 2446 – 2737 meters in elevation. The Gordon Gulch catchment is mainly within the upper montane climatic zone. Average annual rainfall is 519 mm per year with the maximum occurring in May and minimum during winter months. The catchment contains three distinct types of vegetation cover: 1) aspen (*Populus tremuloides*) groves near the stream, 2) open meadows, and 3) the forested hillslopes. The north-facing hillsides are densely vegetated by lodgepole pine (*Pinus contorta*) and some western Douglas-fir (*Pseudotsuga menziesii*). The south-facing slopes support less densely vegetated areas of ponderosa pines (*Pinus ponderosa*) and aspen. The ponderosa pine individual used in this study is located on a south-facing slope near the southeast edge of the catchment (40° 0’ 46.289”N, 105° 27’ 43.715”W) approximately 100 meters north of the Gordon Gulch stream, and was chosen as a representative pine of those on the south-facing hillslopes of this catchment.

![Figure 2.1: Map of the study area with Gordon Gulch stream (blue line), location of the study tree (green dot), and 40-foot elevation contours.](image-url)
The field site is underlain mainly by biotite gneiss and is characterized by unglaciated low-relief remnants of a dissected Tertiary erosion surface. The soils are characterized as typic haplustolls with varying ranges of percent sand, silt, and clay with depth. Percent sand by volume ranges from 55 to 65 percent. Silt ranges from 25 to 50 percent with higher silt content in the shallow layers (< 8 inches depth) and lower contents in deeper layers. Clay content is approximately 10 percent, but ranges from 2 to 15 percent. Along the hillslopes, soil depth is approximately 30-50 centimeters (NRCS Soil Survey, 2015). The soil profile is underlain by a saprolite layer consisting of highly weathered rock that extends five to seven meters in depth (Befus et al., 2011).

2.4 Background

In this section, we first review common point-measurement techniques for soil moisture and transpiration monitoring. We then discuss ERI and its current applications in soil moisture monitoring and tree imaging.

2.4.1 Soil moisture and transpiration point measurements

Soil moisture is commonly measured using techniques such as time-domain reflectometry (TDR), gravimetric methods, direct-push based sensor probes, and neutron probes. One common limitation of many soil moisture measurement techniques is the limited spatial coverage in heterogeneous soil plots. Not only are physical soil characteristics often heterogeneous in forest environments, but the effect of transpiration on the spatial distribution of water content is key to characterizing water movement within vadose zone. In trees, sap flux is a commonly used method for monitoring transpiration and is typically based on heat dissipation velocities. Sap flux is a point measurement that is scaled up based on an assumed uniform radial sapwood distribution, making it susceptible to errors due to asymmetry of the sapwood thickness. Such asymmetry can be caused by branching or the direction of sunshine and wind and often results in significant over- or under-estimation of mean sap velocity when using a limited number of sap flux sampling points (Vertessy et al., 1997). The radial distribution of sap flux density is also subject to diel and seasonal variability that can also lead to error up to 40% of total daily transpiration (Fiora and Cescatti, 2006; Ford et al., 2004).

2.4.2 Electrical resistivity imaging

The electrically conductive property of water has been used to investigate soil moisture content for several decades. Bouyoucos et al. (1940) buried porous plaster-of-Paris blocks that
were embedded with electrodes into soil plots and saw changes in conductivity as the soil moisture content ranged from field capacity to wilting point. Agricultural applications of ERI have looked to help optimize soil water reserves and irrigation practices by imaging areas of high infiltration and drainage (e.g. Banton et al., 1997; Michot et al., 2003). Al Hagrey et al. (2006) and Al Hagrey and Michaelsen (2002) demonstrated that ERI can determine changes in soil-water distribution due to infiltration at the field scale. ERI has been successfully used to monitor spatial and temporal soil moisture distributions in heterogeneous areas such as crop fields, naturally vegetated hillslopes, and earthen embankments (e.g. Beff et al., 2013; Brunet et al., 2010; Chambers et al., 2014; Schwartz et al., 2008; Zhou et al., 2001). The major advantage of using ERI techniques for investigating daily and seasonal patterns in soil moisture is the large spatial coverage. Although there are uncertainties associated with the reconstructed conductivity maps made from these data, ERI provides better spatial resolution than dense arrays of point measurements such as TDR (Nijland et al., 2010; Schwartz et al., 2008).

ERI has also been applied to tree ecology in a limited number of studies. Tatter et al. (1972) used resistance measurements to determine the stage of deterioration of decaying or discolored wood. ERI has also been used to study living trees and trunk disks; for example, Al Hagrey (2006) found an inverse relation between ERI and moisture content measured from tree cores. ERI has successfully imaged cavities and fungus within tree trunks due to infestation and decay (Al Hagrey, 2006; Nicolotti et al., 2003; Skutt et al., 1972). Despite these successes, the literature on the electrical properties of trees is relatively limited and conceptually scattered. Studies typically focus on only a few species and vary regarding specific electrical properties investigated, thus hindering the ability to make generalizations about the connections between electrical properties and processes within trees (Gora and Yanoviak, 2015).

2.5 Methods

We collected a series of data around a single ponderosa pine surrounded by several meters of open space so that potential effects from nearby trees were minimized. The closest neighboring tree is 4 meters east of the study tree. The data collected included electrical conductivity of the soil and tree, soil moisture content, sapflow, and soil and tree temperature. Below, we outline these methods.
2.5.1 Data collection

Time-lapse ERI data were collected on a square plot surrounding the tree to monitor changes in soil moisture. 63 stainless steel electrodes were inserted into the ground approximately 10 cm, forming a 3.5 m by 3.5 m grid around the tree (Figure 2.2). Each row and column contained 8 electrodes spaced 0.5 m apart. Due to the location of the tree, one row contained only 7 electrodes. An IRIS Syscal Pro Switch 96 (IRIS Instruments, Orleans, France) coupled with an IRIS switch box was used to collect ERI data. To shorten data collection time to capture the expected diel cycling with high temporal resolution, a dipole-dipole array was used. In this array, current is injected into two electrodes and the potential difference is measured at many other pairs of electrodes simultaneously. This array provides the advantage of better resolving lateral variations in conductivity than other arrays. Approximately every 30 minutes, a series of 16 2D surveys were collected, one down each column and across each row of the electrode grid. Data were collected for periods varying from 24 to 48 hours approximately every two weeks from May to October in 2014. These time frames were chosen to examine the spatial and temporal changes of soil moisture influenced by tree transpiration on both daily and seasonal time scales. The contact resistance between the electrodes and the soil plot were below 20 kohms, which is reasonable for sandy soils. Measurements were collected twice during each survey, known as stacking, for quality assurance/quality control. The mean stacking error over all surveys was 1.1%.

Figure 2.2: The electrode grid for ground conductivity surveys (A). Spacing is 0.5 m between each electrode. Temperature probe clusters are placed outside the grid to minimize their effect on conductivity surveys. Electrode configuration for the conductivity surveys on the trunk of the tree (B).
Time-lapse ERI surveys were also performed on the xylem within the bole of the tree at each time step to relate the changes in conductivity with sapflow measurements. Steel nails were used as electrodes and hammered 2 to 3 centimeters into the xylem of the tree. The electrode ring was placed one meter above the ground to avoid the effects of axial boundary conditions which become significant when the electrode ring is too close to the ground (more details on this are outlined in the section on inversion). The 24 electrodes were spaced 5 centimeters apart around the 125-centimeter circumference of the tree and connected to the IRIS switch box (Figure 2.2). Contact resistance between the electrodes within the tree xylem was approximately 100 kohms, which restricted current from being driven into the tree for parts of the surveys. Approximately 40% of the data were not used due to this issue. Despite this, approximately 200 data points were still collected with low stacking errors at each time step.

A series of additional data were also collected at the site. To compare ERI measurements to transpiration, we installed heat-pulse sapflow sensors in eight trees within 60 meters of the study tree. Sapflow was not measured directly in the study tree to avoid any feedbacks between the sapflow instrumentation (stainless steel needles) and ERI methods that both inject current into the tree. However, we believe the surrogate measurements are meaningful in that the variance in timing of transpiration in a series of trees local to our field site was minimal. The heat-pulse ratio method was used to determine sapflow: two thermocouples were installed into the xylem of the tree, one above the other. Between the two thermocouples, a heat source is installed which injects a current. The sapflow velocity is logarithmically related to the heat dissipation above and below the heat source. The mean sap flux is then calculated and converted to transpiration as described in Burgess and Turner (1998).

Soil volumetric water content was measured at one location 0.5 meters outside of the upper left corner of the electrode grid and collected data every 15 minutes at 10 cm and 20 cm depths with Decagon EC-5 sensors and a CR1000 data logger (Figure 2.2). The porosity of the soil plot was assumed constant in time and therefore the change in volumetric water content was used as a proxy for the change in soil moisture over time. Lastly, temperature data were collected for the soil, air, and tree xylem throughout the study period to correct ERI data for changes in temperature. HOBO Pendant Temperature and Light Loggers were placed in the soil at 10 cm and 20 cm depth outside each corner of the electrode grid. The temperature within the
tree xylem was measured with a CR1000 data logger and 3 type T (copper-constantan) thermocouples placed 2-3 centimeters into the xylem and 12 centimeters above tree electrodes 1, 9, and 17 (Figure 2.2).

### 2.5.2 Raw ERI data analysis

The raw apparent conductivity data in the tree and ground were used to examine the general temporal trends prior to inversion. Data with stacking standard deviation values greater than 2.5% and 10% were excluded from the ground and tree datasets, respectively. The apparent conductivity data were spatially averaged and corrected for changes in temperature within the soil and the tree xylem according to Equation 2.1:

$$\sigma(T) = \sigma(T_0)[1 + \alpha(T - T_0)]$$

where $\sigma$ is apparent conductivity (ohm-m), $T$ is standard temperature (degree C), $T_0$ is the in situ temperature, $\alpha$ is the fractional change in conductivity per change in degree Celsius assumed to be 0.02 (Hayley et al., 2010).

### 2.5.3 Ground survey inversions

ERI ground survey data were inverted using R2 version 2.7, based on a regularized objective function combined with weighted least squares as defined in Binley and Kemna (2005). The objective function is defined in Equation 2.2:

$$\psi(m) = (W_d[d - f(m)])^2 + \beta(W_m[m - m_{ref}])^2$$

where $m$ is the model vector of resistivities (the reciprocal of conductivity), $d$ is the measured resistance data, $W_d$ is the data weighting matrix based on measurement error reported as standard deviation of each stack, $f(m)$ is the forward solution of the resistances operating in the model, $W_m$ is the model weighting matrix based on a second-derivative filter that acts as a smoother, $\beta$ is the weight that controls the relative significance of the model misfit (first term on the right) and the model roughness (second term on the right), and $m_{ref}$ is the starting model. The time-lapse conductivity inversions from each collection period were performed with a starting model ($m_{ref}$) that was equal to the inversion of the first time-step of each 2-day collection period. For each time-step, a 2.5D inversion was performed on each of the 16 ground ERI surveys.

A finite-element mesh was created with 5 cm x 5 cm elements to 60 cm depth and 350 cm width. Outside this area, element size gradually increased, totaling 2400 elements. The resulting tomograms depict a smoothed representation of the bulk electrical conductivity within
the soil plot. The resolution of the inversion varies across the model space due to the variability in data collection procedure and the extent of smoothing within the model. The diagonal of the resolution matrix describes the degree to which the data informed the value of each pixel. The resolution matrices did not show significant variability between time steps on the daily or seasonal time scales. The diagonal of the resolution matrix showed a mean range of percent differences from -7% to 3% and -8% to 10% over a 24-hour period and a 6-month period, respectively. Spatially, the resolution of the inversion decreases with depth and is lowest towards to bottom corners of the inversion space (Figure 2.3).

Temperature corrections were performed on the time-lapse inversions to eliminate the effects of varying temperatures over the daily and monthly periods. Temperature data from the 8 temperature probes at varying locations and depths were compiled into a matrix and linearly interpolated between data collection points. The temperature correction method described in Equation 2.1 was used on the inversions as described by Hayley et al. (2010).

2.5.4 Tree survey inversions

Inversions of the tree surveys were performed with code developed in Comsol that was modified to fit a 2.5D model in a circular domain using the same objective function as described by Equation 2.2. To fit the shape of the tree trunk, a triangular mesh was used for both forward and inverse modeling. There were 616 triangular elements used for inversion and each of the inversion elements was further divided into four smaller elements during forward modeling for convergence purposes. The modeling weighting matrix $W_m$ was assigned according to Binley et al. (1996).
The 2.5D model with a circular domain was validated by comparing forward model results to a slice of a 3D cylinder model inversion with the ERI survey in the center of the cylinder. When the height of the cylinder was at least 0.75 meters (thus the ERI survey is 0.375 meters above the ground) the 2.5D and 3D models matched within 3% relative error. At lower heights the boundaries began to have significant influence. The ERI survey in the tree is approximately one meter above ground so the 2.5D model gives a good approximation of the real 3D model.

As previously mentioned, 40% of the survey data could not be used for the inversion due to the high contact resistance from some of the electrodes. The locations of the available data varied among those surveys. A sensitivity analysis was performed on the inversions to evaluate the resolution distribution with these available measurements and is plotted for one time step during the June 24 – June 26 data collection period (Figure 2.4a). The sensitivity is high close to the boundary and decreases towards the center of the tree trunk. This distribution is expected, as the electrodes are located just inside the surface of the bark. Results within the outer regions of the tree trunk can be regarded with confidence, while the results within the inner regions are less robust due to lower sensitivity.

2.6 Results and Discussion

In this section we discuss the results of the study, first addressing the results of ERI within the ponderosa pine and sapflow patterns. Second, we discuss the results of the ERI on the surrounding soil plot and soil moisture patterns. Lastly, we discuss the feedbacks between the subsurface and the ponderosa pine.

2.6.1 Data within the ponderosa pine

ERI data on the tree bole cross-section revealed a spatially heterogeneous distribution of conductivity (Figure 2.4b). The inner core of the tree had low conductivity values due to the lower water content in the hard, dry heartwood of the tree. The conductivity values increased towards the outside area of the cross-section where the water content is higher in the living sapwood. The inner core conductivity values ranged from 5 to 10 times lower than the outer area, similar to previous ERI studies (Guyot et al., 2013; Martin, 2012).

The distribution of the higher conductivity (sapwood) areas was not uniform around the tree, with patches of high conductivity on the southeast and northeast sides of the cross-section and slightly lower conductivity patches on the northwest side. While asymmetry was expected
due to predominant wind and sunlight directions, the locations of some of the asymmetry seen in the study tree was not expected. Typically, there is more sapflow activity on the sunlit side of the tree (al Hagrey, 2006), so higher conductivity was expected to be located on the south side of the tree. The patch with the highest consistent conductivity values is located on the south side of the tree, between electrodes 8 and 10. However, a second high conductivity anomaly is located on the NE side of the outer portion of the tree between electrodes 14 and 20 (Figure 2.4b).

Tree core samples were taken to investigate the low conductivity anomaly on the south side of the tree between electrodes 11 and 13. The contact between sapwood and heartwood was blurred by oily resin bands in 5 of the 7 cores, which are likely evidence of a transition from sapwood to heartwood (Figure 2.4b). These bands create patches of low conductivity, making the ERI delineation of the heartwood boundary difficult, considering the low resolution in this inner core region. In this study, we were primarily interested in changes within the sapwood, putting higher priority on data in the outer edge of the tree.

![Figure 2.4: Sensitivity matrix of tree inversions (a). Resolution is highest towards the outside of the cross-section, where most changes are expected to occur. Tree cores were collected at seven locations around the tree (b) and resin bands were found (squares). The depth to heartwood was measured from these cores and a potential heartwood/sapwood (HW/SW) boundary is shown by the dotted line.](image)

Temperature can have a large effect on changes in electrical conductivity. While bole temperature data were collected at three points around the tree, these data only correspond to the outer ring, or the xylem, as temperature probes were inserted only 2 cm into the trunk (Figure 2.5). We expect that this thin ring is exposed to the largest temperature effects, and that the inner portion of the tree (the heartwood) does not experience as much temperature variation. However,
we were unable to insert temperature probes so deeply without damaging the tree, and because little is known about thermal diffusion through tree trunks, it was not possible to confidently correct the data for temperature effects. However, during higher transpiration times there was an approximately 80-100% increase in conductivity in the outer areas of the tree. If temperature effects were to be corrected for, the increase of conductivity during times of high transpiration would only be larger. This suggests that the increase of conductivity during the day is largely due to increases in sapflow activity but may also include small effects of temperature variations.

![Figure 2.5: Tree bole temperature during each collection period in degrees Celsius.](image)

As mentioned above, portions of the outer ring of the tree cross-section showed increases of conductivity during periods of high transpiration. However, the average conductivity of the entire cross-section showed a different pattern. During low periods of sapflow (< 50% of daily mean) within a given diel cycle, bulk tree conductivity was high (Figure 2.6). As sapflow increased during the day, the bulk conductivity within the tree decreased. This daily cycle is likely due to the refilling of water storage within the tree. Stored water within stem tissue outside the hydraulic pathway and within sapwood has been found to contribute up to 50% of daily transpiration in specific species of trees (Goldstein et al., 1998; Holbrook & Sinclair, 1992; Waring & Running, 1978). In arid and semi-arid climates, soil-water availability becomes low in the dry summer months, thus increasing the vulnerability to embolism (air within the xylem), especially in tall trees where the tension within the xylem is higher. Ponderosa pines have been found to minimize this vulnerability by avoiding levels of xylem tension via use of stored water and radial movement of water between xylem conduits (Barnard et al., 2011).
Figure 2.6: Vapor pressure deficit (VPD) and precipitation during each collection period (A), volumetric water content (B), sapflux velocity (C), spatially averaged tree conductivity (dotted lines in D), and spatially averaged ground conductivity (dashed lines in D).
Phillips et al. (2003) found that use of stored water was concentrated to favorable times for photosynthesis, typically in the morning and early afternoon. Thus, the lower conductivity values within the tree during the day are likely due to lower bulk water content within the tree as it uses stored water. When sapflow decreases in the late afternoon, the bulk conductivity increases as the tree refills the stored water.

The average tree conductivity increased by 33% from May to the beginning of October. Volumetric water content and nutrient uptake of ponderosa pines have been found to decrease during drier summer months (Domec et al., 2005), so this increase in conductivity is likely not due to changes in water content or nutrient concentrations. While the daily pattern in conductivity can be explained by tree water storage, as discussed above, the physical cause of the increasing seasonal pattern of bulk conductivity in the bole of the tree is not well understood.

2.6.2 Data within the soil

The spatial distribution of the ground conductivity was highly heterogeneous (Figure 2.7). In general, the highest conductivity values (regardless of time of day) were located closest to the tree (<0.5 m lateral distance). The conductivity decreased moving farther from the tree, until approximately 2.5 m away, where it began to increase again (Figure 2.7). On average, this spatial distribution is approximately radial. The high conductivity values close to the tree likely indicate high water content in either the soil near the tree or the roots themselves. The decrease in conductivity with distance from the tree is likely due to the movement of water towards the tree. However, the conductivity distribution is likely also dependent on the location of the roots. When the soil is very dry (Figure 2.7c) there are some areas of higher conductivity that do not follow the radial pattern, showing soil water that is drawn toward the roots and not necessarily directly toward the tree.

The spatial distribution of the conductivity also varies with depth (Figure 2.8). During the day, conductivity values are lower and more spatially heterogeneous, and there is clear variability with depth. The conductivity is high near the tree at shallow depths, but is low near the tree at deeper depths (Figure 2.8a). This could be evidence of a tap root, more water uptake in deeper soils, hydraulic redistribution, or a combination. Without invasive procedures, it is difficult to parse these possibilities apart.
As the summer progressed, the average ground apparent conductivity decreased from 1.3 mS/m to 0.65 mS/m, due to the seasonal drying out of the soil (Figure 2.9). Ground apparent conductivity temporarily increased from a daily mean of 0.79 mS/m on July 16 to 0.92 mS/m on August 4 and returned to 0.72 mS/m on September 3 (Figure 2.9). This pattern was associated with the summer monsoon season during this time that caused a temporary increase in the soil moisture (27%). The magnitude of daily fluctuations of ground apparent conductivity showed a decreasing trend from early spring to late summer (Figure 2.9), which will be discussed further in Section 2.6.3.

Figure 2.7: Resistivity percent change at four times during the 2-day period from June 24 – June 26. Percent change of resistivity from the first time-step during the 2-day period is shown. Higher change represents lower soil moisture content. During the day the water content close to the tree is higher than the surrounding soil plot (a,c). In the early morning, the soil moisture content is higher throughout the site and shows less spatial variability (b,d).
Figure 2.8: Resistivity percent change for two times during the June 24 – June 26 data collection period at different depths: June 24 at 15:26 (a) and June 25 at 07:25 (b).

Figure 2.9: Daily mean apparent conductivity (mS/m) for each data collection period decreased from late spring (May) to late fall (Oct). Error bars are the mean standard deviation of the average ground conductivity for each data collection period. This represents the average magnitude of daily fluctuation of soil moisture content of the data prior to inversion.

2.6.3 Feedbacks between the tree and the subsurface

Diel patterns of ground apparent conductivity were related to diel sapflow patterns (Figure 2.8). From May to July, when the sapflow was high (at least 50% greater than daily mean), apparent conductivity of the soil plot decreased by 9.1% on average. Similarly, when sapflow was low (< 50% of daily mean), the apparent conductivity of the soil increased by 11% on average. During transpiration, root uptake decreases the soil moisture content and thus the
conductivity of the soil plot. When the tree transpiration slows and the sapflow sharply decreases, the tree is no longer strongly drawing water towards it. This allows the soil to be replenished with water, thus increasing the ground conductivity. Several mechanisms could be controlling the re-wetting process. While there is likely a difference of matric potential between the soil plot under the influence of the tree and the surrounding soil, the potential difference required to cause lateral movement of soil water would need to be relatively high in soil with such low moisture content. Monitoring of the matric potential was not conducted in this study, but tensiometers could be used to further investigate spatiotemporal changes in matric potential due to transpiration. A second process by which re-wetting could be occurring is hydraulic redistribution, where roots move soil moisture from plentiful areas to water-depleted areas in the lateral or vertical direction. Estimates of the average amount of water moved by hydraulic redistribution in other field sites range two orders of magnitude (0.04 – 3.2 mm/d) across varying plant species and ecosystems (e.g., Neumann and Cardon, 2012). Studies on old growth ponderosa pine and Douglas fir stands have shown that during dry conditions, hydraulic redistribution contributes an average of 0.1 – 0.2 mm/d of water use (Brooks et al., 2002; Meinzer et al., 2004; Warren et al., 2005; Warren et al., 2007). The time-series of normalized soil moisture data (Figure 2.7) shows a pattern characteristic of hydraulic redistribution, where there is a nocturnal increase of soil moisture instead of a steady value. Occasionally, the nocturnal increase exceeded the previous day’s soil water maximum. This occurrence shows that there may be a larger contribution of hydraulic redistribution in this drier climate than in previous studies, which have found up to 35% of transpired water is due to hydraulic redistribution in ponderosa pines (Brooks et al., 2002). The ERI images showed lower conductivity with depth (Figure 2.8), suggesting water is likely moving from deep to shallow depths, but further investigation is needed to support this hypothesis.

As noted above, the magnitude of daily fluctuations of ground conductivity decreased by 52% from June to October (Figure 2.9). Several explanations could account for this result. There is less water in the soil plot in the late summer, which would force the tree to uptake less water. This would result in smaller conductivity fluctuations due to less water being taken from and returned to the soil during the diel cycle. Data from June support this hypothesis: with decreases in soil moisture (55%), decreases in sapflow (23%) and decreases in ground conductivity fluctuations (52%) occur. This would suggest a soil-moisture-limited system. However, this
hypothesis does not hold true for the entire summer. Data from June 24-26 and August 12-13 have similar average daily soil moisture contents (0.068 and 0.062, respectively), average daily sapflow (3.4 cm/hr and 3.8 cm/hr, respectively), and average daily apparent ground conductivity (0.90 mS/m and 0.87 mS/m, respectively). However, the average daily fluctuation of ground conductivity is 58% higher for June 24-26 than August 12-13. This could be due to the tree drawing water from a deeper, perhaps more consistent water source during August when the tree has been subjected to drier antecedent conditions. This has been found to occur in ponderosa pine stands during very dry conditions in northeast Oregon (Warren et al., 2007). A second hypothesis is that more significant hydraulic redistribution is occurring in August, where water is taken up by the roots in areas of high soil moisture content (deeper depths) and redistributed to areas of low soil moisture content (closer to the surface).

2.7 Conclusions

In this study, we present the first time-lapse ERI dataset mapping changes in a connected tree-soil system. The source and timing of water uptake by vegetation varies with fluctuating soil moisture conditions. Active transpiration (periods of high sapflow) drives water towards the tree, drying out the soil. The spatial distribution of this decrease in soil moisture is not homogeneous within the soil plot. The variability in soil moisture changes in both vertical and lateral directions is likely due to root distribution and preferential pathways towards the roots. When the tree is not transpiring (periods of low sapflow), the soil plot is replenished with water. We hypothesize that a combination of matric potential-driven water movement and hydraulic redistribution drives the re-wetting process; further investigations should include matric potential data to properly address the soil moisture pathways. Climate and seasonal conditions also affect the time and source of water uptake by vegetation. The daily fluctuations in soil moisture became less prominent in the drier summer months. We hypothesize this is due to a switch of tree water source from the shallow soil profile to deeper, more consistent source water, which we can see within the ERI inversions.

Because of the small scale of this study, only a specific portion of the relation between hydrologic and ecologic processes was investigated. While soil moisture and transpiration are directly linked, understanding of the effect of vegetation on subsurface flow and streamflow is vital to water management on a larger scale. In this study, the movement of soil moisture was captured, but where the water was coming from and going to could not be concluded with small-
scale ERI monitoring alone. To further explore how the subsurface water storage processes influence the connected between transpiration and streamflow, a combination of hillslope-scale geophysical and isotopic methods could be used. Time-lapse geophysical imaging would provide high resolution monitoring of soil moisture, while the isotopic data from subsurface, stream, and tree water could give insight into water movement pathways.

Though changes in transpiration rates were not explicitly determined from the ERI data in this study due temperature factors, ERI did capture the timing of the daily change in water content in the tree and the spatiotemporal variability of active sapwood. Common assumptions when upscaling sap flux measurements include: (1) that the outermost xylem is where sapflow is most active, (2) sapflow activity is greater on the sunlit side, and (3) there is linear decline in sapflow from outer xylem to heartwood boundary. The results of the ERI surveys on the tree trunk clearly show many of these assumptions are appropriate, but are grossly overgeneralized.

Further research regarding the thermal diffusivity from the outer to inner trunk of trees and how time-lapse ERI can be corrected for changes in temperature within the tree itself should be done to improve the application of ERI to transpiration monitoring. The results of this study indicate that the combined use of geophysical methods and standard point measurements overcome previous limitations to the investigation of soil-plant-atmosphere relations.
CHAPTER 3
FUTURE WORK

This research was successful in mapping the movement of soil moisture due to transpiration patterns on daily and seasonal scales within the small area of influence of a single tree. We also present the first application of time-lapse electrical resistivity imaging (ERI) to transpiration spatiotemporal patterns. As with any research study, important questions still remain. Two possible research extensions are outlined below including: 1) expanding the investigation of transpiration, subsurface flow, and streamflow interactions on the hillslope scale and 2) improving ERI transpiration monitoring.

3.1 Expansion to the Hillslope Scale

Because of the small scale of this study, only a specific portion of the relation between hydrologic and ecologic processes was investigated. While soil moisture and transpiration are directly linked, understanding of the effect of vegetation on subsurface flow and streamflow is vital to water management on a larger scale. In this study, the movement of soil moisture was captured, but where the water was coming from and going to could not be concluded with ERI monitoring alone. To further explore how the subsurface water storage processes influence the connected between transpiration and streamflow, a combination of geophysical and isotopic methods could be used. Time-lapse geophysical imaging would provide high resolution monitoring of soil moisture, while the isotopic data from subsurface, stream, and tree water could give insight into water movement pathways.

3.2 Improvement of ERI transpiration monitoring

In this study we presented the first application of time-lapse ERI to monitor transpiration without the use of a tracer. Research is still needed to broaden the use of this method. One limitation to ERI is that the solutions are highly underdetermined. Conductivity is dependent on several physical properties such as ion concentration, temperature, water content, and pH. Time-lapse ERI can be used to monitor one of these physical properties if the conductivity can be corrected for changes in other physical properties or the physical properties can be assumed constant. Previous studies on electrical properties of trees and applying geophysical methods to
trees have successfully identified spatial changes across the trunks of trees, but temporal changes are still poorly understood.

Considerable ground-truthing for ERI in trees is still needed, especially for use in monitoring transpiration. Temperature can have a significant effect on time-lapse ERI. Research on the thermal diffusivity through the trunk of a tree and how it is related to changes in conductivity is needed to isolate changes in water content from changes in temperature. The results of this study show that on the daily scale, changes in conductivity are primarily due to changes in water content of the tree. However, on the seasonal scale, the physical interpretation of changes in conductivity was not clear. Combining tree cores and other methods of ground-truthing over the period of time-lapse ERI would help to constrain the interpretations.
REFERENCES CITED


