



Examining diel patterns of soil and xylem moisture using electrical resistivity imaging



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SUMMARY

The feedbacks among forest transpiration, soil moisture, and subsurface flowpaths are poorly understood. We investigate how soil moisture is affected by daily transpiration using time-lapse electrical resistivity imaging (ERI) on a highly instrumented ponderosa pine and the surrounding soil throughout the growing season. By comparing sap flow measurements to the ERI data, we find that periods of high sap flow within the diel cycle are aligned with decreases in ground electrical conductivity and soil moisture due to drying of the soil during moisture uptake. As sap flow decreases during the night, the ground conductivity increases as the soil moisture is replenished. The mean and variance of the ground conductivity decreases into the summer dry season, indicating drier soil and smaller diel fluctuations in soil moisture as the summer progresses. Sap flow did not significantly decrease through the summer suggesting use of a water source deeper than 60 cm to maintain transpiration during times of shallow soil moisture depletion. ERI captured spatiotemporal variability of soil moisture on daily and seasonal timescales. ERI data on the tree showed a diel cycle of conductivity, interpreted as changes in water content due to transpiration, but changes in sap flow throughout the season could not be interpreted from ERI inversions alone due to daily temperature changes.

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1. Introduction

Ecological controls on hydrologic pathways and storage in forested catchments are often most pronounced during low-flow or baseflow conditions, which typically coincide with the growing season in temperate environments. At these times, evapotranspiration (ET) can comprise greater than 50% of the water that exits the catchment (Hewlett, 1982) and regulates catchment storage. Despite significant correlations between transpiration and diel (24-h) streamflow in catchments of varying sizes and locations (Reigner, 1966; Bond et al., 2002; Boronina et al., 2005; Butler et al., 2007; Barnard et al., 2010; Graham et al., 2013), how the transpiration signal is propagated throughout the subsurface is dependent on complex, connected mechanisms, and remains poorly understood (e.g., Richards and Caldwell, 1987; Burgess et al., 2000; Bleby et al., 2010). For example, stable isotope studies

have indicated that water extracted by forests differs from water generating baseflow in some streams, suggesting a complicated system of subsurface connections (Dawson and Ehleringer, 1991; Brooks et al., 2010).

Diel fluctuations in soil moisture are common in vegetated areas where water content declines during the day when transpiration extracts water from the subsurface and may partially recover throughout the night (Barnard et al., 2010; Moore et al., 2011). Two mechanisms have been proposed to explain the recovery of soil moisture during the night: diffusion recharge and hydraulic redistribution. For the first mechanism, soil moisture may be transferred within the soil matrix simply by diffusion from wetter areas to drier areas; however, this process is very slow and its impact is likely minimal (Richards and Caldwell, 1987; Domec et al., 2010). For hydraulic redistribution, roots passively move soil moisture from plentiful areas to water-depleted areas in the lateral or vertical direction due to diurnal changes in the water potential gradient between the root and the soil matrix (Caldwell and Richards, 1989; Dawson, 1993; Burgess et al., 1998). During transpiration, the water potential within the plant declines below that

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of the soil resulting in a net flux of water into the roots. When transpiration ceases, the water potential in the roots can rise higher than the potential in the soil, allowing water to move back into the soil matrix. Estimates of the average amount of water moved by hydraulic redistribution range two orders of magnitude (0.04–3.2 mm/d) across species and ecosystems (e.g., Neumann and Cardon, 2012). Although several studies have now documented hydraulic redistribution, understanding the complexities of root distributions and their role in hydrologic connectivity in the subsurface remains a pressing concern in hydrology (Good et al., 2015; Evaristo et al., 2015).

Quantifying vegetation–subsurface connections is difficult due to complexities in measuring the dynamic and heterogeneous nature of plant root distributions, water uptake patterns, transpiration, and soil moisture inputs, all of which are difficult to capture with standard point measurements. Soil moisture is commonly measured using techniques such as time-domain reflectometry (TDR), gravimetric (mass) methods, direct-push based sensor probes, and neutron probes (e.g., Dobriyal et al., 2012). One common limitation of many soil moisture measurement techniques is the limited spatial coverage in heterogeneous soil plots; additionally most measurement techniques exploring root systems and soil moisture are disruptive to the soil matrix (Maeght et al., 2013). Not only are physical soil characteristics heterogeneous in forest environments, but so is the effect of transpiration and tree interception on the spatial distribution of water content, which is key to characterizing water movement within vadose zone. In trees, sap flow sensors, which use heat as a tracer for water movement, are commonly used for monitoring and quantifying transpiration (e.g., Granier, 1987; Burgess et al., 2001). Sap flux is a point measurement that is typically 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, slope aspect, and reaction wood formation and can result in over- or under-estimation of total tree transpiration when using a limited number sampling points (Vertessy et al., 1997). Additionally, if diurnal and seasonal variation in sapflux rates between the inner and outer xylem are not accounted for, total daily transpiration can be overestimated by up to 40% (Ford et al., 2004; Fiora and Cescatti, 2006).

Geophysical methods can be used to overcome some of the limitations of point measurements through minimally invasive, spatially exhaustive, 3D monitoring without sacrificing temporal resolution. For example, electrical resistivity imaging (ERI) has been a well-established method to image changes in soil moisture for several decades (e.g., Daily et al., 1992; Zhou et al., 2001; Samouëlian et al., 2005; Chambers et al., 2014). Bouyoucos and Mick (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. More recently, ERI has been successfully used to monitor spatial and temporal soil moisture distributions in heterogeneous areas such as naturally vegetated hillslopes (e.g., Brunet et al., 2010), across vegetation boundaries (e.g., Jayawickreme et al., 2010), and most commonly, in agricultural systems (e.g., Hagrey and Michaelsen, 2002; Schwartz et al., 2008; Beff et al., 2013; Garré et al., 2013). Some 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), or to explore water vs. nutrient limitations in cropped fields when used in conjunction with carbon isotopic data (Hussain et al., 2015). ERI has been used to explore root water uptake in a variety of settings, including in sand dunes during rainfall (Fan et al., 2015), in agricultural field sites under irrigated treatments (e.g., Srayeddin and Doussan, 2009; Cassiani et al., 2015), as well as at the large-lysimeter scale (e.g., Garré

et al., 2011); diel cycling of water content is something noted in some of these data sets (e.g., Werban et al., 2008). These data may also be useful for understanding soil moisture persistence (e.g., Ghannam et al., 2016) over broad scales. Although there are uncertainties associated with the reconstructed bulk electrical conductivity maps made from resistance data, ERI provides better spatial resolution than dense arrays of point measurements such as TDR (Schwartz et al., 2008; Nijland et al., 2010); however, the relation between moisture content and electrical conductivity is spatially variable and dependent on multiple variables, making estimates of moisture content directly difficult (e.g., Friedman, 2005; Day-Lewis et al., 2005; Garré et al., 2013).

Here, we explore the connection between soil moisture and tree transpiration coupling traditional point-scale measurements with ERI to monitor spatially exhaustive moisture content changes within the soil and tree throughout a growing season. ERI has previously been applied to a few studies in forest ecology. In an early study, Tattar 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; for example, 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 (Skutt et al., 1972; Nicolotti et al., 2003; Hagrey, 2006) and delineated sapwood from heartwood (Hagrey, 2006; Bieker and Rust, 2010; Guyot et al., 2013; Wang et al., 2015). The resistivity within trees varies significantly among species, and these results suggest these variations are due to anatomical and physiological differences (Gora and Yanoviak, 2015). While diel fluctuations in tree sap flow have been measured by naturally occurring voltages (Gibert et al., 2006), to the best of our knowledge, no time-lapse ERI studies within trees as coupled to the subsurface have been employed. Here, we aim to (1) evaluate the application of ERI as a minimally invasive method to monitor high-resolution spatial and temporal changes in soil and tree water content during one growing season and into the fall and (2) relate these water content patterns to the seasonal variation in transpiration and explore their feedbacks.

2. Material and 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 m east of the study tree. The data collected included electrical conductivity of the soil and tree, soil moisture content, sap flow, and soil and bole temperature.

2.1. 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 (Fig. 1). The general goal of the BCCZO is to explore the role of weathering and erosion on the form and function of the shallow subsurface. Gordon Gulch is approximately 2.7 km² and ranges from 2446 to 2737 m in elevation within the upper montane climatic zone. Average annual precipitation is 519 mm with the maximum occurring in May, and potential evapotranspiration is ≈500 mm/year. The soils are characterized as typic haplustolls varying in composition with depth. Percent sand by weight ranges from 55% to 65%. Silt ranges from 25% to 50% with higher silt content in the shallow layers (<20 cm depth) and lower contents in deeper layers. Average clay content is approximately 10%. Along the hillslopes, soil depth is approximately 30–50 cm (NRCS Soil Survey, 2015); at our site soil depth is approximately 30–35 cm. The soil profile is underlain by highly

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