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Research papers

Spatiotemporal soil and saprolite moisture dynamics across a semi-arid woody plant gradient ☆,☆☆

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ABSTRACT

Woody plant cover has increased 10-fold over the last 140+ years in many parts of the semi-arid western USA. Woody plant cover can alter the timing and amount of plant available moisture in the soil and saprolite. To assess spatiotemporal subsurface moisture dynamics over two water years in a snow-dominated western juniper stand we compared moisture dynamics horizontally across a discontinuous canopy, and vertically in soil and saprolite. We monitored soil moisture at 15 and 60 cm and conducted periodic electromagnetic induction and electrical resistivity tomography surveys aimed at sensing moisture changes within the root zone and saprolite. Timing of soil moisture dry down at 15 cm was very similar between canopy patches and interspace. Conversely, dry down at 60 cm occurred 22 days earlier in the interspace than under canopy patches. After rainfall, interspaces with more shrubs showed greater increases in soil moisture than interspaces with few shrubs. For the few rainfall events that were large enough to increase soil moisture at 60 cm, increases in moisture occurred almost exclusively below the canopy. Soil water holding capacity from 0 to 150 cm was a primary driver of areas that were associated with the greatest change in distributed electrical conductivity - an indicator of changes in soil moisture - across the growing season. Vegetation was also correlated with a greater seasonal change in electrical conductivity at these depths. The seasonal change in resistivity suggested moisture extraction by juniper well into the saprolite, as deep as 12 m below the surface. This change in deep subsurface resistivity primarily occurred below medium and large juniper trees. This study suggests how tree roots are both increasing infiltration below their canopy while also extracting moisture at depths of upwards of 12 m. Information from this study can help improve our understanding of juniper resilience to drought and the hydrologic impacts of semi-arid land cover change.

1. Introduction

The hydrologic impacts of woody plant encroachment in semi-arid environments such as with western juniper (*Juniperus occidentalis*) expansion into sagebrush ecosystems are poorly understood. Across the western USA over the last 140+ years, woodlands have encroached into sagebrush and grassland ecosystems principally due to grazing and fire exclusion (Tausch et al., 1981; Miller et al., 2005; Romme et al., 2009). This has been followed by restoration efforts to remove woody plants (e.g. Bureau of Land Management, 2015). Increases (decreases) in woody plant cover typically decrease (increase) total runoff (Bosch and Hewlett,

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1982; Huang et al., 2006; Zégre et al., 2010; Zou et al., 2014; Qiao et al., 2015). However, documented hydrologic responses of woody plant removal are not always consistent in semi-arid areas. For example, while one would expect decrease in woody plant cover to increase streamflow, in one case tree die-off decreased streamflow (Guardiola-Claramonte et al., 2011) and in another tree expansion increased streamflow (Wilcox and Huang, 2010). In other cases reductions in woody plant cover were found to have a negligible effect on streamflow (Clary et al., 1974; Baker, 1984; Baker and Ffolliott, 2000). This leads some to conclude that woody plant removal in semi-arid regions has a negligible impact on streamflow (Hibbert, 1983; Kuhn et al., 2007; Ffolliott and Gottfried, 2012). These assertions are often based on the assumption that these plants can access water at deeper depths than herbaceous cover, thereby facilitating greater dry out of the subsurface which reduces subsequent streamflow (Zou et al., 2014). But few studies quantify these subsurface hydrologic processes at both shallow and deep depths. These uncertainties about woody plant impacts on streamflow have motivated this study that aims to improve our process-based understanding of the subsurface hydrological processes in these systems.

The impact of changes in woody plant cover on subsurface water processes is of particular importance to land managers and downstream users in water-limited systems. Soil water dynamics in the near-surface control the phenology and plant productivity in water-limited environments (Loik et al., 2004; Schwinning and Sala, 2004; West et al., 2007; Robinson et al., 2008; Breshears et al., 2009; Penna et al., 2013). Water dynamics in the deep soil and saprolite zones often control streamflow generation and groundwater recharge (Carey et al., 2010; Chauvin et al., 2011; Gabrielli et al., 2012), and provide a moisture pool for some deep rooted semi-arid plants (Breshears et al., 2009; Graham et al., 2010; Schwinning, 2010) including potential hydraulic lift to draw up deep moisture to shallow soil layers (Dawson, 1996; Armas et al., 2010). In the semi-arid western USA, where soil moisture is a limiting factor in primary productivity, understanding the duration of plant available water is particularly important. For example, an earlier reduction in plant available water can increase vegetation vulnerability to drought (Grieu et al., 1988; Littell et al., 2008). Earlier reductions in plant available water could be realized in future years which are projected to experience less precipitation and increased temperatures (Abatzoglou and Kolden, 2011), and a decreased snow to rain ratio that could further reduce streamflow (Berghuijs et al., 2014).

Elucidating how semi-arid woody plants alter subsurface fluxes is often done by comparing subsurface moisture dynamics between vegetation patches and interspace (e.g. Eddleman and Miller, 1991; Padien and Lajtha, 1992; Breshears et al., 1997b; Martens et al., 2000; Owens et al., 2006). Semi-arid conifer species are often organized into "patches" with the areas covered by trees being the "patches" embedded in an interspace "matrix" that is dominated by shrubs, grasses, and forbes (Miller et al., 2005). The interspace and patches are often characterized by differences in nutrient dynamics (Padien and Lajtha, 1992), radiation regime (Breshears et al., 1997b; Martens et al., 2000), throughfall (Eddleman, 1986; Eddleman and Miller, 1991; Taucer, 2006; Owens et al., 2006), and snow deposition (Niemeyer et al., 2016). Theoretical work on interactions between patch and interspace vegetation posits that grasses use shallower soil moisture pools earlier in the growing season, whereas woody plants use deeper soil moisture pools later in the growing season (Walker and Noy-Meir, 1982; Peláez et al., 1994; Ryel et al., 2008). Empirical work has shown that indeed woody plants utilize moisture in both shallow and deeper layers while grasses and forbs use shallower moisture (Gifford and Shaw, 1973; Young et al., 1984; Sala et al., 1989; Peláez et al., 1994; Breshears et al., 1997a; Breshears et al., 2009; Seyfried et al., 2005). Previous studies in discontinuous juniper landscapes have observed both earlier depletion of soil water in the grass-dominated interspace compared to juniper patches (Young et al., 1984) and no difference in seasonal soil moisture depletion between the patches and interspace (Breshears et al., 1997a). To adequately understand differences in drought vulnerability between interspace and woody vegetation patches, we must adequately characterize spatiotemporal soil moisture dynamics.

Understanding how shifts in woody plant cover change soil moisture in both space and time requires the triangulation of multiple methods. Assessing differences in soil moisture regimes across patches/interspace or woodland/open plots are often limited to a small number of point-scale soil moisture measurements which are often focused on shallow (<30 cm) soils (Gifford and Shaw, 1973; Young et al., 1984; Breshears et al., 1997a; Seyfried et al., 2005; Robinson et al., 2010; Roundy et al., 2014). This may adequately capture the changes in soil moisture through time in shallow layers but fails to ascertain how these shifts play out across a patches-interspace continuum or how these changes play out in deeper layers in the subsurface (Robinson et al., 2008). Deep moisture in the soil, saprolite, and bedrock is inherently inaccessible for investigation using direct-contact sensors and hence is difficult to quantify. Geophysical methods such as electrical resistivity tomography (ERT) and electromagnetic induction (EMI) enable the collection of spatially contiguous datasets both horizontally and vertically (Sheets and Hendrickx, 1995; Robinson et al., 2008; Parsekian et al., 2015). For this study, we use the definitions of soil, saprolite, weathered bedrock, and fresh bedrock outlined by Anderson et al. (2007) to define the subsurface of the critical zone. From bottom to top, fresh bedrock is unaltered parent material. Weathered bedrock is fresh bedrock that has undergone initial weathering and additional fracturing, but still resembles the fresh parent material in appearance and property. Saprolite is thoroughly weathered rock that has not yet been transported. Finally, soil is defined as disaggregated transportable material (Anderson et al., 2007).

Here we present a study on the differences in subsurface moisture dynamics in space and time between juniper patches and interspace. Our approach was to combine high-temporal resolution soil moisture data with periodic spatial geophysical data to sense changes in moisture at depth and across the discontinuous canopy cover. This is the first study in patch-interspace cover to combine both high temporal resolution data, broad spatial data, and geophysical data at a depth of exploration greater than 5 m to ascertain how canopy patch and interspace subsurface moisture dynamics differ. Our specific objective is to understand how deeply-rooted trees and shallowly-rooted shrubs differ in their influence on seasonal subsurface moisture dynamics. Results show how these variations in soil and saprolite moisture can differ by depth and time in ways relevant to understanding juniper drought resilience and streamflow generation at the watershed scale.

2. Methods

To assess how the presence of trees affect soil moisture in space and time across a discontinuous canopy, we used a combination of continuous soil moisture and temperature measurements at shallow (<1 m) soil depths and periodic geophysical measurements from peak soil wetness in early spring to the driest point in the water year before the onset of fall precipitation.

2.1. Site description

This work was carried out at the Reynolds Creek Experimental Watershed (RCEW) and Critical Zone Observatory in the Owyhee