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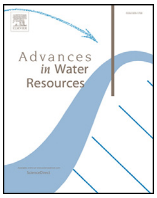

Diverging sensitivity of soil water stress to changing snowmelt timing in the Western U.S.

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ABSTRACT

Altered snowpack regimes from regional warming threaten mountain ecosystems with greater water stress and increased likelihood of vegetation disturbance. The sensitivity of vegetation to changing snowpack conditions is strongly mediated by soil water storage, yet a framework to identify areas sensitive to changing snowpack regimes is lacking. In this study we ask two questions: (1) How will changing snowmelt alter the duration of soil water stress and length of the soil-mediated growing season (shortened to water stress and growing season, respectively)? and (2) What site characteristics increase the sensitivity of water stress and growing season duration to changes in snowmelt? We compiled soil moisture at 5, 20 and 50 cm depths from 62 SNOTEL sites with >5 years of records and detailed soil properties. Soil water stress was estimated based on measured wilting point water content. The day of snow disappearance consistently explained the greatest variability in water stress across all site-years and within individual sites, while summer precipitation explained the most variability in growing season length. On average, a one day earlier snow disappearance resulted in 0.62 days greater water stress and 36 of 62 sites had significant relationships between snow disappearance and water stress. Despite earlier snow disappearance leading to greater water stress at nearly all sites, earlier snow disappearance led to both significant increases (4 of 62) and decreases (5 of 62) in growing season length. Satellite derived vegetation greenness confirmed site-dependent changes could both increase and reduce maximum annual vegetation greenness with earlier snow disappearance. A simple soil moisture model demonstrated the potential for diverging growing season length with earlier snow disappearance was more likely in areas with finer soil texture, greater rooting depth, greater potential evapotranspiration, and greater precipitation. More work is needed to understand the role of decreasing snowpacks, summer precipitation, and deeper soil processes in modulating sensitivity to earlier snowmelt. The potential for heterogeneity in mountain environments to cause diverging growing season length from earlier snowmelt over relatively small spatial scales has important implications for water budgets and development of refugia to regional warming.

1. Introduction

Changes in the timing and magnitude of snowmelt from regional warming are widespread across the Western U.S. and globally (Barnett et al., 2005). Compared to summer rainfall, snowmelt provides disproportionate benefits for recharging soil moisture and groundwater (Harpold et al., 2014, Bales et al., 2011, Jasechko et al., 2014) and sustaining transpiration late in the growing season (Hu et al., 2010). Consequently, snow water is critical to forest productivity and mitigating disturbance from insects and fire (Hu et al., 2010, Westerling et al., 2006). However, we lack a framework capable of identifying areas sensitive to altered snowmelt patterns based on soil properties, water demand, and hydroclimate. While physically-based models provide some insight about future soil water availability under changing snowpacks (Hamlet et al., 2007), they are difficult to parameterize at the scales that soils and snowpack heterogeneity are observed in mountain ecosystems (Bales et al., 2011, Grant et al., 2004).

Deciphering connections between soil water availability and vegetation response has been limited by a lack of soil hydrology observations. In snow dominated regions, soil water storage is typically filled during snowmelt (Harpold and Molotch, 2015) and declines as a consequence of drainage and evapotranspiration over the growing season (Harpold et al., 2014, Bales et al., 2011). However, the correspondence between peak soil moisture timing occurring coincident with snow disappearance (Harpold and Molotch, 2015) and the duration of late season water stress is relatively

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unexplored. Shallow soil moisture in water-limited systems in Western U.S. often reaches wilting point water content (i.e. 1500 kPa or the suction where vegetation has difficulty accessing water) later in the growing season. The timing and duration of soil water stress is strongly controlled by the wilting point water content of a particular soil type, which must be estimated via intensive laboratory techniques. The few hillslope to small watershed studies that have made co-located observations of soils and climate have shown that variations in snowpack distributions, soil properties, and summer rainfall cause large differences in water availability over relatively small distances (Bales et al., 2011, Grant et al., 2004, Smith et al., 2011, Webb et al., 2015). Compounding these observational complexities is evidence that mountain forests can access deep water stores in soils, regolith, and rock (Bales et al., 2011). Moreover, in some systems the water used for transpiration appears distinct from the water generating streamflow or groundwater recharge (McDonnell, 2014). These difficulties observing soil-mediated water stress have increased reliance on coarser models and remote sensing observations to infer the consequences of changing snowpacks on soil water availability (Garcia and Tague, 2015).

Several lines of evidence suggest that smaller and earlier snowmelt can increase vegetation water stress and forest disturbance severity. These lines of evidence typically invoke altered soil moisture as the link between changing snowpack regimes and forest health, but nearly always lack ground-based soil moisture observations. For example, Parida and Buermann (2014) found strong relationships between shorter snow-covered seasons and reduced summer vegetation greenness (i.e. Normalized Difference Vegetation Index, NDVI) across much of North America. They used the Palmer Drought Severity Index (PDSI) as a proxy for soil moisture to explain reductions in late season soil moisture as the primary driver of reduced vegetation productivity. Barichivich et al. (2014) used an index similar to PDSI and soil moisture estimates from land surface models to identify changes in snowmelt timing as the primary driver for inter-annual variations in NDVI across boreal regions of North America. These results are consistent with strong relationships between snow water equivalent (SWE) and vegetation greenness found in the Sierra Nevada mountains of California by Trujillo et al. (2012). Only a handful of studies have used ground-based observations of snow and vegetation. For example, Hu et al. (2010)) showed that smaller snowpacks in Colorado led to less net ecosystem exchange because forests relied on snow water late into the growing season. Soil moisture remains the likely mechanism linking changing snowmelt to vegetation response across these studies, however, validation of these mechanisms with field observations is lacking.

The future health of water-limited Western U.S. forest ecosystems will depend on the processes that store precipitation and release it late in the summer. While strong evidence exists that soil hydrological processes vary at the plot- to stand-scale (Bales et al., 2011, Grant et al., 2004), the implications of process heterogeneity for soil-mediated water stress in mountain environments is relatively unexplored. In this study, we make use of a relatively new soil moisture network, that includes co-located observations of soil moisture, snowpack, precipitation, and soil properties, across a hydroclimatic gradient of Snow Telemetry (SNOTEL) sites in the Western U.S. Using this dataset we ask two questions: (1) How will changing snowmelt alter the duration of soil water stress and length of the soil-mediated growing season (shortened to water stress and growing season for brevity)? and (2) What site characteristics increase the sensitivity of the length of water stress and growing season to changes in snowmelt? This study provides much needed field verification of soil water stress that is often invoked in Western U.S. forests but rarely measured; thus, our findings provide new insights into the ecohydrological implications of changing snowpack regimes.

2. Materials and methods

2.1. Climate and soil observations

A subset of 62 sites was selected from all SNOTEL sites that had soil properties and a minimum of five years of soil moisture and climate records. Observations of SWE (snow pillow), precipitation (weighing gauge), and soil moisture were obtained from online databases [http://www.wcc.nrcs.usda.gov/snow/, accessed 9/2/2015]. Soil moisture was measured at 5, 20, and 50 cm based on soil dielectric permittivity (Stevens Hydra probe I and II, Stevens Water Monitoring Systems, Inc.) using a standard calibration for all soil types with a measurement uncertainty of 3.4% (Seyfried et al., 2005). No attempt was made to distinguish the results between the two soil moisture sensors because of a lack of metadata. Precipitation and SWE measurements did not require quality control or gap filling. Soil water content data required removal of non-realistic values (i.e. >1 and <0) and screening and removal of artifacts during first 1-2 years following installation. Missing values were gap filled using cubic convolution spline interpolation in Matlab [Mathworks, 2014]. Years with >100 missing days were excluded from the analysis.

Several climate variables were calculated for each site-year based on the methods of Harpold et al. (2012). Maximum SWE was the last day with the annual maximum value. Annual precipitation (P) was the water year (October 1st to September 30th) accumulated precipitation. The ratio maximum SWE to annual P was the SWE:P ratio. The day of snow disappearance was the first day after maximum SWE where SWE equaled zero. Summer P was the accumulated precipitation between snow disappearance and September 30th. The melt rate was the average daily SWE loss between the day of maximum SWE and snow disappearance.

Soil properties that were co-located with the soil moisture sensors were downloaded from the National Cooperative Soil Survey (NCSS) Soil Characterization Database [http://ncsslabdatamart.sc.egov.usda.gov, accessed September 2, 2015]. All soil analyses were completed by NRCS National Soils Survey Center Kellogg Soil Survey Lab in Lincoln, Nebraska following standard procedures. In the soil analyses, coarse rock fragments are removed prior to the soil water retention curves being developed, which could affect the water stress determination. Only sites with >2 measured horizons in the top 50 cm were used in the analysis. The specific soil properties used in the analysis were total porosity, water content at 33 kPa (assumed to be field capacity), and water content at 1500 kPa (assumed to be wilting point). In 12 of 62 sites, wilting point and field capacity water content were not reported for at least one horizon and were estimated using the ROSETTA model (Schaap et al., 1998) based on measured clay fraction, sand fraction, and bulk density.

2.2. Determining water stress and growing season

We developed relationships based on soil moisture and soil properties to estimate the duration of soil water stress (shortened to water stress) and the length of the soil-mediated growing season (shortened to growing season). We acknowledge that these soil-mediated definitions of water stress and growing season are different from those used in the ecology literature that are typically based on plant phenology (Hu et al., 2010, Inouye, 2008). A profile weighted water stress value was estimated on a daily time step using soil moisture and soil properties. Each soil horizon