1
2
3
4
5 ***Diverging Sensitivity of Soil Water Stress To Changing Snowmelt Timing in the Western U.S.***
6
7
8
9

10
11
12
13
14 Adrian A. Harpold, Natural Resources and Environmental Science, University of Nevada, Reno
15
16
17
18

19 For Publication in Advances in Water Resources

20 3/22/2016
21

Diverging Sensitivity of Soil Water Stress To Changing Snowmelt Timing in the Western U.S.

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.

Keywords: soil moisture; snowmelt; water stress; growing season; climate change; mountain hydrology; refugia

54 1. Introduction:

55 Changes in the timing and magnitude of snowmelt from regional warming are widespread across
56 the Western U.S. and globally [1]. Compared to summer rainfall, snowmelt provides
57 disproportionate benefits for recharging soil moisture and groundwater [2-4] and sustaining
58 transpiration late in the growing season [5]. Consequently, snow water is critical to forest
59 productivity and mitigating disturbance from insects and fire [5,6]. However, we lack a
60 framework capable of identifying areas sensitive to altered snowmelt patterns based on soil
61 properties, water demand, and hydroclimate. While physically-based models provide some
62 insight about future soil water availability under changing snowpacks [7], they are difficult to
63 parameterize at the scales that soils and snowpack heterogeneity are observed in mountain
64 ecosystems [3,8].

65
66 Deciphering connections between soil water availability and vegetation response has been
67 limited by a lack of soil hydrology observations. In snow dominated regions, soil water storage is
68 typically filled during snowmelt [9] and declines as a consequence of drainage and
69 evapotranspiration over the growing season [2,3]. However, the correspondence between peak
70 soil moisture timing occurring coincident with snow disappearance [9] and the duration of late
71 season water stress is relatively unexplored. Shallow soil moisture in water-limited systems in
72 Western U.S. often reaches wilting point water content (i.e. 1500 kPa or the suction where
73 vegetation has difficulty accessing water) later in the growing season. The timing and duration
74 of soil water stress is strongly controlled by the wilting point water content of a particular soil
75 type, which must be estimated via intensive laboratory techniques. The few hillslope to small
76 watershed studies that have made co-located observations of soils and climate have shown that
77 variations in snowpack distributions, soil properties, and summer rainfall cause large differences
78 in water availability over relatively small distances [3,8,10,11]. Compounding these
79 observational complexities is evidence that mountain forests can access deep water stores in
80 soils, regolith, and rock [3]. Moreover, in some systems the water used for transpiration appears
81 distinct from the water generating streamflow or groundwater recharge [12]. These difficulties
82 observing soil-mediated water stress have increased reliance on coarser models and remote
83 sensing observations to infer the consequences of changing snowpacks on soil water availability
84 [13].

85

86 Several lines of evidence suggest that smaller and earlier snowmelt can increase vegetation water
87 stress and forest disturbance severity. These lines of evidence typically invoke altered soil
88 moisture as the link between changing snowpack regimes and forest health, but nearly always
89 lack ground-based soil moisture observations. For example, Parida and Buermann [14] found
90 strong relationships between shorter snow-covered seasons and reduced summer vegetation
91 greenness (i.e. Normalized Difference Vegetation Index, NDVI) across much of North America.
92 They used the Palmer Drought Severity Index (PDSI) as a proxy for soil moisture to explain
93 reductions in late season soil moisture as the primary driver of reduced vegetation productivity.
94 Barichivich et al. [12] used an index similar to PDSI and soil moisture estimates from land
95 surface models to identify changes in snowmelt timing as the primary driver for inter-annual
96 variations in NDVI across boreal regions of North America. These results are consistent with
97 strong relationships between snow water equivalent (SWE) and vegetation greenness found in
98 the Sierra Nevada mountains of California by Trujillo et al. [15]. Only a handful of studies have
99 used ground-based observations of snow and vegetation. For example, Hu et al. [5] showed that
100 smaller snowpacks in Colorado led to less net ecosystem exchange because forests relied on
101 snow water late into the growing season. Soil moisture remains the likely mechanism linking
102 changing snowmelt to vegetation response across these studies, however, validation of these
103 mechanisms with field observations is lacking.

104

105 The future health of water-limited Western U.S. forest ecosystems will depend on the processes
106 that store precipitation and release it late in the summer. While strong evidence exists that soil
107 hydrological processes vary at the plot- to stand-scale [3,8], the implications of process
108 heterogeneity for soil-mediated water stress in mountain environments is relatively unexplored.
109 In this study, we make use of a relatively new soil moisture network, that includes co-located
110 observations of soil moisture, snowpack, precipitation, and soil properties, across a
111 hydroclimatic gradient of Snow Telemetry (SNOTEL) sites in the Western U.S. Using this
112 dataset we ask two questions: 1) How will changing snowmelt alter the duration of soil water
113 stress and length of the soil-mediated growing season (shortened to water stress and growing
114 season for brevity)? and 2) What site characteristics increase the sensitivity of the length of water
115 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 Hydraprobe I and II, Stevens Water Monitoring Systems, Inc.) using a standard calibration for all soil types with a measurement uncertainty of 3.4% [16]. 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. [17]. 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://ncsslabsdatamart.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 [17] 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 [5,18]. A profile weighted water stress value was estimated on a daily time step using soil moisture and soil properties. Each soil horizon was assigned a daily soil moisture value by the soil moisture sensor within that profile. If no soil moisture sensors intersected the soil profile, the soil moisture is interpolated between the nearest two horizons or assigned the top or bottom soil moisture sensor if it was above or below the sensors, respectively. Soil water stress was then defined for each horizon with a binary yes or no. The soil profile water stress was the depth and available water content (AWC is field capacity minus wilting point water content) weighted summation of the soil horizons. Consequently, larger depths and AWC increased the influence of individual horizons on the profile-weighted soil water stress values. An example time-series for one year is shown in Figure 1 to illustrate the timing of water stress relative to the day of maximum SWE and snow disappearance. The example in Figure 1 is typical of the soil moisture recession found after snowmelt in most site-years.

A daily estimate of soil water stress for each soil profile was used to calculate water stress and growing season. The water stress was the summed daily soil water stress from the day of maximum SWE to October 1st of each year. Thus, if the entire soil moisture profile was below wilting point water content for a given day the water stress would increase by one day. If only

part of the soil moisture profile was below wilting point the water stress would increase by a fraction less than one day. The growing season was the number of days between the day of maximum SWE and October 1st that the soil profile was not experiencing water stress. The sum of water stress and growing season equaled the total number of days from day of maximum SWE to October 1st. In other words, if the timing of maximum SWE was fixed then the days of water stress and growing season were 1:1 inversely related, i.e. the growing season would decrease by one day for a one day increase in water stress. Cut-off dates between September 1st and October 1st generally had small effects on inter-annual differences in growing season and water stress values.

2.3 Remote Sensing Datasets

Remote sensing-derived datasets were used to expand the inferences possible using the ground-based SNOTEL observations. The normalized difference vegetation index (NDVI) was extracted from MODIS cloud free days in the 500 m pixel of each site. The timing and magnitude of annual maximum NDVI was found for each site from 2001 – 2014. Only the sites with >5 years maximum NDVI that could be calculated from at least 3 cloud-free images between June 1st and August 31st (49 of 62 sites) were used in the analysis. Additionally, potential evapotranspiration (PET) was estimated from MODIS-derived MOD16 product [18] that applies the Penman equation. Average total PET was taken from each 1000 m pixel that contained a SNOTEL site from 2001 – 2014. Topography from the Shuttle Radar Topography Mission (SRTM) with a resolution of 100 m was used to calculate local slope and topographic wetness index using GIS. The coarser 100 m elevation was used due to uncertainty in the reporting of the location of SNOTEL sites by NRCS.

2.4 Soil Moisture Model At An Idealized Snow Site

We adapted a soil moisture model to investigate the role of snowmelt timing on soil water stress. The model was developed by Laio et al. [19] and a detailed mathematical description of the model is provided in that publication. The model operates as a water budget model with only seven parameters needed to estimate evapotranspiration rate and leakage: soil depth (Z_r), soil porosity (n), soil moisture sufficient for evaporation to equal potential evapotranspiration (s^*), wilting point water content (s_w), field capacity water content (s_{fc}), hydraulic conductivity (K_s),

and an empirical parameter describing the soil water retention curve (β). The ET rate could have three states depending on the soil moisture (s):

$$ET(s) = \begin{cases} 0 & 0 < s \leq s_w \\ E_p \frac{s - s_w}{s^* - s_w} & s_w < s \leq s^* \\ E_p & s^* < s \leq 1 \end{cases}$$

Similarly, leakage below the root zone could have two states that were controlled by soil moisture:

$$L(s) = \begin{cases} 0 & 0 < s \leq s_{fc} \\ [e^{\beta(s-s_{fc})} - 1] \frac{K_s}{e^{\beta(1-s_{fc})} - 1} & s_{fc} < s \leq 1 \end{cases}$$

The daily ET and leakage rate was then value multiplied by the total porosity ($n \cdot Z_r$) to estimate fluxes. Interception was assumed to be zero. The only changes from Liao et al. [19] model was replacing the stochastic precipitation forcing with an empirical snowmelt routine and forcing evapotranspiration to zero at wilting point rather than the hygroscopic point.

The soil moisture model is simplified and several assumptions are applied to investigate the role of snowmelt on soil water stress under different soil and climatic conditions. The seven soil parameters described above were taken from Liao et al. [19] for sand, loamy sand, sandy loam, loam, and clay. We developed two modeling exercises to aid our understanding of growing season response to changing snowmelt timing. First, we assumed a rooting depth of 70 cm in all cases and three PET scenarios represent broad climatic variations, low (45 cm/year), medium (90 cm/year), and high (135 cm/year). Second, we allowed rooting depth to vary between 40 and 170 cm in increments of 15 cm and PET to vary between 45 and 170 cm/year in increments of roughly 17 cm/year. We then estimated the day of snow disappearance that maximized the growing season length. In both modeling exercises, daily PET was calculated assuming an annual sinusoidal temperature curve with minimum of -10 °C on day 90 (December 30 in non-leap year) of the water year and a maximum of 20 °C on day 270 (June 28 in non-leap year) of the water year. The PET was then calculated using the Hamon method [19] with a latitude of 41 degrees. The Hamon daily PET was multiplied by a coefficient that ranged from 1.0 to 4.0 to achieve the desired PET scenarios, similar to what is done in other applications of the Hamon equation [20]. A best-fit relationship between the amount of maximum SWE and the day of

snow disappearance was developed from all site years (see Supplemental). The maximum SWE was varied between 25 and 175 cm, which resulted in a snow disappearance between May and July. The relationship between snow disappearance and day of maximum SWE from all site-years was then used to estimate the daily melt rate as the maximum SWE divided by the time elapsed between the date of maximum SWE and snow disappearance (see Supplemental). To better understand the role of snowmelt no post-melt rainfall was simulated.

The goal of the soil hydrology model was to investigate the sensitivity of water stress and growing season to variations in climate and soils. There was no effort made to match the response or conditions of any particular site. Instead the model represents an idealized snow-dominated site that has water and energy regimes that are characteristic of the SNOTEL sites investigated. The model has several limitations that should be recognized for its intended application. First, evapotranspiration is only limited by soil water and is estimated with a temperature-based PET model. Therefore, ET is not effectively modeled in terms of vapor pressure deficits, light, or temperature. Second, soils are idealized as homogenous so that soil properties are constant throughout the profile. Third, we assume that ET goes to zero below wilting point soil moisture to be consistent with our definition of water stress, despite the fact that water can be evaporated above the hygroscopic point.

3.7 Statistical Analyses

This study uses a combination of statistical techniques to characterize the influence of climate and soil predictors on the response of water stress duration and growing season length. First, Spearman rho values were calculated as a non-parametric measure of statistical dependence between water stress and growing season with the predictor variables. P-values for the Spearman rho were computed using the exact permutation distribution. The strongest climate predictor variable was determined based on the lowest p-value below 0.10 because the number of years differed across sites. The best-fit slope of select relationships were computed based on linear regression and maximizing the R^2 values as one minus the ratio of the error sum of squares to the total sum of squares; p-values were computed based on F-statistics. Non-linear relationships were also computed (i.e. power-law and exponential), but never explained significantly more variability than linear relationships. The objective the linear regression was to

characterize the sensitivity of the relationship based on the best-fit slope among different predictor variables, rather than to develop a predictive relationship.

We performed regression tree analysis to clarify the relative importance of different predictor variables on site-level water stress and growing season. The regression tree was based on all continuous variables. The regression tree analysis was performed in Matlab (Mathworks version R2013) based on the methods of Brieman et al. [21]. The optimized regression tree was pruned to minimize the cross-validated error based on the minimum leaf size using the average results of 50 runs of a ten-fold cross validation (see Supplemental). The accuracy of the optimized tree was assessed based on the linear correlation coefficient between observed and predicted values.

3. Results

3.1 Site Physiography and Soil Water Response

The hydroclimate varied substantially across 62 sites from six Western U.S. states (Table 1). Site photographs showed that 58 of 62 sites were forested, with 36 in conifer forests, 16 in deciduous forests, 6 in mixed forests, and 4 in sagebrush/woodlands. The sites were in low relief areas of minor topographic convergence (average slope of 7 percent and average topographic wetness index of 1.3). The majority of the sites were snow dominated, with an average SWE:P ratio of 0.5 and average maximum SWE of 50 cm. The average summer precipitation varied by an order of magnitude from 6 to 60 cm. Across all site-years the average snow disappearance was May 12th, with dates at individual sites that varied from February 22nd to July 2nd. The earliest snow disappearance was in Eastern Oregon and Northern Nevada (Figure 2a). The snow disappearance had a very strong power-law relationship with maximum SWE ($R^2=0.78$, $p<0.001$, see Supplemental) across all site-years. Similarly, a linear relationship explained significant variability in snow disappearance based on the day of maximum SWE ($R^2=0.75$, $p<0.001$, see Supplemental). Other significant correlation between predictor variables included annual P and maximum SWE ($\rho=0.88$), annual P and melt rate ($\rho=0.79$), melt rate and maximum SWE ($\rho=0.93$), which are considered in the prediction of water stress and growing season (Table 2).

The soil properties and soil water response had considerable variability across the 62 sites. Soil texture varied from sand dominated to silt dominated (Table 1), with an average of 47% sand and

37% silt. Correspondingly, the wilting point water content averaged 12% but had a coefficient of variation (CV) of 0.42. The average length of soil moisture records was >10 years. The duration of water stress averaged 49 days across sites, with a CV of 0.53. The growing season averaged 102 days, and was less variable than water stress with a CV of 0.25. The variations in water stress and growing season allowed predictive relationships to be developed across the larger region and at the site-level.

3.2 Predicting the Duration of Water Stress

Water stress was more strongly correlated to snowpack timing predictors across 643 site-years than precipitation magnitude or snowmelt rate. Date of snow disappearance and the day of maximum SWE had the largest Spearman rho coefficients of -0.48 and -0.45, respectively (Table 3) and were strongly correlated to each other ($\rho=0.93$, $p<0.001$). Annual P and maximum SWE had lower Spearman rho with water stress of -0.34 and -0.37, respectively (Table 3). The Spearman rho of melt rate and summer P with water stress were similar (-0.35 and -0.38, respectively), while the SWE:P ratio had a lower rho value (Table 3). The strongest correlation with water stress was snow disappearance, which had a best-fit linear slope indicating that a one day earlier snow disappearance resulted in 0.62 days increase in water stress (Table 3 and Figure 3a). Similarly, a 1 cm decrease in annual P led to 0.31 day increase in water stress, whereas a 1 cm decrease in summer P led to a 0.97 day increase in water stress (Table 3).

The variance in water stress explained by snowpack timing and precipitation magnitude at 62 sites was similar to that found across all site-years. Annual precipitation, maximum SWE, and snow disappearance had the highest rho values with site-level water stress of -0.65, -0.59, and -0.66 on average, respectively, and were significant ($p<0.10$) predictors at 32, 27, and 27 sites, respectively (Table 4). The other predictor variables had rho values of <0.49 with water stress and had significant relationships at <21 sites (Table 4). When the best predictor variable was selected for each site based on lowest p-value below 0.10, annual precipitation explained the most variance at 25 sites followed by snow disappearance at 14 sites and summer precipitation at 12 sites (Table 4).

The site-level relationships between snow disappearance and water stress consistently had a negative slope, suggesting that earlier snow disappearance led to an increase in water stress. The average slope of the site-level snow disappearance-water stress relationships was -0.57 day/day, but significant slopes ranged from 0.18 to -2.3 day/day. Significant slopes less than -1 day/day occurred in 6 sites and suggested that for each day earlier snow disappearance there was >1 day increase water stress. Significant relationships between snow disappearance and water stress occurred at sites with a large range of average snow disappearance (11.8 to 126.3) and water stress duration (29.3 to 141.2 days) (Figure 3b). Generally, slopes were more negative in sites with greater average water stress and less negative in sites with smaller average water stress (Figure 3b). Sites with strong negative relationships between water stress and snow disappearance were distributed across the Western U.S., with the Sierra Nevada showing consistent high negative correlation (Figure 4a).

A regression tree analysis showed that snow disappearance, annual P, and summer P explained the majority of variability in water stress (Figure 5). The optimized regression tree explained 67% of the variability in water stress using 12 branches. The first branch was based on snow disappearance before/after May 4; sites with snow disappearance before May 4 averaged 92 days of water stress, whereas sites after May 4 averaged 57 days of water stress. The two second-level branches were both based on summer P. Summer P greater than about 20 cm resulted in substantially shorter water stress duration on both branches. The lower level branches were based on annual P, snow disappearance, and AWC. The regression tree results were consistent with correlation analyses, indicating that snow disappearance is the primary driver of water stress duration.

3.3 Predicting the Growing Season Length

The length of the growing season was more difficult to predict than water stress using climatic predictors across all site-years. The only significant predictor of growing season length across all site-years was summer P (Table 3). The slope of the best-fit relationship between summer P and growing season indicated that the growing season would increase by 1.2 days for each 1 cm increase in summer P (Figure 6a). Although the other climate predictors led to non-significant

relationships with growing season, the best-fit slopes suggested lower precipitation magnitudes and lower SWE:P ratios reduced growing season length (Table 3).

In contrast to combined site-year analyses, most climatic predictors had significant relationships with inter-annual variability in growing season at the site-level. The summer precipitation, day of maximum SWE, and melt rate explained the most variability in growing season, with significant relationships in 22, 22, and 18 sites respectively (Table 4). Summer precipitation and day of maximum SWE were the best predictors (lowest p-value) in 21 and 13 sites, respectively (Table 4 and Figure 6b). The average slope of the annual P and growing season relationship was more than eight times smaller than the slope of the summer P and growing season relationship (Table 4). Despite a strong relationship between snow disappearance and water stress, there were only nine sites with significant relationships between snow disappearance and growing season and the average slope was near zero. Of the nine sites with significant relationships between growing season and snow disappearance, five had negative slopes and four had positive slopes. Sites with a positive growing season-snow disappearance correlation (i.e. sites where growing season decreased with increasing water stress) were generally in the Pacific Northwest and Utah (Figure 4b).

A regression tree was able to explain 41% of the growing season variability based on six branches (Figure 7). Consistent with the correlation analysis, summer P was the first-level branch. Sites with summer P greater than 16 cm had average growing season lengths of 117 days, whereas sites with summer P less than 16 cm had average growing season lengths of 75 days. The second and third-level branches were wilting point and percent sand.

3.4 Relationship Between Water Stress and Growing Season

The duration of water stress was strongly correlated with growing season ($\rho=-0.88$, $p<0.001$) across all site-years and showed that increased water stress corresponded with smaller growing season (Figure 8a). The slope of the best-fit relationship between water stress and growing season indicated that each 1 day increase in water stress caused the growing season length to shorten by 0.74 days and that site-years with zero water stress will have a growing season of 162 days (Figure 8a). Site-years with larger annual precipitation generally had shorter growing

seasons compared to sites with similar water stress but less precipitation (Figure 8a). There was significant correlation between site-level water stress and growing season length at 36 of 62 sites (Figure 8b).

Despite a widespread increase in water stress with earlier snow disappearance, we observed a diverging response of growing season length: some sites had longer growing seasons with earlier snow disappearance, while other sites had a shorter growing season (Figure 9). To illustrate this diverging trend, we plotted the change in growing season versus the change in water stress with a 10 day earlier snow disappearance (Figure 9a). Sites that had >5 day increase in water stress from a 10 day earlier snow disappearance generally had a decrease in the growing season length. Five sites had significantly shorter growing season when snow disappeared earlier. Conversely, sites with <5 day change in water stress with earlier snow disappearance could have increasing growing season length. Four sites had significantly longer growing seasons with earlier snow disappearance. Interestingly, the 62 sites are roughly split between those showing a tendency toward longer growing season and those with shorter growing seasons with earlier snow disappearance (Figure 9b). Generally, sites with a tendency toward longer growing seasons with earlier snow disappearance had shorter average growing season lengths (Figure 9).

3.5 Vegetation Greenness Response to Soil Water Stress

The peak annual vegetation greenness, measured using MODIS-derived NDVI, was sensitive to site-level and inter-annual variability in water stress and snow disappearance. The average site-level NDVI was negatively correlated with snow disappearance (Figure 10a, $\rho=0.26$ and $p=0.07$). The analysis was restricted to the 49 sites with >5 years of concurrent NDVI, water stress, and growing season estimates. At the site-level, 20 of 49 sites had significant relationships between NDVI and snow disappearance timing, with 2 of 20 showing an increase in NDVI with earlier snow disappearance (Figure 10b). Similarly, 1 of 49 sites had significantly positive NDVI-water stress relationships and 10 out of 49 sites had significantly negative relationships (Figure 10c). Sites with negative NDVI-snow disappearance relationships tended to have average annual PET <120 cm (Figure 10b). These results support the finding of diverging tendencies to longer and shorter growing seasons with earlier snow disappearance.

3.6 Explaining Growing Season Response With A Soil Moisture Model

A soil water budget model was used to investigate how interactions between PET, rooting depth, snowpack dynamics, and soil properties could cause both decreases and increases in growing season with earlier snow disappearance. We used two model exercises: 1) fixing rooting depth at 70 cm and using three PET scenarios across different soil types and 2) allowing both PET and rooting depth to vary across within a given soil type.

Using the first modeling exercise, fine texture soils (i.e. clay and silt) had longer growing seasons and more variable response to snow disappearance than coarser textured soils (i.e. sand) for a given snow disappearance and PET value (Figure 11a-c). Increasing PET led to smaller differences among growing season length for different soil types and a monotonic increasing relationship between growing season and snow disappearance (Figure 11). Only in the unrealistically low PET scenario (45 cm/year) did all soil types show evidence of an optimum snow disappearance that maximized growing season length (Figure 11a). Thus, the model exercise demonstrated that sites with lower water demand (i.e. lower PET) and higher water retention (i.e. fine texture) were most likely to have shorter growing season length with later snow disappearance. Conversely, higher PET and lower water retention (i.e. coarse texture) led to increasing growing season length with later snow disappearance. However, given that the minimum site-level PET was near 100 cm/year, the model exercise could not adequately explain why numerous sites had increasing growing season length with earlier snow disappearance.

In the second modeling exercise we allowed the rooting depth to vary across different soil textures and found the timing of snow disappearance that maximized the growing season (Figure 11d-f). In coarser soil texture, like sand, we observe a monotonic relationship of increasing growing season length with earlier snow disappearance (Figure 11f), consistent with the first modeling exercise (Figure 11c). However, finer soil textures had optimum growing season lengths that suggested growing season length could increase with earlier snow disappearance (Figure 11d-e). An optimum snow disappearance date was most likely to occur as soil texture became finer, PET was reduced, and rooting depth was increased. These results could help explain why diverging growing season lengths with earlier snowmelt were not observed in the range of PET found at the sites, i.e. assumption of rooting depths of 70 cm may have

underestimated actual rooting depths. The soil hydrology model thus, met its principal goal to identify mechanisms/properties causing sensitivity of water stress and growing season to changes in snowpack dynamics without being trained to any individual site.

The observations of both increasing and decreasing growing season length with earlier snow disappearance were substantiated with the soil water budget model. Observations and model results were consistent in showing that increasing PET, coarser soil types, and reduced rooting depths generally led to positive snow disappearance-growing season relationships. Conversely, sites with lower PET, finer soil textures, and deeper rooting depths generally had more parabolic snow disappearance-growing season relationships, meaning that snow disappearance later than an optimum date led to shorter growing seasons. The dependence of snow disappearance-growing season relationships on soil texture and PET was also consistent between model results and observations. The snow disappearance-growing season relationships were sensitive to soil texture, with sites having negative snow disappearance-growing season relationships generally having a greater fraction of clay and silt (Figure 12). The four significantly negative snow disappearance-growing season relationships had an average clay plus silt fraction of 52% versus only 39% at the five sites with significantly positive snow disappearance-growing season relationships. Similarly, the median PET and dryness index (PET divided by annual P) for the four sites with significantly negative snow disappearance-growing season relationships was 147 cm/year and 1.16, respectively, compared to 164 cm/year and 1.63, respectively for sites with positive snow disappearance-growing season relationships. We did not have the observations needed to test the dependence on rooting depth. The observation and model results confirmed that the physical mechanisms capable of driving the observed snow disappearance-growing season relationships depended on interactions between soil properties, water inputs, and water demand.

4. Discussion

We found that cessation of snowmelt (i.e. day of snow disappearance) explained more variability in the duration of soil water stress than any other climatic predictor across all site-years and at individual sites. Across all site-years, snow disappearance-water stress relationships had Spearman rho values that were >0.10 larger than precipitation and SWE predictors, with the

exception of day of maximum SWE which was strongly related to snow disappearance (power law $R^2=0.79$, see Supplemental). At the site level, snow disappearance was significantly correlated (average $\rho=0.66$) to water stress at 36 of 62 sites and explained the most variability of any predictor in 14 of 62 sites (Table 4). Summer P and maximum SWE were the strongest predictors at only 12 and 6 sites, respectively. These findings are consistent with previous remote sensing and ground-based observations suggesting that snowmelt timing is strongly related to vegetation greenness [15] and net ecosystem exchange [5]. Our results imply that factors leading to earlier snow disappearance, namely reduced maximum SWE and earlier or faster melt [15, 17], will increase water stress even without changes in the amount of precipitation. Despite the strong relationships between climate predictors and water stress, only summer P had significant relationships with growing season (Table 3 and 4). As expected, greater summer P led to longer growing seasons (Figure 6 and 7). Contrary to expectations, however, greater annual P and later snow disappearance did not have a consistent relationship with growing season length (Table 3). Although decreases in growing season length were strongly predicted by increases in water stress at both the site-year and site-level (Figure 8), sites with lower sensitivity to increasing water stress from earlier snow disappearance could have increased growing season length because of an earlier start to the growing season (Figure 9).

Our empirical and model results demonstrated that a diverging response of growing season length (i.e. increases and decreases) with earlier snow disappearance was due to a number of site factors. Sites with high water demand, coarser soils, shallow rooting depths, small summer P, and earlier snow disappearance were most sensitive to increased water stress from shifts to earlier snowmelt (Figure 11 and 12). As a consequence of a strongly non-linear soil moisture recession (Figure 1), water stress could shift between 0.2 longer to 2.3 days shorter per day earlier snow disappearance (Figure 9a). This non-linear relationship is consistent with non-linear soil evaporation and precipitation relationships found at sites in Idaho, which were due to reduced evaporation from prolonged snow cover but increased evaporation from wetter soils [22]. Conversely, areas with fine soil texture, low water demand, deep rooting depths, large summer P, and later snow disappearance had the greatest potential for increased growing season from earlier snowmelt (Figure 11 and 12). A simple conceptualization invokes competition between energy and water limitations to explain this divergent response: 1) in water limited

systems earlier snowmelt shifts soil moisture recession earlier and extends the duration of water stress, 2) in energy limited systems earlier snowmelt leads to earlier growing seasons that overcompensate for increased water stress at the end of the growing season. The site-level dryness indexes supports the potential of both water and energy limitations at SNOTEL sites, with 10 sites having a dryness index below one (see Supplemental). Additionally, 3 of 4 sites with longer growing seasons resulting from earlier snow disappearance had dryness indexes near one, implying energy limitations at these sites (Figure 12). Sites with less water deficit (i.e. higher snowfall and lower PET) and greater soil water storage (i.e. finer soil texture and greater rooting depths) were more likely to be energy limited and thus, candidates for longer growing seasons with earlier snow disappearance. It has been widely recognized in tree-ring studies that climate can cause diverging ring width response (e.g. both increased and decreased growth) depending on local site conditions [23-25]. The postulated tradeoffs between water versus energy limitations are likely to drive complex spatial patterns in the sensitivity of water stress to earlier snow disappearance over typical gradients in soil properties, topography, and climate.

Our finding that earlier snowmelt led to both increases and decreases in growing season length (Figure 9) was supported by significant negative and positive correlation between maximum NDVI and snow disappearance timing at individual sites (10b). Evidence of diverging effects of earlier snow disappearance on soil moisture regimes and aboveground greenness have important implications for explaining previous inferences based on large-scale modeling and remote sensing. For example, our results are broadly consistent with hydrological modeling showing decreasing July 1st soil moisture due to earlier snowmelt over the latter part of the 20th century, but provide an explanation for contradictory trends towards increased soil moisture in the Pacific Northwest and other scattered locations [7]. Similarly, Parida and Buermann [14] found both negative and positive snow season-NDVI relationships within close proximity (i.e. adjacent one degree grid cells) across much of Western North America. Barichivich et al [12] also used modeled soil moisture datasets over the boreal region of North America to demonstrate significant, but highly variable, vegetation greenness from lower summer soil moisture. While some of the spatial variability in vegetation response to changing snowmelt could be attributed to summer rainfall [14], our results suggest that variations in snowmelt, water demand, rooting depth, and soil properties could also cause spatial variability in vegetation response.

This study is the first to employ regional-scale soil moisture observations that include soil water retention information to understand snowmelt-water stress relationships. However, limitations in the SNOTEL network hamper scaling these results across mountain areas. In particular, SNOTEL sites are located in flat topography and lack soil moisture transects needed to quantify the role lateral redistribution of water. Lateral redistribution can be a critical process in controlling runoff generation and hydrological partitioning [26-28]. It is also difficult to assess either actual or potential ET at the SNOTEL sites because they do not measure the necessary energy fluxes, with the temperature measurements having accuracy issues, see Oyster et al. [29]; hence, our decision to use coarser remote-sensing derived PET products in our analysis. Another limitation in the SNOTEL measurements is the lack of deep soil moisture measurements, which forced an assumption that soil water stress in the top ~70 cm was a proxy for vegetation water stress. There is a body of literature contrary to this assumption, suggesting that mountain forests access water from deeper water stores [3]. An important finding of our modeling results was that diverging growing season response was strongly dependent on rooting depth, with very little evidence for longer growing seasons with earlier snow disappearance when rooting depths were <70 cm (Figure 11). However, we know that roots are heavily distributed in the top 70 cm of the soil profile [26] and that porosity decreases rapidly within forest soil profiles [27]. Identifying the water used for transpiration remains an active field of research [28] and observations of deeper soil and rock water content are rare [29]. Therefore, we are left to infer a relationship between water stress within the top 70 cm and the entire rooting profile, but recognize that site differences in rooting and soil depth could confound growing season response. Finally, defining the beginning of the growing season is difficult across diverse sites. However, evidence exists that both energy/temperature and water limitations can limit transpiration prior to snowmelt [30]. While new ground-based observation networks of soil moisture [30] have removed some of these limitations in the SNOTEL network, they generally lack co-located soil property and climate observations that have proven critical for interpreting soil water availability.

The novel finding that growing season response diverges with earlier snowmelt cessation (Figure 9) suggests a more nuanced discussion of sensitivity of forest ecosystems to changing snowmelt

dynamics is needed. Earlier snow disappearance led to increased soil-mediated water stress at nearly all sites (Figure 9a). The implications of increased forest water stress are clear: higher likelihood of severe fires [6], greater sensitivity to insect disturbance [31], and less ecosystem productivity [5]. However, in a subset of wetter sites, earlier start to growing season overcompensated for increased soil water stress at the end of the growing season. Thus, these sites showed both increased water stress and longer growing season from earlier snow disappearance. This diverging response suggests a ‘drier will get drier’ hypothesis at these mountain sites; in other words, sites already experiencing sizable soil water stress and earlier snowmelt are most likely to see increased water stress with earlier snow disappearance. Conversely, the sites that will benefit from a longer growing season with earlier snow disappearance will likely be energy limited (Figure 11 and 12). A longer growing season has the potential to alter basin-scale water and carbon budgets by promoting shifts of forests to higher elevations and landscape positions that have historically been energy/temperature limited [32]. Moreover, the potential for increased growing season from earlier snowmelt could support refugia in isolated landscape positions that are capable of sustaining forests over extended periods of drought [24]. For example, shaded hillslopes with greater soil development and organic matter content might experience longer growing season from earlier snow disappearance that cannot be captured by coarser soil and climate datasets typically used in modeling efforts. These results thus, support refining hypotheses for widespread mass 21st century tree mortality to include soil-mediated hydrological refugia [33]. It is important to note that changes in summer P could also have important effects on growing season length [10,13] that were not the focus of this study. Capturing small-scale differences in soil properties and snowmelt remain challenging with current observation techniques, although high resolution hyperspectral remote sensing offers the potential for fine-scale observations of vegetation health over large spatial extents. Future efforts should test the hypothesis of divergent growing season length using high-resolution spatial observations and begin quantifying the impacts on water and carbon budgets at larger scales.

5. Conclusions

Using a novel set of regional-scale ground-based observations, we demonstrated that alterations to the day of snow disappearance will have greater impacts on soil water stress than the magnitude of winter or summer precipitation. Of the 62 sites investigated, 36 had significant

relationships between earlier snowmelt and the duration of soil water stress. Due to the non-linear nature of soil moisture recession, a one-day earlier snow disappearance could increase water stress by greater than one day. Earlier snow disappearance can be caused by decreased maximum SWE or earlier/faster snowmelt, which both have the potential to shift snow disappearance earlier under expected regional warming. Importantly, the role of snow disappearance suggests the potential for increasing water stress is not predicated on decreasing winter precipitation, but this finding will require further validation. Despite the widespread relationships between earlier snow disappearance and increased water stress, earlier snow disappearance led to both increases and decreases in the duration of the non-water stress season. Both modeling and empirical results indicated that increased water deficit (i.e. lower precipitation and higher PET) and reduced soil water storage (i.e. coarser soil texture and shallow rooting depths) resulted in shorter growing season from earlier snow disappearance, whereas sites that exhibited longer growing seasons from earlier snow disappearance were likely to have lower water demand and greater soil water storage. Variability in soil hydrological processes can help explain previous sensitivity to reduced vegetation greenness from earlier snowmelt across the Western U.S. Our results suggest that trends towards increased vegetation greenness with earlier snowmelt are plausible and heretofore not effectively incorporated into our understanding of the effects of earlier snowmelt on ecohydrological functioning. Given that soils and climate vary considerably across complex topography characteristic of mountain areas [2,3,8,11], these divergent responses to earlier snowmelt could be occurring at spatial scales much smaller than the resolution of hydrological models and remote sensing observations (i.e. <1 to 30 km). Diverging sensitivity to growing season across relatively short distances could promote forest refugia to altered snowmelt timing in some landscape positions. Identifying the spatial extent and regional distribution of these diverging soil water responses will be critical to understanding the future risk of soil water-mediated ecohydrologic processes to altered snowpack regimes.

Acknowledgements:

An NSF post-doc fellowship (EAR 1144894) provided support during the initiation of this research and USDA NIFA (NEV05293) and NASA EPSCoR (NNX14AN24A) provided support for completion of this work. The author is grateful for the work of undergraduate researchers

635 Brooke Stamper and Kevin Kauffman for helping to compile the necessary datasets. Three
636 anonymous reviewers and the Associate Editor substantially improved the manuscript.
637

638 **References:**

- 639 [1] Barnett TP, Adam JC, Lettenmaier DP. Potential impacts of a warming climate on water
640 availability in snow-dominated regions. *Nature* 2005;438:303–9.
641 doi:10.1038/nature04141.
- 642 [2] Harpold AA, Molotch NP, Musselman KN, Bales RC, Kirchner PB, Litvak M, et al. Soil
643 moisture response to snowmelt timing in mixed-conifer subalpine forests. *Hydrological*
644 *Processes* 2014;29:2782–98. doi:10.1002/hyp.10400.
- 645 [3] Bales RC, Hopmans JW, O'Geen AT. Soil moisture response to snowmelt and rainfall in
646 a Sierra Nevada mixed-conifer forest. *Vadose Zone Journal* 2011.
- 647 [4] Jasechko S, Birks SJ, Gleeson T. The pronounced seasonality of global groundwater
648 recharge. *Water Resources Research* 2014. doi:10.1029/90WR02774.
- 649 [5] Hu J, Moore DJP, Burns SP, Monson RK. Longer growing seasons lead to less carbon
650 sequestration by a subalpine forest. *Global Change Biology* 2010;16:771–83.
651 doi:10.1111/j.1365-2486.2009.01967.x.
- 652 [6] Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. Warming and Earlier Spring
653 Increase Western U.S. Forest Wildfire Activity. *Science* 2006;313:940–3.
654 doi:10.1126/science.1128834.
- 655 [7] Hamlet AF, Mote PW, Clark MP. Twentieth-Century Trends in Runoff,
656 Evapotranspiration, and Soil Moisture in the Western United States. *Journal of Climate*
657 2007;20:1468–86. doi:10.1175/JCLI4051.1.
- 658 [8] Grant L, Seyfried M, McNamara J. Spatial variation and temporal stability of soil water
659 in a snow-dominated, mountain catchment. *Hydrological Processes* 2004;18:3493–511.
660 doi:10.1002/hyp.5798.
- 661 [9] Harpold AA, Molotch NP. Sensitivity of soil water availability to changing snowmelt
662 timing in the western U.S. *Geophysical Research Letters* 2015;42:8011–20.
663 doi:10.1002/2015GL065855.
- 664 [10] Smith TJ, McNamara JP, Flores AN, Gribb MM, Aishlin PS, Benner SG. Small soil
665 storage capacity limits benefit of winter snowpack to upland vegetation. *Hydrological*
666 *Processes* 2011;25:3858–65. doi:10.1002/hyp.8340.
- 667 [11] Webb RW, Fassnacht SR, Gooseff MN. Wetting and Drying Variability of the Shallow
668 Subsurface Beneath a Snowpack in California's Southern Sierra Nevada. *Vadose Zone*
669 *Journal* 2015;14:0. doi:10.2136/vzj2014.12.0182.
- 670 [12] McDonnell JJ. The two water worlds hypothesis: ecohydrological separation of water
671 between streams and trees? *Wiley Interdisciplinary Reviews: Water* 2014;1:323–9.
672 doi:10.1002/wat2.1027.
- 673 [13] Garcia ES, Tague CL. Subsurface storage capacity influences climate–
674 evapotranspiration interactions in three western United States catchments. *Hydrology*
675 *and Earth System Sciences* 2015;19:4845–58. doi:10.5194/hess-19-4845-2015.
- 676 [14] Parida BR, Buermann W. Increasing summer drying in North American ecosystems in
677 response to longer nonfrozen periods. *Geophysical Research Letters* 2014;41:5476–83.
678 doi:10.1002/2014GL060495.
- 679 [15] Trujillo E, Molotch NP, Goulden ML, Kelly AE. Elevation-dependent influence of snow
680 accumulation on forest greening. *Nature* 2012;5:705–9. doi:10.1038/ngeo1571.
- 681 [16] Seyfried MS, Grant LE, Du E. Dielectric loss and calibration of the Hydra Probe soil
682 water sensor. *Vadose Zone Journal* 2005;4:1070–9.
- 683 [17] Harpold A, Brooks P, Rajagopal S, Heidbuchel I, Jardine A, Stielstra C. Changes in

- snowpack accumulation and ablation in the intermountain west. *Water Resources Research* 2012;48. doi:10.1029/2012WR011949.
- [18] Inouye DW. Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. *Ecology* 2008;89:353–62. doi:10.1890/06-2128.1.
- [19] Hamon WR. Computation of direct runoff amounts from storm rainfall. *Int Assoc Sci Hydrol Pub* 1963:52–62.
- [20] Lu J, Sun G, McNulty SG, Amatya DM. A comparison of six potential evapotranspiration methods for regional use in the Southeastern United States. *JAWRA Journal of the American Water Resources Association* 2005;41:621–33. doi:10.1111/j.1752-1688.2005.tb03759.x.
- [21] Brieman L, Friedman JH, Olshen RA, Stone CJ. Classification and regression trees. Wadsworth; 1984.
- [22] Wang R, Kumar M, Marks D. Anomalous trend in soil evaporation in a semi-arid, snow-dominated watershed. *Advances in Water Resources* 2013;57:32–40. doi:10.1016/j.advwatres.2013.03.004.
- [23] Driscoll WW, Wiles GC, D'Arrigo RD, Wilmking M. Divergent tree growth response to recent climatic warming, Lake Clark National Park and Preserve, Alaska. *Geophysical Research Letters* 2005;32:L20703. doi:10.1029/2005GL024258.
- [24] Peterson DW, Peterson DL. Effects of climate on radial growth of subalpine conifers in the North Cascade Mountains. *Canadian Journal of Forest Research* 1994;24:1921–32. doi:10.1139/x94-247.
- [25] Dolanc CR, Westfall RD, Safford HD. Growth–climate relationships for six subalpine tree species in a Mediterranean climate. *Canadian Journal of Forest Research* 2013;43:1114–26. doi:10.1139/cjfr-2013-0196.
- [26] McNamara JP, Chandler D, Seyfried M, Achet S. Soil moisture states, lateral flow, and streamflow generation in a semi-arid, snowmelt-driven catchment. *Hydrological Processes* 2005;19:4023–38. doi:10.1002/hyp.5869.
- [27] Tague C, Peng H. The sensitivity of forest water use to the timing of precipitation and snowmelt recharge in the California Sierra: Implications for a warming climate. *Journal of Geophysical Research: Biogeosciences* 2013;118:875–87. doi:10.1002/jgrg.20073.
- [28] Hwang T, Band LE, Vose JM, Tague C. Ecosystem processes at the watershed scale: Hydrologic vegetation gradient as an indicator for lateral hydrologic connectivity of headwater catchments. *Water Resources Research* 2012;48:W06514. doi:10.1029/2011WR011301.
- [29] Oyler JW, Dobrowski SZ, Ballantyne AP, Klene AE, Running SW. Artificial amplification of warming trends across the mountains of the western United States. *Geophysical Research Letters* 2015;42:153–61. doi:10.1002/2014GL062803.
- [30] Larson KM, Small EE, Gutmann ED. Use of GPS receivers as a soil moisture network for water cycle studies. *Geophysical Research Letters* 2008. doi:10.1016/S0022-1694(03)00077-5.
- [31] Kaiser KE, McGlynn BL, Emanuel RE. Ecohydrology of an outbreak: mountain pine beetle impacts trees in drier landscape positions first. *Ecohydrology* 2013;6:444–54. doi:10.1002/eco.1286.
- [32] Goulden ML, Bales RC. Mountain runoff vulnerability to increased evapotranspiration with vegetation expansion. *Proceedings of the National Academy of Science* 2014;111:14071–5. doi:10.1073/pnas.1319316111.

730 [33] Allen CD, Macalady AK, Chenchouni H. A global overview of drought and heat-
731 induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology*
732 *and Management* 2010;259:660–84. doi:10.1016/j.foreco.2009.09.001.
733
734

735 Table 1: Topographic, soil, and climate characteristics for the 62 sites used in the analysis. Mean
736 and standard deviation of site level means in left column and minimum and maximum site level
737 means in the right column.

	Mean $\pm$ SD	Min, Max
Latitude	40.85 $\pm$ 4.69	(14.37, 48.86)
Longitude	-116.15 $\pm$ 3.8	(-121.94, -109.41)
Slope (percent)	7.4 $\pm$ 4.8	(0.5, 21.3)
Topo. Wetness Index	1.3 $\pm$ 1.6	(0.0, 7.4)
Length of Record	10.37 $\pm$ 3.32	(5, 19)
Wilting Point Water Content	12 $\pm$ 5	(2, 24)
Field Capacity Water Content	31 $\pm$ 8	(15, 46)
Available Water Capacity	18 $\pm$ 7	(5, 38)
%Sand	47.3 $\pm$ 17.4	(7.6, 92.8)
%Silt	36.6 $\pm$ 13.4	(6.3, 74)
% Clay	15.5 $\pm$ 10	(0.9, 51.9)
Annual P (cm)	95.6 $\pm$ 41.7	(27.2, 240.7)
Summer P (cm)	21 $\pm$ 8.3	(6.2, 60.7)
Maximum SWE (cm)	49.6 $\pm$ 31.1	(3.1, 153.2)
SWE:P Ratio	0.5 $\pm$ 0.2	(0.1, 1)
Day of Max SWE (days from 10/1)	181.4 $\pm$ 18.2	(128.7, 215)
Melt Rate (cm/day)	1.2 $\pm$ 0.4	(0.5, 2.6)
Day of Snow Diss. (days from 10/1)	222.7 $\pm$ 25.9	(143.5, 273.5)
Duration of soil water stress, DWS (days)	48.9 $\pm$ 26.6	(2.5, 126.3)
Non-water stress season, NWSS (days)	101.5 $\pm$ 25.3	(29.3, 142.7)

738
739
740
741

Table 2: Spearman rho coefficient and number of stations with significant rho values ($p < 0.10$) between the climate predictor variables. Values in the bottom left are rho coefficients and values in the top right are the number of site-level significant relationships out of 62 sites.

	Annual P	Summer P	Maximum SWE	SWE:P Ratio	Day of Max SWE	Melt Rate	Day of Snow Diss.
Annual P (cm)		11	51	20	18	27	47
Summer P (cm)	0.28		7	21	14	16	5
Max. SWE (cm)	0.88	0.02		52	19	37	51
SWE:P Ratio	0.44	-0.39	0.78		11	23	29
Day of Max SWE	0.65	0.09	0.68	0.57		43	38
Melt Rate (cm/day)	0.85	0.11	0.93	0.71	0.72		26
Day of Snow Diss.	0.79	0.07	0.86	0.69	0.93	0.82	

750 Table 3: Spearman rho correlation coefficient and associated p-value and best-fit linear slope
751 between water stress and growing with the seven climate variables using all 643 station-years.

ALL STATION-YEARS	Water Stress (days)			Growing Season (days)		
	rho	p-value	slope	rho	p-value	slope
Annual P (cm)	-0.37	0.003	-0.31	0.04	0.780	0.06
Summer P (cm)	-0.38	0.002	-0.97	0.38	0.003	1.16
Maximum SWE (cm)	-0.34	0.006	-0.29	-0.04	0.740	-0.07
SWE:P Ratio	-0.18	0.167	-23.9	-0.19	0.130	-20.5
Day of Max SWE (days from 10/1)	-0.45	<0.001	-0.72	-0.03	0.838	-0.22
Melt Rate (cm/day)	-0.35	0.006	-14.4	-0.07	0.593	-10.5
Day of Snow Diss. (days from 10/1)	-0.48	<0.001	-0.62	0.03	0.835	-0.03

752
753

Table 4: Spearman rho correlation coefficient and associated p-value and best-fit slope between water stress and growing season with the seven climate variables for each of 62 sites. Rho and slope values are reported as the site level mean $\pm$ one standard deviation. Significant relationships refer to the number of stations with $p < 0.10$ followed by the number of stations where the p-value was the minimum significant value among all climate predictors.

SITE-LEVEL	Water Stress (days)			Growing Season (days)	
	rho	slope	Sig. relations	rho	slope
Annual P (cm)	-0.65 ± 0.25	-0.45 ± 0.66	(32, 25)	0.21 ± 0.46	0.12 ± 0.63
Summer P (cm)	-0.29 ± 0.42	-0.51 ± 1.24	(11, 12)	0.41 ± 0.37	1.08 ± 1.14
Maximum SWE (cm)	-0.59 ± 0.29	-0.54 ± 1.86	(27, 6)	0.15 ± 0.46	0.13 ± 1.58
SWE:P Ratio	-0.29 ± 0.34	-39.0 ± 99.6	(10, 6)	0.04 ± 0.43	5.1 ± 122.5
Day of Max SWE (days from 10/1)	-0.49 ± 0.29	-0.44 ± 0.78	(20, 9)	-0.35 ± 0.47	-0.42 ± 0.85
Melt Rate (cm/day)	-0.33 ± 0.44	-10.7 ± 32.2	(21, 8)	-0.25 ± 0.47	-14.1 ± 28.8
Day of Snow Diss. (days from 10/1)	-0.66 ± 0.25	-0.57 ± 0.5	(27, 14)	0.04 ± 0.49	-0.01 ± 0.68

Figure 1: Example of soil moisture volumetric water content (VWC) response over one water year at three depths with the corresponding wilting point (WP) VWC shown as horizontal dashed lines. The duration of water stress is defined as the depth-weighted VWC below WP after day of maximum SWE and before October 1. The soil-mediated growing season length is the number of days that depth-weighted VWC is above WP after maximum SWE and before October 1. Vertical dashed lines note the date of maximum SWE and DSD. The data is shown for Jackson Peak, Idaho (SNOTEL site #550).

773
774

775
776
777
778

Figure 2: The locations of the 62 SNOTEL sites used in the analysis showing the snow disappearance (a) and wilting point VWC (b) as the symbol color.

Figure 3: The duration of soil water stress versus day of snow disappearance across all station-years (a) and the average for each station (b). Symbols are colored based on annual precipitation (a) and the Spearman rho between the water stress-snow disappearance relationship (b). The 36 of 62 stations that had significant relationships ($p < 0.10$) between water stress and snow disappearance are circled (b).

Figure 4. The Spearman rho correlation coefficient between snow disappearance and water stress (a) and between snow disappearance and growing season (b).

Figure 5: Regression tree results for predicting the duration of soil water stress using climate and soils variable. The pruned-regression tree explained 67% of the variability in water stress ($p < 0.001$) based primarily on snow and precipitation. The blue numbers represent the number of sites in each branch and the black text show the decision for each branch and the average water stress for each leaf.

Figure 6: The growing season length versus summer P across all station-years (a) and the average for each station (b). Symbols are colored based on days of water stress (a) and the slope of the snow disappearance-growing season relationship (b). The 22 of 62 stations that had significant relationships ($p < 0.10$) between summer P and growing season are circled.

Figure 7: Regression tree results predicting the soil-mediated growing season length using climate and soils variables. The pruned-regression tree explained 41% of the variability in water stress ($p < 0.001$) based primarily summer precipitation and soil properties. WP is wilting point soil water content. The blue numbers represent the number of sites in each branch and the black text show the decision for each branch and the average growing season length for each leaf.

813

814

815

816

817

818

819

820

821

Figure 8: The growing season length as a function of duration of soil water stress across all site-years (a) and the site-level averages (b). Symbols are colored based on annual P (a) and the day of snow disappearance (b). Sites with significant water stress-growing season relationships ($p < 0.10$) are circled.

Figure 9: The change in growing season for a 10 day earlier snow disappearance as a function of change in water stress (a) and sorted from smallest to largest (b). Sites with significant water stress-snow disappearance relationships are circled and sites with significant growing season-snow disappearance relationships are squared. The shading refers to the growing season length (a) the duration of water stress (b). The asterisk * refers to the fact that the changes are based on a 10 day earlier snow disappearance. Earlier snow disappearance can lead to both longer and shorter growing seasons.

Figure 10: Relationship between site-level average annual maximum NDVI and snow disappearance (a), the site-level slope of the maximum snow disappearance-NDVI relationship versus snow disappearance (b), and the slope of the water stress-NDVI relationship versus the growing season length. Slope of zero is plotted a dashed line (b and c). Sites with significant relationships ($p < 0.10$) are circled (b and c) and showed both positive and negative slopes.

Figure 11: Modeling growing season as a function of snow disappearance for low (a), medium (b), and high (c) potential evapotranspiration environments for five soil texture types. Modeling the timing of snow disappearance to maximize growing season length for silt (d), sandy loam (e), and sand (f) soil types as a function PET and rooting depth. The line colors in a-c refer to the soil type. The color bar in figure d-f refer to the timing of snow disappearance where maximum growing season length occurs; colors of dark blue refer to monotonically increasing growing season with later snow disappearance (similar to panels b and c), whereas warmer colors refer to an optimum non-monotonic relationship (similar to clay and silt in panel a).

849
850

851
852 Figure 12: The change in water stress for a 10 day earlier snow disappearance versus the change
853 in growing season for a 10 day earlier snow disappearance as a function the percent silt and clay
854 in the vertical axis. Symbols are shaded based on site average dryness index. Symbols with
855 squares signify significant snow disappearance-growing season relationships ($p < 0.10$). Sites
856 with negative changes in growing season (i.e. longer growing season with earlier snow
857 disappearance) tended to have higher silt and clay percentages and lower dryness indexes.
858
859
860
861

Co-located soils and climate data at 62 SNOTEL stations yield new insights into soil water stress and growing season length under changing snowpack dynamics (photos courtesy of Natural Resource Conservation Service)