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Key Points:
- The hydrological signal of snowmelt timing was strongest in shallow soil
- Effects of snowmelt timing on soil moisture lasted 2–4 months
- Advancing snowmelt timing by 2–3 weeks depleted shallow soil water by one third

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Snowmelt timing alters shallow but not deep soil moisture in the Sierra Nevada

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Roughly one-third of the Earth's land surface is seasonally covered by snow. In many of these ecosystems, the spring snowpack is melting earlier due to climatic warming and atmospheric dust deposition, which could greatly modify soil water resources during the growing season. Though snowmelt timing is known to influence soil water availability during summer, there is little known about the depth of the effects and how long the effects persist. We therefore manipulated the timing of seasonal snowmelt in a high-elevation mixed-conifer forest in a Mediterranean climate during consecutive wet and dry years. The snow-all-gone (SAG) date was advanced by 6 days in the wet year and 3 days in the dry year using black sand to reduce the snow surface albedo. To maximize variation in snowmelt timing, we also postponed the SAG date by 8 days in the wet year and 16 days in the dry year using white fabric to shade the snowpack from solar radiation. We found that deeper soil water (30–60 cm) did not show a statistically significant response to snowmelt timing. Shallow soil water (0–30 cm), however, responded strongly to snowmelt timing. The drying effect of accelerated snowmelt lasted 2 months in the 0–15 cm depth and at least 4 months in the 15–30 cm depth. Therefore, the legacy of snowmelt timing on soil moisture can persist through dry periods, and continued earlier snowmelt due to climatic warming and windblown dust could reduce near-surface water storage and availability to plants and soil biota.

1. Introduction

Roughly one-third of the Earth's land surface is seasonally covered by snow [*Edwards et al.*, 2007]. The snowpack serves as a reservoir of water during the cold season that helps sustain hydrological and biogeochemical processes during the warm season. Hydrological processes in seasonally snow-covered (SSC) ecosystems may be particularly vulnerable to radiative forcing from climatic change and windblown dust. A warmer climate will likely deplete soil moisture in the summer directly by increasing evapotranspiration, but also indirectly by advancing the timing of seasonal snowmelt. Dust deposition exacerbates earlier snowmelt by reducing the snow surface albedo [*Painter et al.*, 2010; *Skiles et al.*, 2012]. An earlier onset of melting is causing snow to disappear weeks earlier in the spring [*Pederson et al.*, 2011; *Derksen and Brown*, 2012], and by the end of this century may advance snowmelt-driven runoff by as much as 2 months [*Rauscher et al.*, 2008]. Such large shifts in the timing of water release from snowpack could greatly modify soil water resources during the growing season.

The release of water during snowmelt may be the most important dynamic control on soil moisture in SSC ecosystems. Snowmelt is typically the largest annual wetting event in these ecosystems, restoring hydrologic connectivity to dry winter soils [*McNamara et al.*, 2005]. Controls on the spatial distribution of soil water in SSC ecosystems are complex. Relatively static controls at the landscape scale (e.g., slope, aspect, soil composition) interact with dynamic controls at meter scale and finer resolutions (e.g., timing of water input, plant uptake) to create patches of wetter and drier soils [*Williams et al.*, 2009]. However, we have little predictive understanding of how long and how deep snowmelt timing influences soil water during the growing season.

In order to better understand how earlier snowmelt will impact the distribution of soil water in SSC ecosystems, we must design field experiments to minimize variation in the static controls and maximize variation in snowmelt timing. Natural snowmelt gradients can be used to quantify landscape-scale ecohydrological responses to snowmelt timing [*Ostler et al.*, 1982; *Stanton et al.*, 1994; *Seastedt and Vaccaro*, 2001; *Dunne et al.*, 2003; *Dollery et al.*, 2006; *Baptist et al.*, 2010]. However, interpretations from snowmelt gradients are confounded by landscape-scale variation in soil properties (e.g., texture, organic matter content, depth to bedrock) and microclimate (e.g., slope, aspect, plant shading). Manipulative experiments, on the other hand, can minimize heterogeneity in the static controls using a paired block design, thereby isolating responses of soil moisture to snowmelt timing. To alter snowmelt timing by modifying the snowpack's energy balance, dust and black fabric have been used to reduce the albedo of the snow surface in alpine tundra, thus increasing absorption of solar radiation and accelerating snowmelt [*Steltzer et al*., 2009]. Reflective fabric, on the other hand, shades the snowpack from solar radiation and has been used in subalpine meadow and tundra ecosystems to retard snowmelt [*Stinson*, 2005]. Snowmelt timing can also be altered by manually removing or adding snow with a shovel [*Hardy et al*., 2001; *Dunne et al*., 2003; *Wipf et al*., 2006; *Wipf et al*., 2009], or by installing a snow fence to create a deep windblown drift [*Williams et al*., 1998; *Schimel et al*., 2004].

Although multiple methods of snowmelt timing manipulation have been attempted, few studies have attempted to do so without altering soil water input. Snow removal and addition influence total water input, causing changes in soil moisture that could be unrelated to snowmelt timing. Although this might be realistic in some ecosystems, in other ecosystems, the timing of snowmelt may change in the future without a concomitant change in precipitation amount [*Christensen et al*., 2007; *Christy*, 2012]. Another requirement in isolating soil moisture responses to snowmelt timing is to ensure that the subsequent summer is dry enough to track the downward migration of the soil wetting front [*Buttle*, 1989].

The high-elevation Mediterranean climate of the Sierra Nevada in California provides an ideal combination of abundant snowfall during winter and spring, and almost no precipitation during summer. Thus, the effects of snowmelt timing on soil moisture are not confounded by summer precipitation. Our objective was to quantify the legacy of snowmelt timing on the vertical distribution of soil water during an extended dry period. We expected the control of snowmelt timing on soil moisture to persist longer in deeper soil than in shallow soil. Though shallow soils can generally retain more water because of higher organic matter content, they are also more prone to evaporation because of greater exposure to drying winds. Due to rapid desiccation in shallow soil, we expected that deeper soil would reflect the legacy of snowmelt timing instead.

2. Methods

2.1. Site Description

Snowmelt manipulations were performed in an upper montane mixed-conifer forest in the southern Sierra Nevada (2365 m ASL; 37.068°N; 119.191°W), approximately 30 km east-southeast of Shaver Lake, California. The site is located on a relatively flat (0–5% grade), southwest-facing slope at the Southern Sierra Critical Zone Observatory. The site is in the Kings River Experimental Watersheds, which is operated by the US Forest Service Pacific Southwest Research Station. The mature forest vegetation is composed of red fir (*Abies magnifica*), sugar pine (*Pinus lambertiana*), and Jeffrey pine (*Pinus jeffreyi*) [*Johnson et al*., 2011]. The Sierra Nevada experiences a Mediterranean-type climate with cold wet winters and warm dry summers. Mean annual temperature and precipitation at the elevation of our site is 8°C and 100 cm, respectively. Most precipitation (75–90%) falls as snow at this elevation, and 95% of annual precipitation falls between October and May [*Hunsaker et al*., 2012].

The soil is a member of the Cagwin soil series within the mixed, frigid Dystic Xeropsamments Soil Taxonomic family. The soil is coarse textured and well drained, and is derived from granitic parent material. The soil profile is 50–150 cm thick with a field capacity of ~35% volumetric water content (VWC; $m^3\ m^{-3} * 100\%$) in the upper 30 cm and ~25% VWC below 30 cm [*Bales et al*., 2011]. The organic horizon thickness is 4.2 cm (±0.3 cm standard error), and the top 10 cm of mineral soil is in the A horizon and has a bulk density of 0.75 ± 0.04 Mg m^{-3}, a water-holding capacity of $45 \pm 8\%$ VWC, and 51 ± 4 g of total carbon (C) kg^{-1} dry soil.

2.2. Treatment Design

Experimental plots were established during the summer of 2010 in 12 canopy gaps in the forest (each approximately 10 × 20 m) to minimize tree shading, thereby increasing the efficacy of the snowmelt manipulations. The canopy gaps were created in the late 1970s and early 1980s during sanitation-salvage timber harvest. The relatively flat terrain was chosen to minimize lateral water flow into and out of the plots. The layout of the site consisted of 12 blocks in the canopy gaps, each containing three 16 m^2 plots (4 × 4 m) of all treatments (one control, one accelerated snowmelt, and one delayed snowmelt) spaced 1.0–1.5 m apart and marked at the corners with steel T-posts ($n = 12$). During the fall of 2010 before the treatments were applied, there were no statistically significant differences in forest floor thickness, soil C content (0–15 cm deep), or soil VWC (0–12 cm deep; CD620 Hydrosense System, Campbell Scientific, Inc., Logan, UT), as indicated by one-way analysis of variance ($P > 0.05$; data not shown). A 1.5 m long × 2.5 cm diameter white polyvinyl chloride (PVC) pipe (with color-coded caps for each treatment type) was secured to the top of each T-post. The markers provided a means to locate the plots for snowmelt manipulation (or control) when the spring snow depth decreased below 250 cm.

The snow-all-gone (SAG) date was advanced in one randomly selected plot in each block using black vitreous smelter slag, henceforth referred to by the trade name "black sand" (Waxie Sanitary Supply, San Diego, CA; manufactured by Mission Laboratories, Los Angeles, CA). The black sand was 38.1% silicon dioxide, 27.4% iron oxide, 23.8% calcium oxide, 5.7% aluminum oxide, 3.9% magnesium oxide, and <1% other fused oxides, with angular to subangular granules and a specific gravity of 2.8. A thin layer (<5 mm) of dark-colored particles can accelerate snowmelt by reducing the snow surface albedo (from roughly 0.8–0.2) and thus increasing absorption of shortwave and longwave radiation [*Drake*, 1981; *Warren*, 1984]. The warming effect is greatest when the wind is calm, and when the particles (e.g., dust, ash, sand, soil, or plant litter) are incorporated into the internal ice mixture for optimal surface area contact. To create a layer of sand ~0.5 mm thick, we used a handheld fertilizer spreader to add 800 g m^{-2} (approximately 500 cm^3 m^{-2}), for a total of 12.8 kg of sand per plot. In 2011, we added sand on 25 April and 10 May, as soon as possible after the 2.5 m tall plot markers were visible (Figure 1). In 2012, we added sand on 16 April after peak snow depth. The sand application resulted in a bowl-shaped melting pattern, with the highest rates of melting near the center of each plot. A series of late-spring snow events in 2011, totaling over 60 cm, temporarily covered the layer of sand for roughly 2 weeks, but the treatment effect resumed after the new snow melted. Soil temperature (7.5 cm deep) was not affected by the snowmelt treatments during the 3 months after all plots were snow free ($P = 0.53$ in repeated measures ANOVA), indicating that the sand did not substantially reduce the surface albedo of the forest floor.

To maximize variation in snowmelt timing, the SAG date was delayed in one randomly selected plot in each block using two crossed layers (3.1 × 2.8 m) of 0.15 mm thick white Tyvek® HomeWrap fabric (DuPont Corporation, Wilmington, DE) that were secured with white plastic cable ties to a 3.1 × 3.1 m frame. Tyvek® fabric was chosen because it shades most sunlight, thus primarily reducing the solar radiation component of the snowpack's energy balance. The low-permeability fabric probably reduced sensible heat exchange too but did not modify net longwave radiation because its absorptivity is similar to snow [*Dozier and Warren*, 1982; *Salvaggio and Miller*, 2004]. Tyvek® fabric was also chosen because it is durable enough to resist damage due to water, ice, and wind.

The SAG-delaying frames were constructed from 2.5 cm diameter white PVC pipe, corner connectors (90° angle), and T-connectors to attach 3.1 m long cross pipes on top of the fabric (Figure 1). Frames were centered in the delayed snowmelt plots, and in 2011, the corners were secured with PVC sections or tree branches used as stakes. In 2012, we improved the design by tethering the corners of the frames with rope to the T-posts, and four small white sand bags (2 kg each) were tied on top to ensure that all frames remained in the intended locations. In 2011, we installed the frames on 25 April or 10 May, as soon as possible after the plot markers were visible. In 2012, we installed the frames at the same time as sand addition (16 and 17 April). We began with 12 replicates but four of the frames malfunctioned in 2011 because they were moved by wind (the windblown frames did not disturb the adjacent treatments). The frames also intercepted late-spring snow events in 2011, potentially reducing total water input to the soil by 5 cm of water equivalent. Thus, observed effects of delayed snowmelt on soil moisture were likely conservative. Eight replicates, from the blocks where the delayed snowmelt treatment functioned properly, were included for all treatments (control, accelerated snowmelt, and delayed snowmelt). We present data from the same eight replicates in 2012 to avoid adding treatment duration (i.e., 1 versus 2 years) as a variable. The frames were removed from the delayed snowmelt plots as soon as possible (1 day to 1 week) after the center of each plot was snow free.

2.3. Soil Moisture and Temperature Measurements

Soil volumetric water content (VWC) was measured at three depths in each plot using a MiniTrase Time Domain Reflectometer (Soil Moisture Equipment Corporation, Santa Barbara, CA). The portable instrument was connected consecutively to three pairs of stainless steel waveguides (15, 30, and 60 cm deep). The

Figure 1. Photographs of field manipulations designed to alter the timing of seasonal snowmelt in a mixed-conifer forest without altering total water input to soil. (top left) Snowmelt was accelerated by applying a 0.5 mm layer of black sand atop 4 × 4 m plots to reduce the snow surface albedo, (bottom left) resulting in an earlier occurrence of bare soil. (top right) Snowmelt rate was decreased by covering plots with two layers of white Tyvek® fabric attached to a white PVC pipe frame. The frames were secured in the center of each plot using rope tethered to metal posts at the corners and four small white sand bags tied on top. (bottom right) The fabric shaded the underlying snowpack, resulting in a monolith of late-melting snow (10 cm diameter trace gas sampling rings in an adjacent accelerated snowmelt plot are shown in foreground).

waveguides were located in the center of each plot (~50 cm away from the soil temperature sensor) and were first installed after snow was gone in 2011 (mid-June to early July). In each plot, three averaged VWC readings were recorded for each depth. Measurements spanned a 3 h period on six sampling dates in 2011 (24 June, 19 July, 28 July, 16 August, 16 September, 14 October) and nine dates in 2012 (9 May, 16 May, 24 May, 1 June, 14 June, 25 June, 17 July, 15 August, and 25 September). We did not measure soil VWC when the waveguides were covered by more than 5 cm of snow.

Soil temperature was logged every 1 h (2011) or 2 h (2012) to determine the exact day when the center of each plot became snow free, henceforth referred to as the snow-all-gone (SAG) date. Soil thermometers were installed 7.5 cm below the surface of the forest floor in the center of each plot (HOBO Pendant temperature and light data logger 64K; Onset Computer Corporation, Bourne, MA). Snow-covered soil had a constant temperature between 0.4 and 1.0°C. The SAG date was interpreted as the day when afternoon soil temperatures warmed rapidly above 2°C [*Johnson et al*., 2009]. The SAG dates were corroborated by field observations in 2012 when we were at particular plots on the day they became snow free.

2.4. Data Analysis

Mean VWC (± standard error) was calculated for each treatment (control, accelerated snowmelt, and delayed snowmelt) by sampling date and soil depth combination (0–15 cm, 15–30 cm, and 30–60 cm) using JMP 10.0.0 software (SAS Institute, Cary, NC). No data transformation was necessary for the 0–15 cm VWC. The 15–30 cm VWC equaled 2 * (0–30 cm VWC)—(0–15 cm VWC), because the measured 0–30 cm VWC reflected the measured 0–15 cm VWC averaged with the unknown 15–30 cm VWC for which we solved. Similarly, the 30–60 cm VWC equaled 2 * (0–60 cm VWC)—(0–30 cm VWC). Soil VWC in each depth was analyzed using a repeated measures ANOVA model at alpha level of 0.05. Tukey honest significant difference (HSD) post hoc test was used to identify statistically significant treatment effects on particular dates. Linear regression was used to quantify relationships between SAG date and soil VWC during snow-free periods.

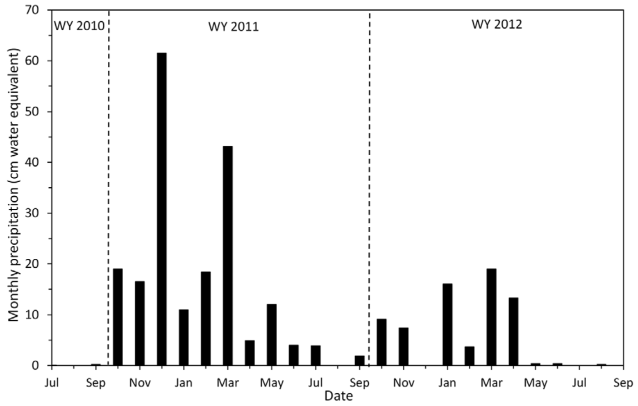

Figure 2. Monthly precipitation during the study period. Data are from the Wishon Dam meteorological station (1996 m ASL, 37.003°N, 118.986°W) which is located 10 km east-northeast of the study site and operated by Pacific Gas and Electric Company. Total precipitation was 196 cm in water year (WY) 2011 and 69 cm in WY 2012. The vertical dashed lines show when one WY ends and another begins.

3. Results

3.1. Interannual Variation in Weather

The weather contrasted greatly during the 2 years of study; the first year was very wet and the second year was very dry. The water year (WY) 2011 was indexed as a wet year for total runoff in California (http://cdec.water.ca.gov/cgi-progs/iodir_ss/wsihist) and was the second wettest year on record (1901–2012). Snow covered the plots continuously for 210 days, from 20 November until 17 June in the control treatment. Precipitation at a similar elevation 10 km east-northeast of the site totaled 196 cm, with almost one-third of this amount falling during December (Figure 2). The maximum snow depth at the site was ∼350 cm, and the total runoff from the Kings River was 168% of average (http://cdec.water.ca.gov/cgi-progs/iodir_ss/b120).

The WY 2012 was indexed as a dry year for total runoff in California and was the fourth driest year on record. Snow cover was shallow and discontinuous. The snow that fell during November melted completely during an extremely dry December. Snow cover returned in January and lasted through April (125 total days of snow cover). The maximum snow depth at the site was ∼150 cm, and the total runoff from the Kings River was 53% of average. Consequently, the SAG date of the control treatment was 52 days earlier in 2012 compared to 2011 (Figure 3).

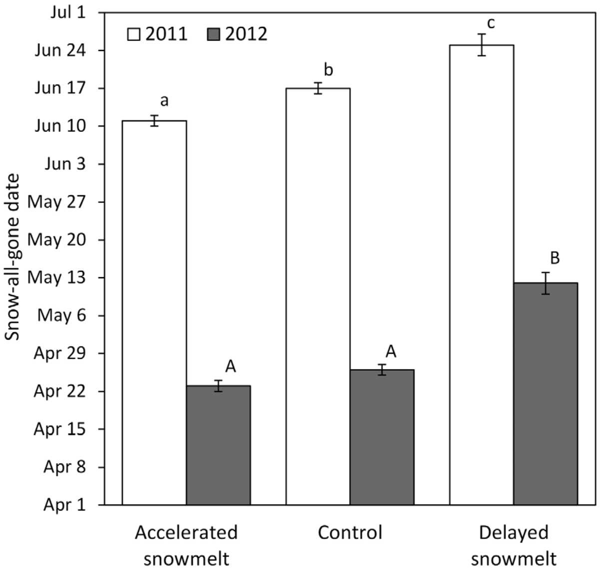

Figure 3. Snow-all-gone (SAG) dates for the accelerated snowmelt (black sand), unmanipulated control, and delayed snowmelt (white fabric) treatments following extremely wet (2011) and dry (2012) winters. Bars display standard errors ($n = 8$). Lowercase (2011) and uppercase (2012) letters indicate statistically significant differences between treatments in Tukey HSD post hoc test at an alpha level of 0.05.

3.2. Snowmelt Treatment Efficacy

The snow manipulations modified the SAG date by 14 days in 2011 and by 19 days in 2012 (Figure 3). Effects of the accelerated and delayed snowmelt treatments on 2011 SAG dates were opposite in direction and similar in magnitude. In drier WY 2012, the magnitude of the treatments varied considerably: black sand advanced the SAG date by only 3 days while white fabric postponed the SAG date by 16 days.

3.3. Soil Moisture

Soil VWC in all measured depths varied seasonally in both years ($P < 0.0001$ for all depths in repeated measures ANOVA). The average rate of soil drying from mid-May until mid-August 2012 in the delayed snowmelt treatment (i.e., the year and treatment combination in which we captured the most complete drying phase) tended to decrease with depth: −0.147% VWC per day in the 0–15 cm depth, −0.141% VWC per day in the 15–30 cm depth, and −0.138% VWC per day in the 30–60 cm depth.

Shallow soils responded more strongly to the snow manipulations than deeper soils in both years (Figure 4). In the 0–15 cm depth, soils underneath delayed snowmelt were wetter (1–9% by volume) than soils underneath accelerated snowmelt. In the 15–30 cm depth, delayed snowmelt increased soil VWC by 2–7% compared to accelerated snowmelt. However, the snowmelt treatments had no effect on soil VWC in the 30–60 cm depth. In 2011, the statistically significant positive correlation between soil VWC and SAG date lasted roughly 2 months in both the 0–15 cm and 15–30 cm depths. In 2012, the positive correlation lasted 2 months in the 0–15 cm depth and at least 4 months in the 15–30 cm depth (Figure 5).

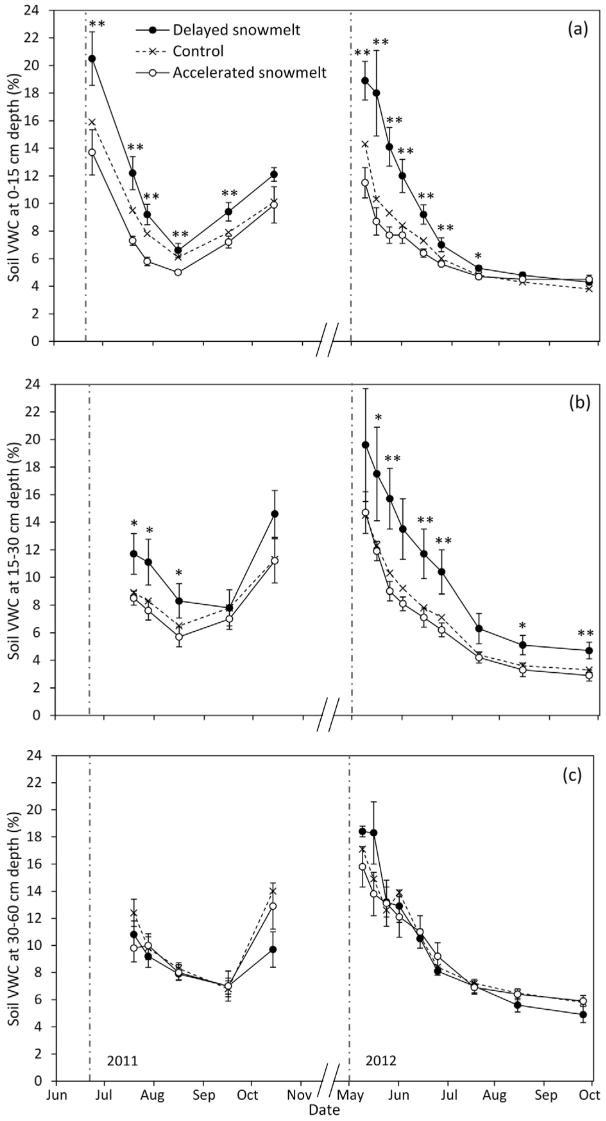

Figure 4. Effects of accelerated and delayed snowmelt on soil moisture in a seasonally dry mixed-conifer forest. Soil volumetric water content (VWC) was measured near the center of each plot using time domain reflectometry (TDR) at three depths below the surface of the forest floor: (a) 0–15 cm, (b) 15–30 cm, and (c) 30–60 cm deep. Gaps in data indicate when TDR probes were not installed yet, covered with snow, or the site was otherwise inaccessible. Gray vertical dashed lines indicate the snow-all-gone (SAG) date for the control treatment in 2011 (24 June 24) and 2012 (1 May). Bars display standard errors for the snowmelt manipulations ($n = 8$). For clarity, error bars are not displayed for the control treatment, but the coefficients of variation were similar as other treatments. Because there was a statistically significant interaction between time and treatment in the repeated measures ANOVA for the 0–15 and 15–30 cm depths (but not for 30–60 cm depth), a one-way ANOVA was performed to compare accelerated and delayed snowmelt on each date; "**" indicates that accelerated and delayed snowmelt differed at an alpha level of 0.05 and "*" indicates an alpha level of 0.10.

4. Discussion

To quantify the effects of earlier snowmelt on soil water resources in the Sierra Nevada, our primary objective was to increase the signal-to-noise ratio of snowmelt timing amidst all the other factors that influence soil moisture. By modifying the snowpack's energy balance to absorb or reflect more solar radiation, we successfully advanced and postponed the SAG date, creating a 2–3 week gradient in adjacent soils where SAG dates presumably used to be similar. Black sand was more effective at accelerating melt during the wet year; the snowpack was twice as deep which allowed more time for the melting action of the sand to differentiate these plots from the unmanipulated control plots. The white fabric, on the other hand, was more effective at delaying melt during the dry year; shading shortwave radiation may have been more important for preserving the snowpack in early spring, before longwave radiation increased in late spring [*Ellis et al*., 2011].

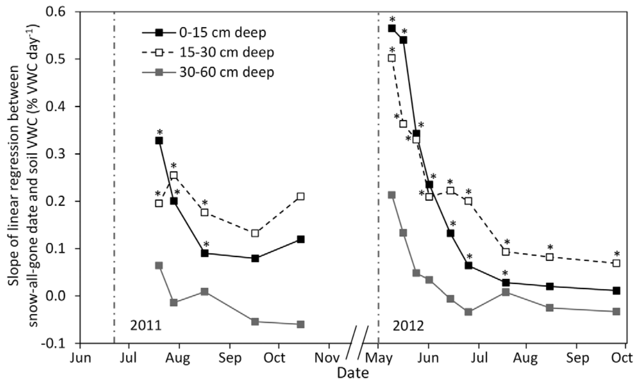

Figure 5. Relation between snow-all-gone (SAG) date and soil volumetric water content (VWC) by depth in a seasonally dry forest. The individual slopes were calculated by linear regression of soil VWC (%) on the *y* axis and SAG date (day of year) on the *x* axis ($n = 24$ for each date). Statistically significant regressions for each depth and date combination are indicated by "*" at an alpha level of 0.05. Gray vertical dashed lines indicate the SAG date for the control treatment.

The influence of snowmelt timing on soil moisture during the summer dry season was weaker than expected in deep soil but stronger than expected in shallow soil. Because redistribution of water by lateral flow is unlikely in these well-drained soils [*Bales et al*., 2011], we suggest that this pattern is instead explained by a vertical redistribution of water. Earlier melt could increase drainage to deep soil moisture and weathered bedrock [*Witty et al*., 2003] because the melt occurs before evaporative demand increases. Our results highlight that predicting depth-specific effects of snowmelt timing on soil moisture is not straightforward. In SSC ecosystems with reliable summer rain, such as the Rocky Mountains in Colorado, the signal of snowmelt timing may be small compared to the "noise" of rain events percolating through the soil profile. In the case of these "wet-summer SSC ecosystems," the vertical distribution of water in the soil profile is probably most strongly controlled by the elapsed time since rain. However, in the case of "dry-summer SSC ecosystems" (and wet-summer SSC ecosystems that experience summer drought), our results suggest that the vertical distribution of soil water is controlled rather by interactions with soil physical properties. We hypothesize that the depth-specific effects of snowmelt timing were related to the vertical distribution of soil C and positively associated water-holding capacity. Also, plant roots are rare in shallow Sierra Nevada soils [*Hart and Firestone*, 1991; *Johnson et al*., 2009] which may partly explain why wet shallow soil stays wet. We did not measure how these properties varied with depth in our plots, but at a nearby site the soil C concentration decreased from 8% in the top 10 cm to 1% below a depth of 30 cm [*Dahlgren et al*., 1997]. A lack of deep C in coarse-textured soil represents a low capacity to store meltwater. Relatively C-rich soil near the surface appears more capable than deeper soil of storing late-melting water during the dry season.

But why did manipulating snowmelt timing by 2–3 weeks modify shallow soil moisture for 2–4 months? We expected changes to be related approximately in a 1:1 fashion, such that a 2 week change in SAG date causes a 2 week modification of soil moisture. In deep soil, this was true; the weak influence of snowmelt timing on soil moisture lasted 2 weeks before disappearing. In shallow soil, however, the modification of soil moisture lasted much longer than the change in SAG date. Statistically significant effects of snowmelt timing lasted 2 months in the 0–15 cm depth, and for at least 4 months in the 15–30 cm depth. An interaction between multiple factors must explain the persistent effect of snowmelt timing on shallow soil moisture. We hypothesize that the responsible interaction occurs between the timing of snowmelt, the timing of evaporative demand, and the soil water-holding capacity. If melt occurs before evaporative demand increases, then a greater portion of water drains to deeper soil, regardless of soil water-holding capacity. If melt occurs after evaporative demand increases, on the other hand, then the C-rich shallow soil can capture more of the slowly melting water, while water retention in deep soil remains constrained by a low water-holding capacity.

Although the exact mechanisms still need to be determined, our results show that earlier water transfer from snowpack to soil can induce a soil water deficit that persists through the growing season. Relative to plots with delayed snowmelt, soils in plots with accelerated snowmelt contained 27% less water in the 0–15 cm depth and 32% less water in the 15–30 cm depth. Therefore, even if annual precipitation and summer temperature stay constant in the future, our results suggest that advancing snowmelt by 2–3 weeks will decrease water storage in shallow soils in dry-summer and drought-prone SSC ecosystems by roughly one third.

A future decrease in soil water availability during the warm season will impact decomposition and nutrient cycling. Water connects microbes to their substrates [*Manzoni et al*., 2012; *Schimel and Schaeffer*, 2012];

therefore, soil drying generally leads to lower abundances of soil biota [*Lindberg et al*., 2002; *Blankinship et al*., 2011], less C processing [*Fuchslueger et al*., 2013; *Sorensen et al*., 2013], and less nitrogen mineralization [*Mazzarino et al*., 1998; *Hungate et al*., 2007]. Depth-dependent responses of soil moisture to snowmelt timing likely translate into depth-dependent effects of snowmelt timing on soil microbial activities. If effects of snowmelt timing on soil moisture occur at the same depth where there is the most C, such as what occurs at our site in the Sierra Nevada, then snowmelt timing could be important for annual C budgets. The soil water deficit induced by earlier snowmelt is large enough and lasts long enough to be important for decomposition, possibly causing an accumulation of surface fuel for wildfire and a decrease in nutrient availability for plants.

As climate change continues in SSC ecosystems, these results imply that plant responses will depend on rooting depth. The most vulnerable perennial plant species in the Sierra Nevada are shallow rooted. Soil water in deeper soil is less sensitive to snowmelt timing and therefore provides a more consistent source of water for plants. This might explain why the legacy of snowmelt timing on shallow soil moisture lasted so long: plant roots are rare in the evaporation-prone organic horizon [*Hart and Firestone*, 1991; *Johnson et al*., 2009] and may contribute little to water loss in shallow soil. An investment in roots and mycorrhizal fungi in deeper soil and weathered granitic bedrock [*Witty et al*., 2003; *Bornyasz et al*., 2005] suggests an adaptation of plants in the Sierra Nevada to high interannual variation in snowmelt timing: invest roots where moisture is dependable. Plant transpiration at a similar elevation as our site is colimited by temperature and precipitation [*Tague and Peng*, 2013]. At higher elevations, transpiration is mainly temperature limited and at lower elevations transpiration is mainly precipitation limited [*Goulden et al*., 2012]. Therefore, even if precipitation amount does not decrease in the future, earlier snowmelt could have the same effect as moving down in elevation, thus intensifying water limitation of plant growth at higher elevations.

In conclusion, by minimizing variation in the static controls on soil moisture in a SSC ecosystem, we gained a quantitative understanding of how soil moisture relates to snowmelt timing, and we learned that snowmelt timing controls spatial variability of soil moisture throughout the snow-free season. Earlier snowmelt alone—unaccompanied by changes in precipitation amount or summer warming—can reduce future soil water resources. We hypothesize that deeper soil moisture reflects landscape-scale controls on water availability, which is important for managing overall forest productivity. Shallow soil, on the other hand, reflects meter-scale variation in the timing of snowmelt infiltration, which is important for managing nutrient availability, C sequestration, and the continued survival of shallow-rooted plants.

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