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Soil-water dynamics and unsaturated storage during snowmelt following wildfire

[B. A. Ebel](#)¹, [E. S. Hinckley](#)^{2,3}, and [D. A. Martin](#)¹

¹US Geological Survey, Boulder, Colorado, USA

²Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado, USA

³National Ecological Observation Network, Boulder, Colorado, USA

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Correspondence to: B. A. Ebel (bebel@usgs.gov)

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Abstract

Many forested watersheds with a substantial fraction of precipitation delivered as snow have the potential for landscape disturbance by wildfire. Little is known about the immediate effects of wildfire on snowmelt and near-surface hydrologic responses, including soil-water storage. Montane systems at the rain-snow transition have soil-water dynamics that are further complicated during the snowmelt period by strong aspect controls on snowmelt and soil thawing. Here we present data and analysis from field measurements of snow hydrology and subsurface hydrologic and temperature responses during the first winter and spring after the September 2010 Fourmile Canyon Fire in Colorado, USA. Our observations of soil-water content and soil temperature show sharp contrasts in hydrologic and thermal conditions between north- and south-facing slopes. South-facing burned soils were $\sim 1\text{--}2^\circ\text{C}$ warmer on average than north-facing burned soils and $\sim 1.5^\circ\text{C}$ warmer than south-facing unburned soils, which affected soil thawing during the snowmelt period. Soil-water dynamics also differed by aspect: in response to soil thawing, soil-water content increased approximately one month earlier on south-facing burned slopes than on north-facing burned slopes. While aspect and wildfire affect soil-water dynamics during snowmelt, soil-water storage at the end of the snowmelt period reached the value at field capacity for each plot, suggesting that post-snowmelt unsaturated storage was not substantially influenced by aspect in wildfire-affected areas. Our data and analysis indicate that snowmelt-driven groundwater recharge may be larger in wildfire-impacted areas, especially on south-facing slopes, because of earlier soil thaw and longer durations of soil-water contents above field capacity in those areas.

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1 Introduction

1.1 Motivation and previous research

Mountainous regions are important sources of surface and groundwater to downgradient population centers. For example, in the United States over 60 million people depend on water from mountain river basins (Bales et al., 2006). Much of the precipitation in mountain areas falls as snow such that snowmelt contributes the majority of regional water supplies (e.g. Flerchinger et al., 1994; Bales et al., 2006). In the Rocky Mountains of North America, wildfire is one of the most significant disturbance regimes (Veblen et al., 1994; Schoennagel et al., 2011), which can affect the quality and quantity of mountain water supplies. In the previous 30 years, wildfire incidence and the duration of fire-prone conditions has increased in the mountainous western US, which can be primarily attributed to earlier snowmelt (Westerling et al., 2006). The trend of increasingly long wildfire seasons and higher wildfire frequency is forecast to continue, with anthropogenically-enhanced global change resulting in shifts to an unprecedented temperature-driven rise in wildfire occurrence (Pechony and Shindell, 2011) and an increase in widespread wildfire synchrony (Kitzberger et al., 2007). The increasing pressure of wildfire and its potential impact on much-needed mountain water supplies (e.g. Ice et al., 2004) creates an imperative that we increase our understanding of wildfire interactions with snowmelt-driven hydrologic response.

Past studies have shown that wildfires can have dramatic consequences for near-surface hydrologic processes, including snow accumulation and melt. Wildfires often devegetate the landscape and remove litter and duff by combustion, thereby changing canopy interception, altering near-surface wind velocities, and exposing soil surfaces to the atmosphere. Such wildfire impacts affect snow accumulation and ablation (Billings, 1969; Farnes, 1996; Winkler, 2011) and the radiation balance (Burles and Boon, 2011). Standing dead trees in the burned area play an important role in the energy balance by attenuating wind speed and reducing incoming shortwave radiation (Burles and Boon, 2011). Effects on snow accumulation are mixed. Silins et al. (2009) found increases

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in snow-water equivalent (SWE) in burned watersheds by a factor of 2–3 compared to unburned watersheds, which they attributed to canopy removal by the fire. Burles and Boon (2011) documented greater snow accumulation, faster snowmelt, and 30 % more available energy for snowmelt in a burned area compared to a nearby unburned area. Drake et al. (2008), however, found statistically significant reductions in SWE after wildfire. While the effects of fire on snow processes can vary by location, we know that post-wildfire changes in snow accumulation and melt can be substantial and ultimately determine the total amount and rate of snowmelt.

Energy balance alterations following wildfire can also affect soil temperatures. Removal of the forest canopy and the insulating layers of litter and duff are the primary causes of soil temperature changes (Bonan and Shugart, 1989), which is compounded by lowering of soil albedo after wildfire (Rouse, 1976; Walker et al., 1986; Chambers et al., 2005). The thermal properties of soils can also be altered by wildfire (Massman and Frank, 2004). Together, these factors can combine to produce increases in soil temperature following wildfire (Sweeney, 1956; Raison et al., 1986; Auld and Bradstock, 1996; Moody et al., 2007). During the period of snow accumulation and melt, these soil temperature increases cause earlier soil thawing (Bissett and Parkinson, 1980). In areas with seasonal soil freezing, the timing of soil thawing exerts major controls on snowmelt infiltration and soil-water dynamics (Iwata et al., 2010, 2011).

Alteration of hydrologic processes following wildfire has been well documented. This alteration results from, for example, changes in soil-hydraulic properties (e.g. Certini et al., 2005), including soil-water retention (e.g. Stoof et al., 2010) and hydraulic conductivity (e.g. Nyman et al., 2010). The partitioning of hydrologic fluxes into surface-water, groundwater, and evaporation can be substantially modified following wildfire because of the changed soil-hydraulic properties (Ice et al., 2004; Shakesby and Doerr, 2006). One of the main consequences of shifts in hydrologic fluxes may be modifications in soil-water storage. It is well established that soil-water storage is important for many hillslope hydrology processes, such as runoff generation (e.g. Tromp-Van Meerveld and McDonnell, 2006a, b; Spence, 2007, 2010), groundwater recharge (e.g. Seyfried et al.,

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2009), and tree/plant survival (e.g. Fahey and Knight, 1986). While known to be a critical component of hydrologic processes, accurate characterization of soil-water storage remains elusive. As noted by [McNamara et al. \(2011\)](#), distributed storage is difficult to quantify at catchment scales because of spatial heterogeneity at the sub-meter scale, resulting in a greater focus on point measurements.

In many mountainous areas, the interactions of wildfire and soil water storage are further complicated by contrasts in hillslope aspect. The distribution of slope aspects in a landscape can have a strong control on soil-water content and vegetation (e.g. Geroy et al., 2011). Differences in energy balance driven by aspect ([Monteith and Unsworth, 1990](#)) that control soil temperature ([Kang et al., 2000](#)) can affect soil characteristics ([Casanova et al., 2000](#)) and soil depths ([Khumalo, et al., 2008](#)). Snowmelt is influenced by aspect (e.g. [Pomeroy et al., 2003](#)) which can affect snowmelt-derived runoff ([Shanley and Chalmers, 1999](#)). Aspect effects can be particularly pronounced when slopes are predominantly north- and south-facing, thus maximizing the contrast between incoming solar energy.

It is clear that wildfire and aspect can interact to produce alterations in snowmelt and soil thawing, soil temperature, and soil-water content. Far less is known about how these linked thermal and soil-water impacts control soil-water dynamics and storage during the snowmelt season. Improved understanding of the timing and quantities of snowmelt-driven hydrologic processes is critical in fire-affected areas where snowmelt is a major annual hydrologic event, and hillslope processes cascade to watershed scale impacts. Sediment transport has been shown to be 2–100 times greater in the snowmelt freshet following wildfire ([Silins et al., 2009](#)). Much of the snowmelt-derived sediment transport increases are the result of the sustained (i.e. 1–4 month) delivery of water to channels, which leads to transport of coarse-grained sediment as bedload ([Moody and Martin, 2001](#); [Malmon et al., 2004](#); [Reneau et al., 2007](#)). Elevated streamflow from snowmelt in burned areas can also impact stream channels by increasing nutrient export, removing periphyton, and altering benthic macroinvertebrate assemblages ([Minshall et al., 2001](#)). Recent reviews of wildfire impacts on water quality have

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illuminated the potential detrimental consequences for drinking water supplies. These impacts are far reaching, including dissolved and particulate constituents (e.g. heavy metals and nutrients), organic matter, and other solutes (Gresswell, 1999; Smith et al., 2011; Emelko et al., 2011). There have been many studies focused on soil-water storage in the unsaturated zone, including snowmelt-dominated environments (e.g. Grant et al., 2004; McNamara et al., 2005; Seyfried et al., 2009; Williams et al., 2009), but almost no research has documented the distribution and persistence of soil-water storage during the snowmelt season following wildfire.

Here we focus on the snowmelt and accompanying subsurface hydrologic response at the hillslope scale in the first winter and spring after a fall wildfire. The study was designed to consider the combined impacts of wildfire and aspect on soil temperature and soil-water content during the snowmelt season. Our analysis includes interactions between the soil thermal and hydrologic states that ultimately control soil-water dynamics and soil-water storage. We compare the Fourmile Canyon results to the nearby (i.e. ~6 km away, ~200 m higher elevation) Gordon Gulch field site of the Boulder Creek Critical Zone Observatory, which was similarly instrumented across north- and south-facing hillslope transects (Hinckley et al., 2012). We also discuss implications of the hillslope hydrology changes for hydrologic processes at the watershed scale.

1.2 Study area

The study area was the 2010 Fourmile Canyon Fire near Boulder, CO in the Colorado Front Range, USA. After initiation on 6 September 2010, extremely dry conditions and high winds drove the rapid spread of the wildfire, which eventually covered 2500 hectares and destroyed over 160 residences before full containment on 13 September 2010 (FEST, 2010). High wind velocities and shifting wind directions resulted in a mosaic burn pattern of low, moderate, and high severities (after Keeley, 2009) at ground level. Elevations in the burn perimeter range from 1940 m to 2620 m. The area has largely igneous geology. Soils are frigid Lamellic and Typic Haplustalfa (USDA, 2010) and are classified by particle size as a gravelly sandy loam (Moreland and Moreland, 1975). Before the wildfire, vegetation was typical of the Foothill *Pseudotsuga-Pinus*

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ponderosa forest (Peet, 1981) above the transition between foothills and montane ecosystems (Marr, 1961). Aspect had a strong control on pre-wildfire vegetation in the area impacted by Fourmile Canyon Fire, with north-facing slopes dominated by aspen (*Populus tremuloides*), Rocky Mountain Douglas fir (*Pseudotsuga menziesii* subspecies *glauca*), and Limber pine (*Pinus flexilis*) and south-facing slopes dominated by ponderosa pine (*Pinus ponderosa*) (FEST, 2010). The pre-fire vegetation typically burns with moderate to high severity during wildfires, with fire initiation primarily driven by extreme drought (Schoennagel et al., 2011).

The strongly continental climate has cyclonic storms in the winter and localized, convective storms in the summer, resulting in a double-peaked precipitation distribution with a peak in April/May and a second (smaller) peak in July/August driven by the North American monsoon (Barry, 1973). Mean annual precipitation is ~500 mm at the Fourmile Canyon area (based on the 20-yr period of record at NADP site CO94 at 39.99° N, -105.48° W; NADP, 2011). Approximately 60 to 75 % of water flux to the subsurface is supplied by snowmelt (Stewart et al., 2004) in this region of the Colorado Front Range. The study area has disparate snow accumulation/melt behavior by aspect, with seasonal snowpack development on north-facing slopes and an intermittent snowpack on south-facing slopes.

We selected study plots with predominately north- and south-facing aspects at different hillslope positions (ridge and midslope) for instrumentation and measurement (Fig. 1). Study plot characteristics are presented in Table 1. We have described soils that have been impacted by wildfire as “burned”, because partial or full combustion of some organic matter has taken place along with heating of mineral soil. Burned plots are south-facing ridge (SFR), south-facing midslope (SFM), north-facing ridge (NFR), and north-facing midslope (NFM). Unburned plots (UB2, UBSControl, UBTemp) are all south or southeast facing. This study is not a true “fully-factorial” experiment, because there is no instrumented unburned north-facing slope. Therefore, we isolate our comparisons to unburned versus burned south-facing slopes and burned north-facing versus burned south-facing slopes.

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2 Methods

2.1 Atmospheric and snow measurements

Snow depths (mm) and air temperatures were measured at the NFM plot with a Judd Communications ultrasonic depth sensor using 3 min temporal resolution and a 1 h running mean of the data to smooth out noise, as recommended by Brazenec (2005). The snow depth sensor was installed at a height of 1.75 m from the ground surface with the ultrasonic sensor positioned normal to the slope. Measured ultrasonic snow depths were corrected using the slope geometry to a vertical (i.e. Cartesian) snow depth. Manual measurements of snow depth (mm), SWE (mm), and snow density (mm mm^{-1}) were made using a ruled tubular sampler with four replicate samples at approximately weekly intervals at all plots. Some storm events were not captured by the regular manual sampling, particularly on the south-facing slope which experienced complete melt within days of deposition. Snow density was reported as SWE/snow depth. The meteorological record from the nearby Sugarloaf NADP site (CO94 at 39.99°N , -105.48°W ; NADP, 2011) was used as a complete record during the snowmelt season to understand trends when data from the ultrasonic sensor and manual SWE measurements were unavailable. Total precipitation at the Sugarloaf NADP site from 1 December 2010 to 1 June 2011 was 279 mm, which was just slightly above the mean precipitation (267 mm) for these same dates during the period of record.

2.2 Soil-water and temperature measurements

Soil-water content ($\text{cm}^3 \text{cm}^{-3}$) and soil temperature ($^\circ\text{C}$) were measured using Decagon 5TE sensors at the NFM, NFR, S Control, SFR, SFM, and UB2 plots at 2 min temporal resolution at the depths shown in Table 1. Sensors are offset in plan-view by ~ 25 cm with increasing depth of installation to minimize disturbance of soil overlying the sensors, which makes individual plot size $\sim 1 \text{m}^2$ in terms of the plan-view footprint. The soil-water content measurements from the Decagon sensors were calibrated in

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the laboratory using disturbed soil samples with the soil from each specific plot using the technique recommended by Cobos and Chambers (2010). The Decagon 5TE sensors estimate unfrozen water content and cannot be used to estimate water content at soil temperatures below freezing without further calibration under freezing conditions (Yoshikawa and Overduin, 2005), so only water content estimates at soil temperatures above zero °C were analyzed. Soil temperature was recorded to a precision of 0.1 °C. Volumetric soil-water content was estimated for the top 3 cm of soil at selected plots using thermogravimetric methods (Topp and Ferré, 2002). Four replicate, approximately 60g soil samples were collected at the selected plots on an approximately weekly sampling schedule. Spacing between the replicate core samples at each plot was approximately 5 cm. Samples were sealed in metal cans and processed in the laboratory within 3 h by drying at 105 °C for 24 h. Samples were weighed before and after drying on a digital balance to 0.001 g with an estimated error of ±0.005 g or <0.01 %. Soil-water storage was estimated from the depth profiles of soil-water content from the automated sensors using numerical integration (a trapezoidal approximation) with the assumption of uniform soil-water content from the 5 cm sensor to the surface.

2.3 Subsurface characterization and hydrologic properties

Local slope was measured with an inclinometer (Table 1). Soil depth was measured by pounding in a steel rod to refusal. Multiple measurements (i.e. 3 to 5) were made at each plot and the maximum depth was recorded because large rocks embedded in the soil profile would otherwise bias measurements toward a smaller-than-actual soil depth (Table 1). Soil-water retention curves for intact cores were measured at UB2, NFM, NFR, SFM, and SFR using the hanging column method (Dane and Hopmans, 2002a), a pressure plate (Dane and Hopmans, 2002b), a dewpoint potentiometer (Gee et al., 1992), and a relative-humidity-controlled chamber (Nimmo and Winfield, 2002). The computer program RETC (van Genuchten et al., 1991) was used to estimate Van Genuchten (1980) parameters for the soil-water retention data. Soil-water content at field capacity was estimated using the Van Genuchten (1980) relations at a matric potential of -340 cm (Koorevar et al., 1983).

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3 Results

3.1 Air temperature, precipitation and snow-water equivalent

The meteorological forces driving both the accumulation and melt of the relatively small seasonal snowpack on the north-facing slope are presented in Figs. 2 and 3. Maximum daily air temperatures declined from above 30°C in early November to near/below 20°C around 10 November, which also coincided with minimum daily air temperatures dropping to near/below 0°C (Fig. 2). This transition in air temperature marked the precipitation phase shift from predominantly rainfall to snow (personal observation). Snowfall amounts in November and December were insufficient to build a seasonal snowpack on the north-facing slope. Most of the seasonal snowpack developed during a prolonged cold period in late January through early February with daily maximum air temperatures below 0°C (Fig. 2), combined with two relatively large snowfall events on 6 February and 8 February (Table 2). The subsequent disappearance of the seasonal snowpack around 3 March 2011 was caused by a warm period in late February and early March (Figs. 2 and 3). The decline in SWE coupled with increases in snow density at the north-facing plots (NFM and NFR) led to snowpack disappearance on 10 March, reflecting microtopographic and shading influences on snow accumulation and melt between the ultrasonic sensor and SWE plots (Figs. 3 and 4).

The south-facing burned plots, in contrast, did not develop a seasonal snowpack, but melted off partially within days of storms and fully within a week. Field observations and photographs, for example, showed near-complete disappearance of snow on burned south-facing slopes within a week of the 8 February 2011 storm. SWE measurements, beginning on 15 February, showed zero values in February and March at SFM and SFR. The unburned south facing plots behaved differently than the burned south facing plots in February and March, with the UBSControl plot accumulating a snow pack because it is in the leeward side of a ridge just below the crest, allowing wind deposition from the north-facing slopes. This unique topographic position caused the UBSControl plot to accumulate the largest seasonal snowpack, yet achieve more

rapid snowpack disappearance (22 February) than the north-facing slopes (Fig. 4). The other unburned south-facing plot, UB2, had a slightly smaller slope (Table 1) compared to the other plots and faces to the southeast, which may have aided in the accumulation of a brief seasonal snowpack that disappeared on the same day as UBControl, 22 February.

A slight increasing trend in air temperature (Fig. 3) and solar insolation after mid March prevented re-establishment of the north-facing snowpack, marking the transition where all the slopes melted off rapidly regardless of aspect. The SWE data for the storms on 12 and 13 April (Fig. 4) and the snow depth record near NFM (Fig. 3) also reflected this transition. This pattern of rapid melt following storms on both north- and south-facing aspects continued until the full transition to precipitation falling as rainfall in early June (Fig. 3). Total precipitation from 1 November 2010 to 1 June 2011 was 326 mm water-equivalent at the Sugarloaf NADP station.

3.2 Soil temperature

Soil temperatures were colder and stayed frozen (i.e. below 0 °C) for longer on north-facing slopes, compared to south-facing slopes. The onset of soil freezing was remarkably similar, regardless of aspect, with shallow (i.e. 5–10 cm) freezing initiated approximately on 25 November (Fig. 5). The primary difference between north- and south-facing slopes was that the north-facing slopes remained frozen nearly continuously from late November to mid March while the south-facing slopes thawed intermittently in response to warm periods (Fig. 5). South-facing slopes did respond to substantial cold periods however, as shown by the frozen conditions re-established during the early February cold period. Aspect-controlled differences for soil temperatures in burned soils are shown by colder mean and median values in Table 3 for north-facing slopes relative to south-facing slopes, by ~2–3 °C, from 1 November 2010 to 1 June 2011. Effects of wildfire on soil temperature are shown by comparing mean and median soil temperatures for the burned (SFM and SFR) and unburned (UB2 and UBControl) plots in Table 3. Unburned plots had lower mean and median soil temperatures,

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compared to the south-facing burned plots. In fact, the unburned south-facing plots had mean and median soil temperatures that are more like burned north-facing plots (Table 3). South-facing burned slopes are the warmest of the compared plots (Table 3).

The end of frozen soil conditions was also impacted by both aspect and wildfire.

North-facing slopes remained frozen nearly continuously until thawing in early to mid March (Fig. 5). South-facing unburned slopes had intermittent freezing from the end of the cold period in mid February to early March at 5 and 10 cm depth and the south-facing unburned slopes were more frequently frozen during this period, relative to the burned slopes. The south-facing burned slopes only intermittently refroze at 5 cm depth, but never refroze at 10 or 30 cm after mid February. Compared to burned north-facing plots, the south-facing burned plots thawed nearly a month earlier. Cessation of frozen conditions on all slopes was approximately on 10 March (Fig. 5). Aspect and wildfire impacts drove major differences in soil temperatures at 5 and 10 cm depth after the end of freezing conditions (i.e. mid March through 1 June). Warm periods in early to mid April and mid May illustrate how much warmer the south-facing burned plots got in the near-surface (i.e. 5 cm depth) relative to the burned north-facing soils (Fig. 5). At 5 cm depth, south-facing burned plots were, on average, 2.5 °C warmer in April and 1.6 °C warmer in May compared to burned north-facing soils, and 1.2 °C warmer in April and 1.3 °C warmer in May compared to unburned south-facing soils.

Burned soils, regardless of aspect, had larger temporal variability in soil temperature as indicated by the larger standard deviation (σ) values at SFM, SFR, and NFR (~6 °C) compared to the σ values at the unburned UB2 and UBSControl plots (~5 °C) (see Table 3). The NFM plot had a σ for soil temperatures closer to the value of ~5 °C for unburned plots, which was likely the result of reduced solar insolation because of shading resulting from convergent hillslope topography. Damping of temperature fluctuations (i.e. reduced in amplitude) with increasing depth is shown by the smaller σ values with depth (Table 3). Larger mean and median values with increasing depth show, as expected, higher temperature at depth in the winter (Table 3).

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3.3 Thermogravimetric soil-water content

Dry soil conditions present in November, which persisted from mid September to soil freezing, were largely unchanged during the frozen winter conditions and only slightly increased at the onset the early March melt events. The near surface (i.e. top 3 cm) of soil, sampled by the thermogravimetric soil-water content measurements, showed a large response to the mid April snowstorms for all burned and unburned plots, regardless of aspect (Fig. 6a). Drainage of soil-water and evaporation were more rapid at the south-facing burned plot (SFR), compared to the burned north-facing and unburned plots. The addition of the unburned north-facing plot (UBNF) in May provided a comparison for burned and unburned soils for both north- and south-facing aspects. Hydrologic response to the 10 May storm showed that peak soil-water content values were similar, 0.3 to $0.35 \text{ cm}^{-3} \text{ cm}^{-3}$, for all soils regardless of aspect or wildfire impact (Fig. 6a). Similar to the response to the mid April storm, the south-facing burned soil drained/evaporated water more readily than the other plots (Fig. 6a).

Fine-scale variability in soil-water content, at the 5 to 10 cm separation distances of the thermogravimetric samples on a given day, undergoes a substantial shift from low to high variability during snowmelt. This fine-scale variability (i.e. 5–10 cm scale) was captured by the between-sample differences of the four replicates taken at each plot on a given day. Immediately following the wildfire, the fine-scale soil-water content variability, captured by the coefficient of variation (CV) was high in the burned north-facing area, nearing a value of unity. Following the early March melt, and corresponding infiltration of snowmelt water, the variability in soil-water content in the burned north-facing soils declined considerably and approached the variability of the unburned soils (Fig. 6b). Fine-scale soil-water content variability on the north-facing burned slope from April though June was approximately the same as the unburned north- and south-facing soils, regardless of snowmelt inputs, while the south-facing burned soils exhibited greater fine-scale variability, in terms of larger CV (Fig. 6b). Controls of soil-water content on this fine-scale variability were minimal in the unburned soils, where CV

appeared to vary independently of soil-water content, as shown by the blue-shaded area in Fig. 6c. In contrast, soil-water content had a moderate to strong control on fine-scale variability in the north- and south-facing burned soils as indicated by the red-shaded area in Fig. 6c. The CV values above 0.5 in Fig. 6c for the north-facing burned soils were all in the early November data and the snowmelt period reduced the soil-water content control (i.e. wetness) on CV.

3.4 Automated soil-water content

Soil-water content dynamics during snowmelt were controlled primarily by aspect, and less by wildfire impacts. The soil-water content at field capacity (i.e. -340 cm) based on retention curve measurements at each plot and RETC-estimated van Genuchten (1980) parameters are shown as dashed lines in Fig. 7. All plots were relatively dry in early November (two months after the fire), especially at the shallow 5 and 10 cm depths, reflecting the prolonged dry period preceding and following the wildfire. Snowfall totaling 18 mm (SWE) between 9 to 22 November that melted and infiltrated caused rises in soil-water content on the burned and unburned south-facing slopes and also at NFR, but did not affect NFM (Fig. 7). The rise in soil-water content at SFR and SFM from this November storm is ahead of UB2 and NFR by several days. Because soil-water content is not shown when soil temperature is less than 0°C, there are large gaps in the soil-water content record for the north-facing slopes in Fig. 7, which are shown by shaded regions in the figure. North-facing burned slopes had essentially the same soil-water content at the start of thaw in early March as when the soil froze in December, suggesting that soil-water dynamics were minimal during this three month period. In contrast, the burned and unburned south-facing slopes remained hydrologically-active, in terms of dynamic soil-water contents, throughout the period from December to early March, punctuated by periods of intermittent freezing (Fig. 7). The burned and unburned south-facing soils behaved relatively the same during December to early March, although UBSControl had very little change in soil-water during this time.

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Large and rapid increases in soil-water content, above field capacity, happened in mid February following the frozen spell for south-facing burned and unburned slopes. This shift in soil water response was presumably due to soil thawing. North-facing slopes did not show a rise in soil-water content in response to thawing until early March, and the response was more gradual and greatly reduced in magnitude relative to the south-facing slopes (Fig. 7). The north-facing slopes did not have soil-water contents above field capacity in response to the March thawing period; it took more than a month longer, until the response to the 12 and 13 April storms for the north-facing slopes to rise above field-capacity. Both the 12–13 April, 10 May and 17 May storms drove soil-water contents at all plots above field capacity and all plots remained near field capacity at the end of the snowmelt season on 1 June (Fig. 7).

North-facing slopes tended to be drier than the south-facing slopes, based on mean and median soil-water contents (Table 3). Unlike soil-temperature, there were no substantial differences in variability in soil-water contents driven by aspect or wildfire impacts, based on the σ values in Table 3. There are no major differences between the mean and median soil-water contents between the burned and unburned south-facing plots, although UBSControl was drier overall, possibly because of its ridgetop position and shallow, well-drained soils. Frequency histograms of soil-water content at the plots further illustrate differences in soil-water dynamics between plots (Fig. 8). NFM had a strongly bimodal distribution of soil-water contents, with dry soil-water contents ($\theta < 0.1 \text{ cm}^3 \text{ cm}^{-3}$) in the pre-melt period and wet soil-water contents ($\theta > 0.1 \text{ cm}^3 \text{ cm}^{-3}$) in the post-melt period. NFR did not have the same bimodal distribution as NFM, instead dry conditions persisted at the 30 cm depth and then abruptly shifted to very wet conditions along with the 5 and 10 cm depths, which is also shown in the timeseries in Fig. 7. SFR had a slightly bimodal distribution of soil-water content, similar to NFM, but with far fewer values at dry soil-water contents and more values at wetter soil-water contents, reflecting the earlier melt, and thus more time was spent in a wet state compared to the north-facing slopes. SFM had a pronounced dry soil-water content peak in the distribution for the 5 cm depth, reflecting the slow transition from

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dry to wet during melt water inputs (relative to SFR) (Figs. 7 and 8). The UBSControl soil-water content distribution was more uniform than the other plots, but shifted overall to drier conditions. At UB2, the soil-water content distribution shows a distinct peak between 0.13 to 0.15 cm³ cm⁻³ and slight shift and long tail towards the wetter soil-water content range.

3.5 Unsaturated storage

Unsaturated storage (see Fig. 9) mimicked the soil-water content trends shown previously. South-facing burned plots had large increases in soil-water storage beginning in mid February at the initial major thaw with large increases in soil-water storage, especially at the 30 cm depth, from the 12–13 April, 22 April, 10 May, and 17 May storms (Fig. 9). North-facing burned plots had slow rises in soil-water storage with the initial thaw in early March and much larger increases in soil-water storage in response to the 12–13 April, 22 April, 10 May, and 17 May storms. UB2 had essentially the same trends in soil-water storage as the south-facing burned plots. The UBSControl plot showed a slow rise in soil-water storage in mid-February and responded to the same spring storms as the other plots. Unsaturated soil-water storage at the end of the season (i.e. 1 June) was remarkably similar between all plots, with the 0–10 cm total water amounting to approximately 2 cm at SFM, SFR, UB2, and UBSControl and slightly lower total amounts for 0–10 cm of approximately 1.3 to 1.7 cm at the north-facing NFM and NFR plots (Fig. 9). The unburned UB2 plot held more water at the end of the snowmelt season than the burned north-facing NFM plot based on the 0–15 cm storage amounts. The two south-facing burned plots SFM and SFR stored more soil-water at the end of the snowmelt season (approximately 6 cm) compared to the north-facing NFR plot (approximately 5.2 cm) based on the 0–30 cm storage amounts.

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4 Discussion

The goal of this research was to examine the soil-water dynamics, soil-water storage, and soil temperature changes during the snowmelt season following wildfire in a mountainous environment. Because of the important role of aspect in snowmelt-driven hydrologic processes and soil temperatures, we instrumented north- and south-facing plots in this study. In this section, we present important conclusions from our results, discuss the context of our findings relative to previous work, and introduce broader-scale implications of our research.

4.1 Soil-water dynamics and unsaturated storage

In the top 3 cm of soil, sampled by the thermogravimetric soil-water content measurements, peak soil-water contents in response to April and May snow storms were similar regardless of aspect or wildfire impact, although the largest peak soil-water contents were for the south-facing unburned slope, UBSF (Fig. 6). South-facing burned slopes, however, had more substantial drainage/evaporation in the top 3 cm following peak soil-water contents, compared to unburned south-facing and burned and unburned north-facing slopes (Fig. 5). At greater depths, observed by the automated soil-water content sensors, aspect played a stronger role than wildfire in dictating the onset of soil-water content increases during spring thaw (Fig. 7). North-facing slopes were drier than south-facing slopes during the snowmelt period (Figs. 7 and 8). For south-facing plots, mean and median soil-water contents from the automated sensors showed little impact from wildfire effects. This result is consistent with other wildfire research in the Rocky Mountains of Colorado during the snowmelt period. For example, Moody et al. (2007) found no significant differences in soil-water content measured at burned and unburned plots using TDR in the winter of 2003–2004. Obrist et al. (2004) measured soil-water contents using TDR in burned and unburned plots in a sagebrush ecosystem and found lower soil-water contents (and consequently lower soil-water storage) during the winter months, which they attributed to decreased snow accumulation in their burned plots.

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Soil-water storage at the end of the snowmelt season was relatively unaffected by aspect or wildfire, essentially converging to field capacity, which was slightly different at each plot (Fig. 9). This finding is important because it suggests that the very-dry soil conditions, that could limit plant regeneration, established before the wildfire and exacerbated in the top 5 cm during the wildfire can be erased during snowmelt. It should be noted that the snowmelt season is typically the apex of soil-moisture in montane environments of the Rocky Mountains. At our field site, it appears that water supply to the subsurface during the snowmelt season is sufficient to drive soil-water content above field-capacity, resulting in substantial soil-water storage at the end of the snowmelt season, regardless of aspect or wildfire effects. Our results showed, however, that wildfire effects and aspect can have strong controls on the timing of increased soil-water storage in response to spring thawing and melting of the snowpack. We found that south-facing burned plots had larger magnitude increases in soil-water storage relative to unburned south-facing slopes in response to spring thawing. Our results also showed that increases in soil-water storage were both earlier and larger in magnitude on burned south-facing slopes relative to burned north-facing slopes. These results, in terms of aspect controls on the onset of soil-water storage dynamics, are consistent with previous work at unburned plots, with south-facing slopes having earlier onset of snowmelt than north-facing slopes (Grant et al., 2004; Litaor et al., 2008; Williams et al., 2009). The paucity of other studies documenting wildfire impacts on soil-water storage prevent comparative assessment of our work in terms of wildfire effects.

4.2 Soil-temperature changes

Our observations of soil temperature showed that aspect has a large impact on soil-temperature, with south-facing burned slopes being ~ 1 to 2°C warmer than north-facing burned slopes, reflecting a difference in solar insolation. Other investigators found similar results on unburned slopes. For example, Franzmeier et al. (1969) measured $\sim 2^\circ\text{C}$ warmer soils on south-facing slopes in the Appalachian Plateau, USA. The work by Kang et al. (2000) documented that the daily maximum-minimum soil

temperature range and the daily average soil temperature were larger on south-facing slopes (in a non-wildfire impacted area in a deciduous forest in Korea). [Kang et al. \(2000\)](#) also noted that the aspect differences in soil-temperature disappeared as the vegetation canopy closed later in the growing season, which suggests that canopy removal by fire is a main driver of soil-temperature differences by aspect, exacerbating solar insolation differences between aspects in unburned areas.

We also observed, on average, $\sim 1\text{--}2^\circ\text{C}$ warmer temperatures on south-facing burned slopes, relative to south-facing unburned slopes, and larger temperature variability in burned slopes. Previous studies showed increased soil temperatures because of decreases in soil albedo ([Chambers et al., 2005](#); [Rouse, 1976](#)). Soil albedo reductions can be relatively large after wildfire, for example, [Rouse \(1976\)](#) documented a decrease from 0.19 to 0.05 after wildfire. Burned soil albedos as low as 0.04 were measured by [Chambers et al. \(2005\)](#). It has also been suggested that surface soil temperature increases following wildfire also result, in part, from incident radiation being distributed over a smaller surface area after devegetation ([Chambers et al., 2005](#)).

The soil-temperature changes observed here after wildfire could substantially affect landscape and ecosystem function. Soil temperature changes can increase carbon fluxes from soils to the atmosphere (e.g. [Trumbore et al., 1996](#)) and affect nutrient availability ([van Cleve et al., 1983](#)). Soil temperatures can affect soil-water retention, which can enhance drainage of soil-water ([Klock, 1972](#); [Nimmo and Miller, 1986](#)). For example, [Klock \(1972\)](#) found that increasing the temperature of a soil column near freezing caused a significant decrease in water retention. Soil temperature is also important for root growth (e.g. [Kasper and Bland, 1992](#); [McMichael and Burke, 1998](#)) and can affect plant phenology (e.g. [Walker et al., 1995](#); [Price and Waser, 1998](#)). Increased soil temperatures after wildfire can also influence important vegetation recovery processes such as seed dormancy breaking and germination ([Auld and Bradstock, 1996](#)). The potential for ecologic and landscape function impacts or impairment, resulting from soil temperature increases following wildfire, exists at the watershed scale for a broad range of processes. Our results suggest that in the snowmelt season, wildfire effects

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on soil temperature and concomitant process changes would be more pronounced on south-facing aspects.

4.3 Comparison of soil-water dynamics to the unburned Gordon Gulch field site

Comparison of the snowmelt-driven soil-water dynamics at these two sites shows strong contrasts. The Gordon Gulch site, which was unaffected by fire, showed strong aspect differences in subsurface flow processes, with north-facing slopes dominated by diffuse unsaturated flow (i.e. through the soil matrix) and south-facing slopes dominated by event-driven preferential flow in the unsaturated zone (Hinckley et al., 2012). These process distinctions at the Gordon Gulch site were supported by tracer data. South-facing soils remained dry while north-facing soils were wetter at Gordon Gulch and these differences persisted through the entire snowmelt period to June 2010. The Fourmile Canyon Fire site examined in this effort, albeit one year later, showed the opposite response, with drier north-facing slopes during the spring thaw and convergence of slopes to similar soil-water contents near field capacity regardless of aspect or wildfire effects. While tracer data were not collected at the Fourmile Canyon site to examine preferential flow, the soil-water content and soil-water storage data suggest predominantly diffuse unsaturated flow on both north- and south-facing plots for burned soils. Soils and vegetation communities are similar between the two sites. The Gordon Gulch site was instrumented during snowmelt season of 2010, the year prior to Fourmile Canyon site, when precipitation from 1 December to 1 June was 304 mm at the Sugarloaf NADP site was 25 mm greater. The reasons for the contrasting hydrologic behaviour during snowmelt between the burned Fourmile Canyon area and the unburned Gordon Gulch area could be, for example, wildfire impacts on preferential flow initiation. Ash from wildfire has also been demonstrated to minimize preferential flow by clogging macropores (Neary et al., 1999; Woods et al., 2010), thus preventing substantial water flux passing through those macropores (Woods et al., 2010). Another possible explanation for the difference in preferential flow on south-facing slopes is reduced soil structure following wildfire.

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Analysis of the soil-water retention data from the south-facing slopes in the Fourmile Canyon area showed porosity losses of $\sim 0.1 \text{ (cm}^3 \text{ cm}^{-3}\text{)}$ and decreased soil-water retention at matric potentials wetter than field capacity, comparing burned and unburned slopes. Given that soil structure is known to promote macropore flow (e.g. Flury et al., 1994; Ghodrati and Jury, 1992), the loss of structure following wildfire at the south-facing Fourmile Canyon sites may have impeded preferential flow initiation. Thus, the presence of ash at the Fourmile Canyon plots or reductions in soil structure that serve as preferential flow paths may explain why preferential flow did not occur as a dominant process on south-facing slopes, in contrast to Gordon Gulch. This study only documented the first year after wildfire, when impacts are typically most pronounced; the wildfire-driven differences in preferential flow significance between the Fourmile Canyon and Gordon Gulch sites may dissipate as the Fourmile Canyon area recovers.

4.4 Implications for watershed-scale processes

Our results suggest that south-facing burned slopes experience an earlier thaw, accompanied by a rise in soil-water content, compared to both unburned south-facing slopes and burned north-facing slopes. In particular, the soil-water contents (Fig. 7) at SFM and SFR rise above field capacity for sustained periods of time, suggesting groundwater recharge may be occurring at these plots for longer durations relative to NFR, NFM, UB2, and UBControl. Research by Bossong et al. (2003) showed that groundwater recharge in semi-arid environments in the Front Range of Colorado is highly seasonal, with most of recharge accompanying snowmelt. Changes in groundwater recharge are then likely to be one of the most substantial watershed-scale impacts of the aspect and wildfire-effect driven soil-water dynamics during the snowmelt season that we have observed at the hillslope scale. Our findings suggest that in mountainous environments affected by wildfire, snowmelt-driven groundwater recharge may be greater in burned areas, and greatest on burned south-facing slopes. We do not, however, have deep wells (i.e. 10's to 100's of meters) to document water table rises. Thus, our connection of near-surface soil-water dynamics to larger scale groundwater system responses is speculative.

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Previous work on post-wildfire groundwater recharge suggested that recharge rates may be greater after fire (Bellot et al., 2001), which was attributed to decreased transpiration fluxes. After plant populations recover, however, the post-wildfire plant succession can cause decreased recharge relative to pre-wildfire vegetation assemblages, as was observed by Obrist et al. (2004) in a snowmelt-driven recharge environment. Plant population recovery then places a strong control on the duration of potential increases in post-wildfire groundwater recharge. At the Fourmile Canyon field area characterized in this effort, vegetation recovery is complex. In the first summer after the wildfire (i.e. following the snowmelt period described herein), striking differences existed in the vegetation regrowth on burned south- and north-facing slopes. By mid-summer 2011, the south-facing slopes were covered with dense vegetation comprised of weedy annuals such as mullein (*Verbascum thapsus*), lamb's quarters (*Chenopodium ssp.*) and tumble mustard (*Sisymbrium altissimum*) and perennial species such as larkspur (*Delphinium nuttalianum*) and bee balm (*Monarda fistulosa*), which probably resprouted from undamaged underground roots. By contrast there was little growth of any vegetation on the burned north-facing slopes except for occasional tufts of an unidentified grass. This disparity in vegetation growth may reflect differences in the seed bank on the two aspects, since prior to the fire the north-facing aspect had a closed-canopy Douglas-fir overstory with almost no understory vegetation. We speculate the growth of vegetation on the south-facing burned slopes could be a response to soil-moisture and temperature conditions during the winter and snowmelt period that primed (Hartmann et al., 2011) the seeds of annuals for germination in the early spring. Thus, the period of enhanced snowmelt-driven groundwater recharge on burned south-facing slopes may be relatively brief (i.e. a few years or less), depending on vegetation recovery. If an aspect-controlled asymmetry develops in groundwater recharge after wildfire, it may drive an emergent asymmetry in baseflow contributions to streamflow in burned watersheds that affects channel geomorphology and riparian areas if the asymmetry is of sufficient duration. This potentially important aspect asymmetry in groundwater supply to streams has yet-to-be quantified biogeochemical and geomorphologic consequences.

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We measured snow-water equivalent, snow depth, soil temperature, and soil-water content as well as estimated soil-water storage for the first winter and snowmelt season following the 2010 Fourmile Canyon Fire in CO, USA. Comparison of burned north- and south-facing slopes showed that north-facing slopes developed a short-lived (~ 1 month) snowpack while south-facing slopes did not. Soil temperatures were $\sim 1\text{--}2^\circ\text{C}$ colder on average and stayed below 0°C longer on north-facing burned slopes, relative to south-facing burned slopes. This aspect-driven soil temperature effect exacerbated by wildfire resulted in north-facing slopes being frozen nearly continuously from late November to mid March, while both burned and unburned south-facing slopes thawed intermittently throughout the winter and achieved seasonal thaw ~ 1 month earlier than north-facing burned slopes. Soil-water dynamics were impacted by both aspect and wildfire, with more rapid soil water content increases on south-facing burned slopes compared to same-aspect unburned slopes, and more rapid rises on south-facing burned slopes compared to north-facing burned slopes. Histograms of soil-water contents show that south-facing slopes are more frequently wet (i.e. higher soil-water contents) than north-facing slopes, which was likely the result of the earlier thaw on south-facing slopes. Soil-water storage increased earlier in response to the earlier thaw on south-facing slopes, relative to north-facing slopes, however soil-water storage was similar regardless of aspect or wildfire impacts at the end of the snowmelt season in early June.

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Table 1. Experimental plot characteristics.

Plot name	Condition	Aspect	Local slope		Soil depth (cm)	Sensor depths* (cm)
			Range (°)	Mean		
UB2	Unburned	Southeast	9–19	14	49	5, 10, 15
UB Temp	Unburned	Southwest	12–23	16	–	–
UBSControl	Unburned	South	15–31	20.5	31	5, 10
NFM	Burned	North	15–22	17.5	42	5, 10, 15
NFR	Burned	North	15–20	17	54	5, 10, 30
SFM	Burned	South	12–19	16	30	5, 10, 30
SFR	Burned	South	12–22	18	30	5, 10, 30

* Sensor depths are the soil-water content and soil temperature sensors.

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Table 2. Major precipitation events (i.e. greater than 10 mm water equivalent) at the field area during the study period from 1 November 2010 to 1 June 2011 based on the Sugarloaf NADP data (NADP site CO94 at 39.99° N, –105.48° W; NADP, 2011).

Date	Total precipitation (water equivalent, mm)
6 February 2011	16.3
8 February 2011	15.7
12 April 2011	25.7
13 April 2011	24.9
22 April 2011	10.7
10 May 2011	38.9
17 May 2011	27.7

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Table 3. Statistics of soil temperature and volumetric soil-water content from the automated sensors (Decagon 5TE).

Plot name	Sensor depth (cm)	Soil temperature			Soil-water content		
		Mean (°C)	σ^* (°C)	Median (°C)	Mean (m ³ m ⁻³)	σ^1 (m ³ m ⁻³)	Median (m ³ m ⁻³)
UB2	5	3.24	4.79	1.50	0.15	0.05	0.14
	10	3.53	4.12	2.40	0.14	0.04	0.13
	15	3.87	3.74	3.10	0.13	0.04	0.12
UBSControl	5	3.92	4.88	2.80	0.13	0.05	0.11
	10	4.12	4.22	3.50	0.14	0.07	0.13
NFM	5	2.33	5.10	1.40	0.12	0.04	0.12
	10	3.19	4.64	2.80	0.12	0.04	0.13
	15	2.92	4.35	2.50	0.12	0.05	0.13
NFR	5	2.92	5.94	1.10	0.13	0.04	0.14
	10	2.65	5.02	1.50	0.16	0.05	0.17
	30	3.52	3.83	3.30	0.12	0.07	0.06
SFM	5	5.57	6.13	4.00	0.14	0.05	0.14
	10	5.14	5.17	4.10	0.17	0.04	0.17
	30	5.84	3.52	5.70	0.17	0.05	0.16
SFR	5	4.56	5.85	2.60	0.19	0.05	0.18
	10	4.70	5.10	3.40	0.18	0.04	0.18
	30	4.96	3.99	4.60	0.17	0.04	0.16

* Standard deviation.



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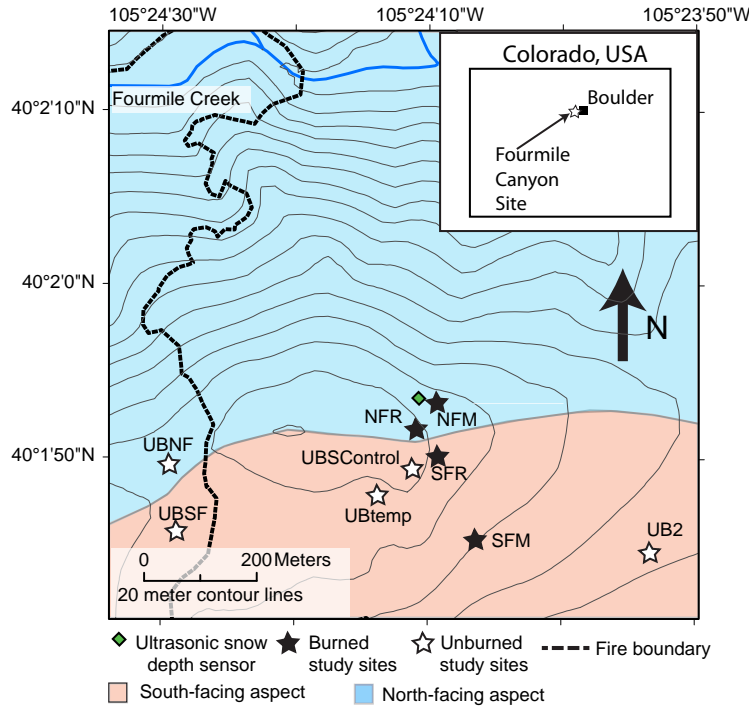


Fig. 1. Map of the experimental plots in the area affected by the Fourmile Canyon Fire near Boulder, CO, USA. Inset map shows the wildfire perimeter within the Fourmile Creek drainage and the black box shows the extent of the finer scale site map.

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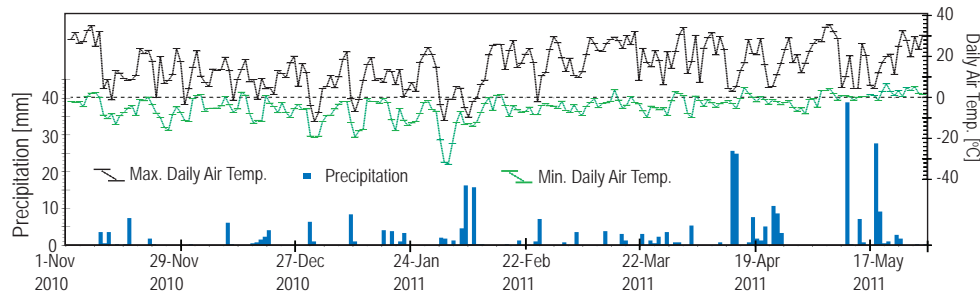


Fig. 2. Timeseries of precipitation and air temperature from the nearby Sugarloaf climate station operated by the NADP program (CO94).

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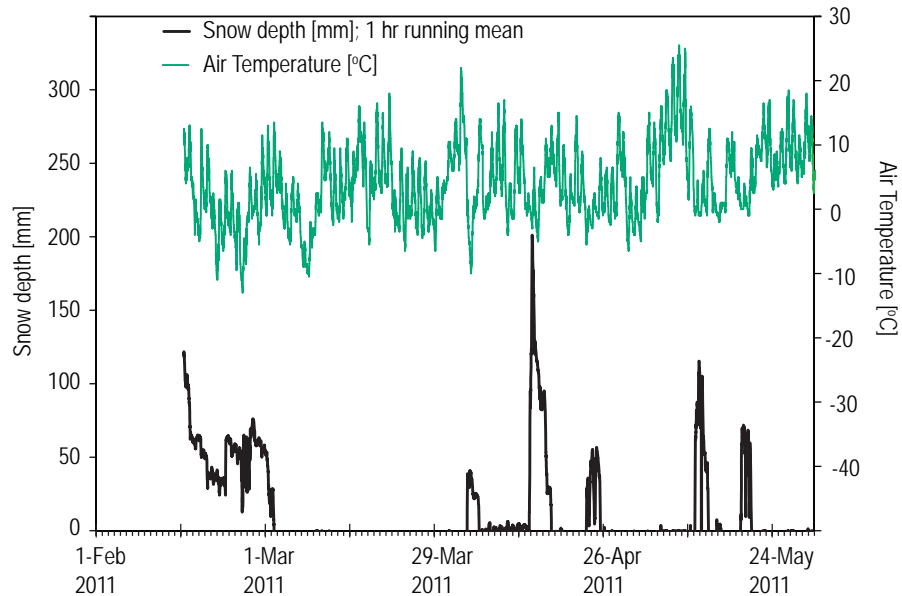


Fig. 3. Snowdepth and air temperature timeseries from the ultrasonic sensor at the north-facing midslope (NFM) plot.

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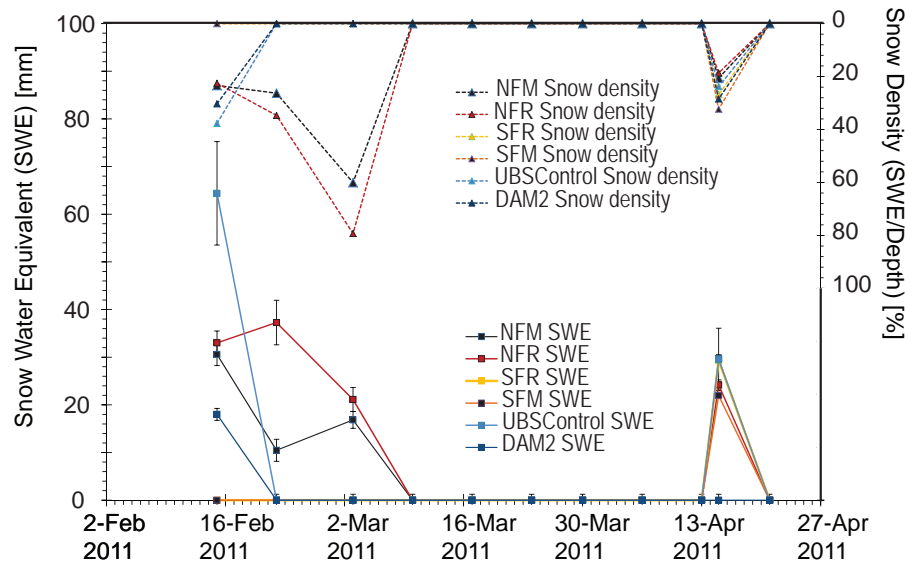


Fig. 4. Snow-water equivalent and snow density timeseries.

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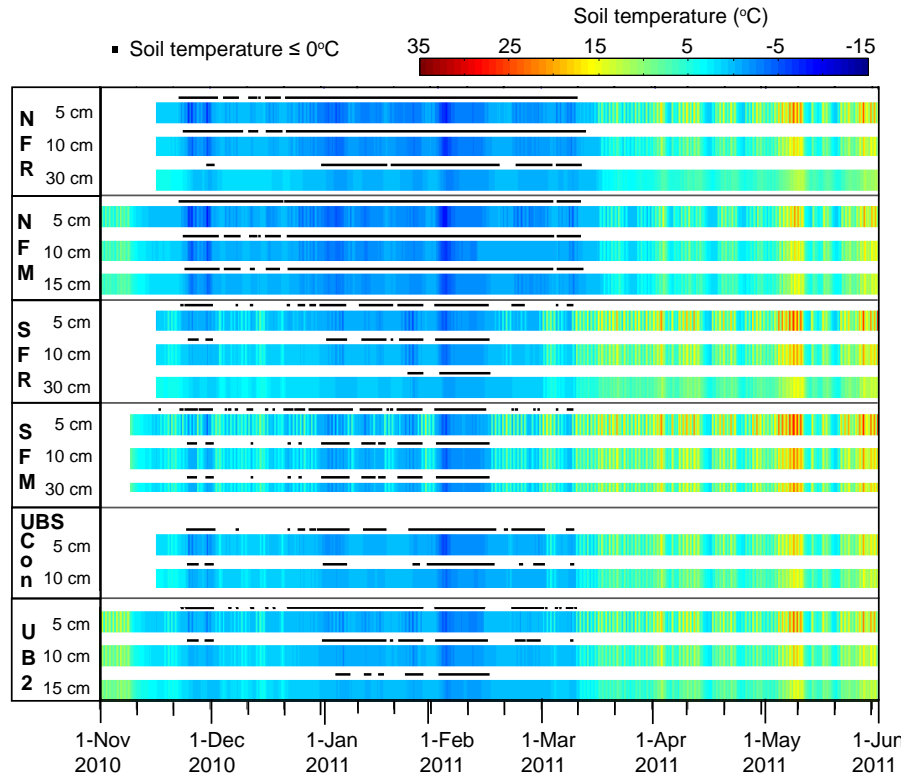


Fig. 5. Soil temperature timeseries as colored bars with black circles denoting frozen soil.

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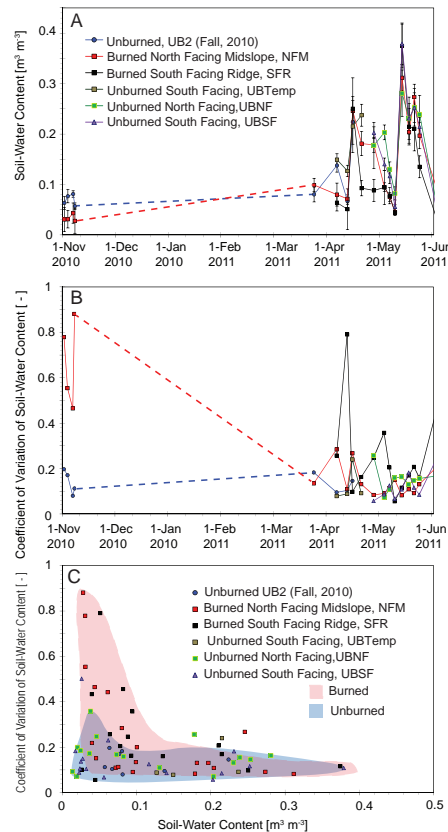


Fig. 6. Thermogravimetric soil-water content. **(A)** Timeseries of soil-water content at selected plots. Error bars represent the standard deviation of four replicate measurements at each plot. **(B)** Timeseries of the coefficient of variability of soil-water content for the four replicate samples at each sampling date. **(C)** Timeseries of the coefficient of variability of soil-water content as a function of the mean soil-water content for that sampling date.

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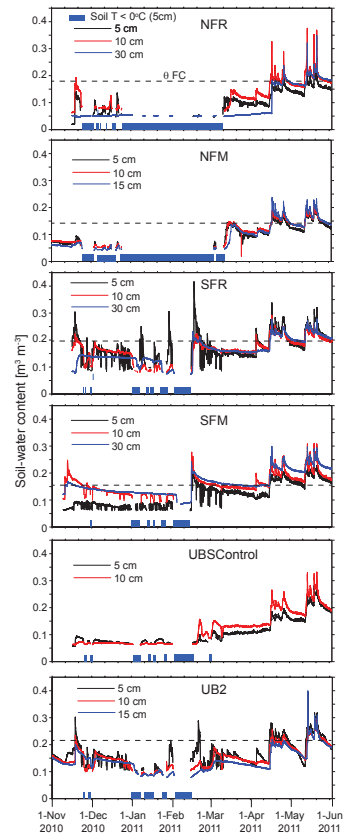


Fig. 7. Automated soil-water content timeseries at 1 min temporal resolution. Water content data are omitted when soil temperature is below zero °C. The dashed line shows the soil-water content at field capacity (θ_{FC}) based on measured retention curves and van Genuchten (1980) relationships at each plot. No retention curve was measured for UBControl so no θ_{FC} value is available.

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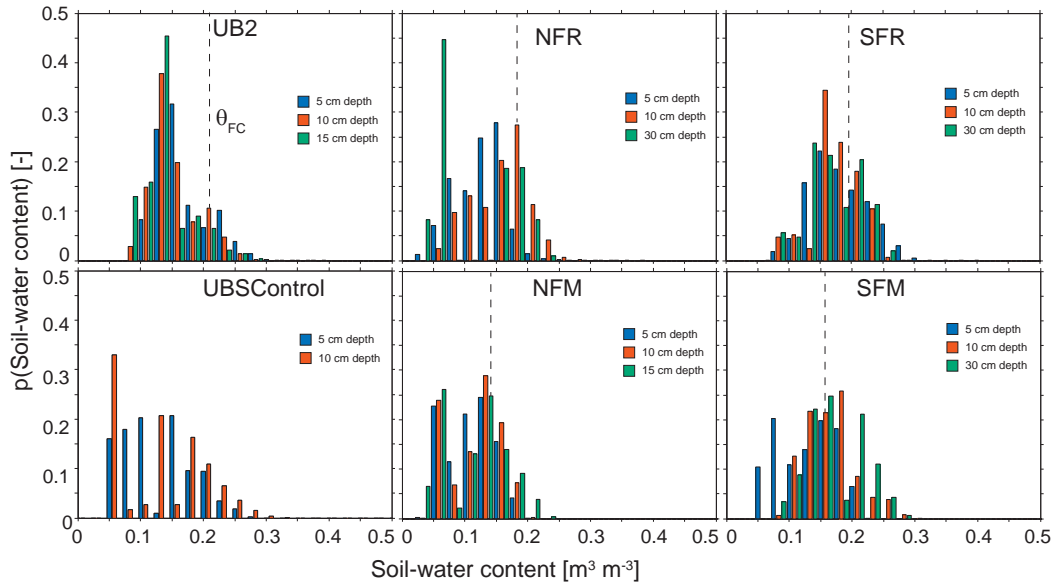


Fig. 8. Probability histograms of automated soil-water content data.

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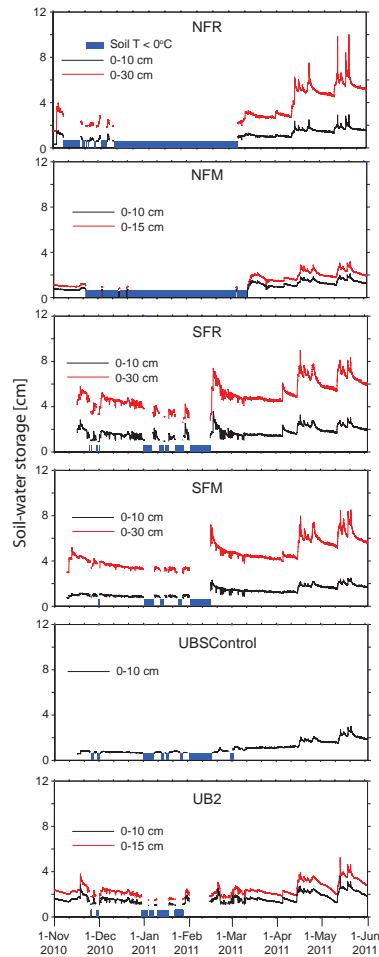


Fig. 9. Soil-water storage during the snowmelt season.

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