

Dust effects on forest snowpack melt and related ecosystem processes are mediated by canopy structure

Gregory E. Maurer^{1*} David R. Bowling¹

22 May, 2014

¹ Department of Biology, University of Utah, Salt Lake City, Utah, USA

* Corresponding author: greg.maurer@utah.edu

Abstract

Dust deposition lowers the albedo of snow and can significantly alter snowpack energy balance. Investigation of aeolian dust deposition in the mountains of the western U.S. has shown that these effects advance the timing of snowpack melt and spring runoff across much of the region. These studies have primarily focused on alpine snowpacks with little to no overstory vegetation. To evaluate the impacts of aeolian dust on ecohydrological processes in forests, we conducted a manipulative experiment in a subalpine conifer forest in Utah's Wasatch Mountains. During the spring of 2010–2012, we added dust to the snow surface in forested plots every 1 to 2 weeks, roughly doubling the natural dust loading. We then measured snowpack ablation in control and dust addition plots, along with below-snowpack and warm season soil temperature (T_{soil}), soil water content (θ), litter decomposition rate (D), soil respiration rate (R_s), and tree xylem water potential (ψ). Differences in ablation between control and dust addition plots were similar in magnitude to differences associated with the canopy structure of the forest. Seasonal patterns in T_{soil} and θ were similar between dust treatments and canopy structure groups. D , R_s , and ψ varied little between dust treatments, but there were significant differences between years. Our results suggest that interannual variability in snowfall had the greatest effect on the soil environment and ecosystem processes. In contrast with alpine areas the effects of aeolian dust on snowpack mass and energy balance in forests are similar in magnitude to those associated with canopy structure.

Keywords

ecohydrology, soil respiration, decomposition, snow hydrology, winter biogeochemistry

Introduction

Dust and other impurities lower the albedo of snow and have additional indirect effects on the energy balance of snow- and ice-covered land surfaces (Warren and Wiscombe, 1980; Hansen and Nazarenko, 2004). During

the spring, solar energy absorbed by particles near the snow surface can hasten the warming and melting of the snowpack (Conway *et al.*, 1996; Painter *et al.*, 2007; Gleason *et al.*, 2013). Recent studies have demonstrated that deposition of aeolian dust on mountain snowpacks leads to a significantly earlier timing of snowpack melt and seasonal water runoff in the hydrologic basins of the western U.S. (Painter *et al.*, 2007; Skiles *et al.*, 2012). Studies that model the effects of dust on snowpack dynamics have sometimes included forested areas, but experiments directly examining the effects of dust deposition on ecological processes have to date been limited to alpine areas where there is no vegetation canopy above the snowpack (Steltzer *et al.*, 2009).

Snowpack energy balance in forested areas differs from that in open, alpine areas. A fraction of incoming shortwave (solar) radiation is intercepted by and warms the canopy, which then increases the emission of longwave (terrestrial) energy towards the snow surface. Snow is an efficient absorber of longwave radiation, and this radiation becomes an important energy source for ablation in below-canopy environments (Link and Marks, 1999a, 1999b; Koivusalo and Kokkonen, 2002; Link *et al.*, 2004; Pomeroy *et al.*, 2009). Dust deposition lowers the shortwave albedo of snowpacks regardless of the presence of a canopy, but it does not appreciably enhance longwave absorption by snow (Warren and Wiscombe, 1980; Painter *et al.*, 2007). The efficacy of dust in perturbing snowpack energy balance below a canopy should therefore depend on the relative contributions of shortwave and longwave radiation, which are strongly influenced by canopy structure and radiative transfer (Link and Marks, 1999a; Sicart *et al.*, 2004; Ellis *et al.*, 2011; Lawler and Link, 2011). At present we know of no manipulative studies that have addressed the effects of dust deposition on snowpack melt in forested areas.

Reduced snowpack and earlier melt timing are associated with a variety of effects on ecosystems. Active microbial communities are present beneath seasonal mountain snowpacks, and their activity is tied to below-snowpack temperature and water availability. The melting of spring snow triggers the turnover of these communities and an associated flush of nutrients (Brooks *et al.*, 1998; Jaeger III *et al.*, 1999; Lipson *et al.*, 1999). The spring snow melt also marks the beginning of a more physiologically active period for many organisms, and changes in the timing of melt can alter the timing of emergence, greening, and flowering in alpine plant communities (Steltzer *et al.*, 2009), and activity of birds and animals (Inouye *et al.*, 2000; Ozgul *et al.*, 2010). Warm season activity by plant and soil communities in snow-dominated ecosystems depends heavily on snowmelt water (Brown-Mitic *et al.*, 2007; Litaor *et al.*, 2008; Riveros-Iregui and McGlynn, 2009), and differences in snowpack size and melt timing can have a significant effect on forest productivity (Molotch *et al.*, 2009; Tague *et al.*, 2009; Hu *et al.*, 2010). Perturbations to snowpack ablation by dust events may therefore have a significant effect on a variety of ecosystem processes.

Dust deposition has changed since the settlement of the western United States, largely due to human-driven land use and land cover change (Neff *et al.*, 2008; Painter *et al.*, 2010; Ballantyne *et al.*, 2011). Recent studies have revealed declining trends in snowcover extent, duration, and snowpack size in the region over this time period (Hamlet *et al.*, 2005; Mote *et al.*, 2005; Mote, 2006; Dyer and Mote, 2007). These trends in the timing and magnitude of snowpack ablation are thought to be responsible for shifts toward earlier spring runoff timing in the hydrologic basins of the western U.S. (Dettinger and Cayan, 1995; McCabe and Clark, 2005; Regonda *et al.*, 2005; Stewart *et al.*, 2005; Hamlet *et al.*, 2007). The snowpack and streamflow changes reported in the interior western U.S. (Clow, 2010; Nayak *et al.*, 2010; Harpold *et al.*, 2012) are consistent with regional and global trends in earth surface temperature change, but may also be attributable, in part, to the effects of aeolian dust deposition on mountain snowpacks (Painter *et al.*, 2010). According to model projections, increasing trends in aridity and temperature in the western U.S. will continue and intensify in the coming century (Brown and Mote, 2009; Seager and Vecchi, 2010; Kapnick and Hall, 2012). These trends bring a high likelihood of widespread vegetation change and greater aeolian dust fluxes (Westerling *et al.*, 2006; Logan *et al.*, 2010; Munson *et al.*, 2011; Anderegg *et al.*, 2011),

which may act as a positive feedback for further hydroclimatic changes in the region.

Though numerous studies suggest that increased dust deposition in the western U.S. will lead to hydrologic and ecological change, few direct experiments have been performed. Given that changes in dust deposition are concomitant with changes in temperature, aridity, vegetation cover, and other factors, it is critical that the mechanisms of ecosystem responses to dust deposition be investigated. We added dust to the snowpack beneath a subalpine conifer forest in Utah and measured resulting changes in snow water equivalent (SWE), snow ablation, and the soil environment, including soil temperature (T_{soil}) and soil water content (θ). We then monitored the response of vegetation and soil biological processes, including xylem water potential (ψ), soil respiration flux (R_s), and litter decomposition rate (D), to this snowpack manipulation. We hypothesized that dust addition would increase the rate of spring snowpack melt, leading to earlier snow melt, decreases in warm season θ , and changes in the seasonal pattern of T_{soil} . We expected responses from vegetation and soil biological processes that would follow the timing and magnitude of changes θ and T_{soil} . This experimental design and fortuitous timing allowed us to assess the role of within-forest differences in canopy structure and high interannual variability in snowpack dynamics.

Methods

Site description

In the spring of 2010, 2011, and 2012 we conducted a snowpack manipulation at a Rocky Mountain subalpine forest to measure the impact of dust deposition on snow ablation below a conifer canopy. The study took place in a mature conifer forest on a south facing slope at 2895 m (40°, 36' N, 111°, 35' W) in the Wasatch Mountains near Salt Lake City, Utah. Dominant conifer species in this forest were *Abies lasiocarpa* (subalpine fir) and *Picea engelmannii* (Engelmann spruce), and there were small patches of the deciduous *Populus tremuloides* (quaking aspen). This forest was intentionally chosen for its patchy, open canopy structure and southern aspect, which we assumed would allow significant transmission of shortwave radiation through the canopy.

Beneath this canopy, we delineated 10 × 60 meter study plots with long edges oriented parallel to the direction of the site slope. In 2010 we established a pilot snowpack manipulation consisting of one control and one dust addition plot. At this stage we attempted to control for canopy structure by measuring stem density of the study forest and locating our study plots in areas of the forest with similar density. However, as we added replicates, we decided to additionally account for canopy structure using hemispherical photography (described below). In 2011 we added two replicates to each treatment for a total of three 10 × 60 m plots per treatment. Control and dust addition treatments were randomly assigned to the plots. In October of 2009, we installed a weather station in a clearing outside the study forest. We also installed six soil moisture sensor profiles (CS-616, Campbell Scientific, Inc., Logan, UT, USA; EC-5, Decagon Devices, Inc., Pullman, WA, USA) and two soil temperature sensor profiles (Decagon EC-5) in each treatment. In September 2010 we added an additional sensor profile for θ (Campbell CS-616) and for T_{soil} (Campbell CS-107), for a total of seven θ and three T_{soil} profiles per treatment. The sensors in each profile were installed at 5, 20, and 60 cm below the top of the mineral soil horizon. Thirty-second readings of T_{soil} and θ were logged and then averaged every half hour with Campbell Scientific 23X dataloggers. See Figure 1 for a schematic of the experimental design.

Snowpack dust addition

Dust provenance: For the 2010 pilot project, we collected dust from the Chinle-Moenkopi formation of the Colorado Plateau. This geologic formation is a source for aeolian dust for some areas of the southern Rockies (Neff *et al.*, 2008; Lawrence *et al.*, 2010). After the pilot project was complete, however, our colleagues established that the Wasatch Mountains receive significant amounts of dust from Great Basin regions to the south and west (Steenburgh *et al.*, 2012). Based on this new understanding of Wasatch dust sources, we changed the dust source for the remainder of the study. The Milford Flat fire near Filmore, UT in the summer of 2007 was the largest wildfire in Utah history, and the burned area has become a recognized source of the windblown dust deposited in the Wasatch Mountains (Steenburgh *et al.*, 2012; Hahnenberger and Nicoll, 2012; Miller *et al.*, 2012). In March of 2011 we collected dust from drifts of wind-deposited material along a roadway through the Milford Flat fire scar. Though this material had different spectral characteristics than the Colorado Plateau dust, it visibly darkened the surface of the snowpack when applied. The material collected from both dust sources was sifted to < 500 μm . This size threshold is larger than the typical size class for aeolian dust (Lawrence *et al.*, 2010) but produced material that could be easily scattered across our 10-m wide plots.

Dust application: During the spring, dust was scattered by hand from the edge of the dust addition plots on to the surface of the snowpack. Care was taken to avoid trampling the snowpack inside the plots. We timed these dust additions to follow new snow events and, when possible, to precede clear, sunny weather. A new dust addition occurred every 1 to 2 weeks at times that maximized the exposure of the dust on the snowpack surface to shortwave radiation, and thus its effect on the snow melt rate. We anticipated that six artificial dust events per year, at a loading rate at roughly 5 grams per square meter would more than double the annual ambient dust loading observed in our region (Lawrence and Neff, 2009). We applied dust six times in 2010 and 2011 and only four times in 2012 due to a smaller snowpack and early spring snowmelt in that year. To verify that dust addition had increased the amount of particulate matter in our snowpack above ambient levels, we collected cores of the full snowpack column from all plots once the final dust application was made each year. In 2011 and 2012 we also measured ambient particulate matter loading in a clearing near our forest. In 2011 the clearing measurement was made by excavating a full snowpit on May 23 and sampling the entire snowpack in 10-cm increments. For the rest of the spring after this full snowpit collection, we collected surface cores ($n = 3$) on a storm board following each natural dust event, and the dust mass in these cores was added to the total dust loading from the snow pit. In 2012, three full snowpack cores were collected in the clearing on the same day as those collected in the canopy, and there were no further dust events after this collection. Snow cores and pit samples were thawed, filtered through weighed glass fiber filters (Whatman Grade GF/A, GE Healthcare Bio-Sciences, Pittsburgh, PA, USA), and the filters were oven dried and weighed to determine total particulate matter loading at each location. From these filters, we removed particulate matter that was clearly forest litter (needles, bark, scales, etc.) and weighed it separately.

Snow measurements: At six locations in each plot ($n = 18$ in each treatment), snow water equivalent (SWE) of the snowpack was measured prior to each dust addition, and on a roughly weekly schedule once ablation began. Measurement locations were marked and remained the same (± 3 m) for the duration of the experiment. SWE measurements were made using a Federal aluminum tube snow sampler (Union Forge, Yakima, WA, USA). Precipitation and SWE data from the Brighton SNOTEL site (Site 366, USDA, Natural Resources Conservation Service, <http://www.wcc.nrcs.usda.gov/snow/>) were used for some of our analyses. This station was located at the edge of a clearing < 2 km from our study forest, at an elevation of 2670 m on a similar aspect to our study site.

Ecosystem process measurements

Below-snow soil respiration: During spring of 2011 and 2012 we measured R_s below the snowpack using the diffusion gradient method outlined in Sommerfeld et al. (1996). Nine 10-cm diameter stainless steel mesh gas inlets were placed on the soil surface before the snowpack developed in control and dust addition treatments (18 inlets total). These inlets were routed to a central gas collection location between the plots using 0.64-cm diameter tubing (Type 1300, Synflex Specialty Products, Mantua, Ohio). Collection tubes were capped with stainless steel gas-tight removable fittings (Swagelok Co., Solon, Ohio, USA). At sampling time, tubes were uncapped and attached to a small gas pump (NMP850, KNF Neuberger, Inc., Trenton, NJ, USA) via an inline flowmeter (Gilmont Instruments, Barrington, IL, USA). A volume of gas equal to the volume of the tubing was pumped away, and the pump was then isolated from the tubing. The gas in the tube was then sampled using a syringe (Becton, Dickinson and Company, Franklin Lakes, NJ, USA) through a septum (Hamilton Co., Reno, NV, USA) upstream of the pump and transferred to a pre-evacuated glass vial (Labco Exetainer, Labco Ltd., Lampeter, Ceredigion, UK). Three samples of air were collected using the syringe above the snowpack on each sampling date. Upon return to the laboratory, the CO₂ mole fraction in these samples was measured by injecting 0.5 ml of gas into a closed-loop infrared gas analyzer system (LI-7000, Li-Cor Biosciences Inc., Lincoln, NE, USA; see Moyes *et al.*, 2010). Soil respiration rate was calculated using Fick's law with adjustments for snowpack properties by

$$F = \rho_a \eta \tau D \frac{dC}{dz}$$

where ρ_a is the molar density of air (adjusted for temperature and pressure), η and τ are the porosity and tortuosity of the air-filled snowpack, respectively, D is the molecular diffusivity of CO₂ in air (adjusted for temperature and pressure following Massman, 1998), and C is the mole fraction of CO₂ at height z (see Bowling and Massman, 2011).

Warm-season respiration: During the snow-free season we measured R_s from polyvinyl chloride collars roughly twice per month using a Li-Cor 6400 infrared gas analyzer with a 6400-09 soil chamber attachment. In 2010, the unreplicated pilot plots were measured ($n = 10$ locations per treatment), and in 2011 and 2012 four measurements were made in each of all six plots ($n = 12$ locations per treatment). Collars were inserted about 2.5 cm into the soil surface in an evenly-spaced line down the middle of each plot and were moved by 1 meter in a random direction at the start of each new season. Measurements of T_{soil} at 5 and 15 cm depth (thermocouple probe, Omega Engineering Inc., Stamford, CT, USA), and surface θ were taken at each respiration collar at the same time (Campbell Scientific CS-620 probe).

Warm-season xylem water potential: In spring 2010 we selected 18 mature subalpine fir trees in the pilot plots ($n = 9$ per treatment) and measured predawn and midday ψ using a pressure chamber (PMS Instrument Co., Albany OR, USA) roughly twice per month until the fall. In 2011 we added three subalpine fir saplings (DBH < 2cm) in each plot for measurement of ψ ($n = 9$ per treatment). In 2011 and 2012 we measured predawn and midday ψ in these saplings on the same schedule as R_s measurements. We continued in these years to measure a subset of the mature subalpine firs ($n = 5$ per treatment), but less frequently than in 2010. We did not control for the horizontal area of the rooting zone of these trees, and the roots of measurement trees may have extended beyond our plot boundaries (Day *et al.*, 1989).

Litter bag mass loss (decomposition rate): In fall of 2010, we collected needle litter from canopy conifers at the site on tarps and oven dried. Five grams of litter were then sewn into nylon and fiberglass mesh litter bags (0.2mm nylon mesh bottom, 1.7mm fiberglass screen top). On October 15, 2010, at 36 locations in the study forest (18 per

treatment), we placed a group of 5 litter bags on the forest floor and secured them with metal staples ($n = 90$ bags per treatment). From the time of placement until spring 2013, we returned to each litter bag group immediately following spring snowmelt and in late fall (\sim Oct 15) each year to collect one bag per location. Collected bags were placed in a drying oven for 48 hours and decomposed litter was carefully removed from the bag and weighed. Bags that were disturbed or damaged by animals ($n = 26$) were excluded from analysis.

Mass loss was described using an exponential decay model with two pools, one fast and one slow cycling (Adair *et al.*, 2008; Harmon *et al.*, 2009). This model took the form

$$L_t = L_{0f}e^{-\lambda_f t} + L_{0s}e^{-\lambda_s t}$$

where L_t is the fractional litter remaining at time t , L_{0s} and λ_s are the initial fraction and decay constant of the slow-cycling litter pool, λ_f is the decay constant of the fast-cycling litter pool, and L_{0f} is the initial fraction of the fast-cycling pool and is defined as $1 - L_{0s}$. We fit this model to our data using the nonlinear least-squares method (Adair *et al.*, 2010).

Hemispherical photos

On several dates in 2012, we took hemispherical photographs of the canopy at all SWE measurement, litter bag, and warm season R_s locations, and at each soil sensor profile. For each photo, the camera tripod was adjusted to 1 m above the snow or soil surface, the camera lens was leveled, and upward looking photos were taken with a circular fisheye lens (8 mm F3.5 EX DG Circular Fisheye, Sigma Corporation, Kanagawa, Japan). In order to capture the with- and without-leaves canopy structure, we took photos at SWE measurement locations on April 24 (no leaves), at soil profiles and litter bag/respiration locations on July 17 (after aspen leaf out) and again at soil profiles on October 17 (after aspen leaf fall). We analyzed each digital photo using Gap Light Analyzer v2.0 software (Frazer *et al.*, 1999). For each photo, this software calculates a value of canopy openness, the percent of a 180° sky view not occupied by canopy, and direct-beam transmissivity, the percentage of above-canopy radiation transmitted to the forest floor. The size of our ψ measurement trees and their variable rooting area prevented meaningful characterization of canopy structure above them.

Statistical analysis

We compared the effect size of dust versus canopy structure on snowpack ablation by fitting a simple statistical model to our data. In this model, parameters for incoming solar radiation (measured as PAR), air temperature, and new snowfall (as SWE measured at the Brighton SNOTEL site) were used to predict the change in SWE between one measurement date and the next. The basic form of this model was

$$dSWE_{it} = \beta_0 + \beta_1 AirT_{it} + \beta_2 Snow_{it} + \beta_3 Pin_{it} + \epsilon_{it}$$

where $dSWE_{it}$ was the change in SWE measured at location i and time t , $AirT_{it}$, Pin_{it} , and $Snow_{it}$ are the integrated air temperature, incoming solar radiation, and snowfall measured at time t , respectively, $\beta_{0...3}$ were the intercept and regression coefficients for these independent variables, and ϵ_{it} was the residual error. We fit this model to our SWE measurements using least-squares regression. Because we expected the influence of these independent variables to vary according to treatment and canopy structure, we also tested the significance of

interaction terms between our independent variables and treatment (control or dust addition), canopy radiation transmission (high or low), and canopy openness (open or closed).

We used a multilevel linear model with sample date as a random variable (a repeated measures design) to test for differences in SWE during the accumulation period, which we defined as the first four SWE measurement dates of the field season. We compared differences in SWE between treatments and canopy groups with this technique. Similar multilevel model tests were used for comparisons of R_s , T_{soil} , θ , and xylem ψ . To test for interannual differences in these variables, measurement location was the random variable since the same locations were measured in all years.

Results

The Wasatch Mountains experienced three very different winters during the years of our snowpack manipulation experiment (Figure 2). In 2011, this region had a near record breaking large snowpack, and in 2012 it had a near record breaking small snowpack. The 2010 snowpack was intermediate with peak SWE similar to the long-term average. These differences allowed us to compare our snowpack and ecosystem process measurements between widely contrasting years.

Snowmelt manipulation

Dust addition visibly darkened the surface of the snowpack and successfully increased the load of particulate matter in the snowpack beyond the ambient snowpack dust load at the site. We measured the total particulate content of the snowpack in an adjacent clearing (no canopy present) and in control and dust addition plots and found that our dust additions roughly tripled the mass of particulates found in the clearing and doubled the load found in the control snowpack (Table 1). A large proportion of the particulate matter found in both control and dust addition snowpacks was forest litter derived from the canopy (Table 1). A similar proportion of the total particulate loading of the clearing snowpack in 2012 was also forest litter (Table 1).

Our experimental treatment resulted in small differences in measured SWE and snowpack ablation between the control and dust addition treatments (Figure 3a, b, and c). There was significantly less SWE in the dust addition treatment when compared to the control during the accumulation period of 2010 ($p < 0.05$; Figure 3a). During 2011 and 2012, however, treatment differences in SWE accumulation were statistically indistinguishable (Figure 3b and 3c).

There was a large range of variability in canopy structure in our forest, and this influenced snow accumulation and ablation. Canopy openness, the percentage of a 180° sky view not occupied by the tree canopy, ranged from 16.7 to 50.7%. Canopy transmission, the percentage of above-canopy solar radiation (adjusted for seasonal solar zenith) transmitted to the forest floor, ranged from 11.5 to 68%. Snow water equivalent was higher under open and high transmission canopy areas when compared to closed and low transmission canopy areas (Figure 3d, 3e, and 3f, canopy transmission groups not shown). Differences between open and closed canopy were statistically significant in 2011 and 2012 ($p < 0.05$) and differences between high and low transmission groups were significant in 2012 ($p < 0.05$).

Interannual variations in SWE at our study forest were much larger than the differences between treatments or between canopy groups in any single year. For all SWE measurement locations in the forest, mean SWE during

the 2011 accumulation period was 898 mm (S.D. = 158 mm), which was higher than the mean in 2010 (479.4, S.D. = 120) and 2012 (322, S.D. = 79). Pairwise comparisons of accumulation period SWE between individual years indicated significant differences in SWE ($p < 0.0001$; Figure 3).

Empirical ablation model

Visual inspection of the spring SWE depletion curves in 2010–12 revealed similar ablation rates for control and dust addition treatments (Figure 3a, b, and c), but indicated a slightly higher rate in the open compared to the closed canopy groups (Figure 3d, e, and f). We tested whether this difference was significant by fitting a statistical model of snowpack ablation to our SWE measurements for 2011 and 2012 (Figure 4). Without interaction effects, our model fit the data reasonably well in 2011 ($R^2 = 0.70$) and 2012 ($R^2 = 0.78$). Air temperature, snowfall, and incoming solar radiation were all significant predictors of variation in $d\text{SWE}$ in both years ($p < 0.002$).

Dust treatment and canopy structure both significantly impacted the ablation during at least part of the experiment. We tested several interaction terms in our statistical model to test whether the differences between treatment and canopy structure groups were significant. There were significant differences in ablation between the control and dust addition treatments in 2011 ($p < 0.02$). In 2012, however, the treatments were not statistically distinguishable. We also assigned each measurement location to an open or closed canopy and a high or low canopy transmissivity group and tested these groups as interactions in the model. Areas with high canopy transmissivity had faster ablation in 2011 ($p < 0.05$) and in 2012 ($p < 0.001$). Areas beneath an open canopy had faster ablation in 2011 ($p < 0.02$) and in 2012 ($p < 0.001$).

Soil temperature and water content

Average θ and T_{soil} were similar between treatments and canopy groups during 2011 and 2012. We constructed 95% confidence intervals around the mean T_{soil} and θ data from all sensors in control or dust addition plots and from all sensors classified as open and closed canopy (Figure 5 and 6). During the majority of each year, these intervals overlapped, indicating that the means of T_{soil} and θ were not statistically different between treatment or canopy groups. There were some minor differences in the dynamics of these variables between treatments or canopy groups that are detailed in the Discussion section.

During the time periods when below-snowpack (Jan–Jun 2011 and 2012) and warm season (Jun–Oct 2011 and 2012) R_s measurements were made, we examined 24-hour average values of T_{soil} and θ from soil profile sensors and handheld measurements. We found some significant differences in T_{soil} and θ between treatment and canopy groups that are presented in Appendix A and summarized in the Discussion section. These differences were generally small and were associated with only minor variations in ecosystem processes among these groups.

Overall, interannual variability was the largest driver of differences in T_{soil} and θ (Figure A.1–A.6). Comparisons between years showed that below-snowpack T_{soil} and θ were significantly higher in 2011 (large snowpack) than 2012 (small snowpack; $p < 0.05$ – 0.0001 depending on depth). During the warm season, between-year θ comparisons indicated significantly wetter soils in 2011 than in other years ($p < 0.01$ – 0.0001 , depending on depth). This was observed with soil profile sensors at all depths and with the handheld sensors (2011 and 2012 only). Soils were generally warmest, measured by profile or handheld sensors, in 2012, but these differences were not significant.

Ecosystem processes

Ecosystem processes showed few significant differences between control and dust addition treatments in any year. Below-snow R_s was slightly higher in dust addition treatments compared to the controls in 2011 and 2012, but these differences were not statistically significant ($p > 0.05$; Figure 7). During the warm season, there were no significant differences in R_s between treatments in any year (Figure 8). Xylem ψ did not vary in response to the dust treatment (Figure 9). Neither saplings nor mature firs showed significant differences in predawn or midday xylem ψ between control and dust addition treatments in any year tested.

The two pool decay model fit our litter bag mass loss data well, and there were small differences in litter decomposition rate between the treatments (Figure 10). The λ_f and λ_s for the control locations were 6.0×10^{-3} and 6.7×10^{-5} , respectively, and 7.8×10^{-3} and 8.2×10^{-5} for the dust addition treatment, respectively. The proportion of litter mass in the slow-cycling pool was slightly higher in the dust addition treatment (82% vs 77%) and the dust addition bags lost slightly less mass over the first winter.

There were significant differences in ecosystem processes between years in response to the widely varying winters. Below-snow R_s was significantly higher in 2011 than in 2012 (Figure 7, $p < 0.0001$). Warm season R_s was significantly lower in 2010 than in the two following years ($p < 0.01$), but respiration rates in 2011 and 2012 were not significantly different from each other (Figure 8). It is important to note that the respiration was measured at differing and fewer locations in 2010. Sapling predawn ψ was lower in 2012 ($p < 0.0001$) as was sapling midday ψ ($p < 0.01$). Water potential values of mature firs did not differ significantly between years (Figure 9).

Discussion

Snow accumulation and melt

There were few statistically significant differences in SWE accumulation or ablation between the control and dust addition treatments. The primary radiative effect of dust or other particulate matter in snow is to lower the shortwave albedo of the snow surface and thereby increase its absorption of solar radiation. Secondary effects of dust, such as increases in snow grain size, exposure of below-snow surfaces, and changes in surface roughness also impact snowpack energy balance during the ablation season (Hansen and Nazarenko, 2004; Fassnacht *et al.*, 2009). Our dust addition treatment likely altered the energy balance of the snowpack by one or more of these mechanisms. Several possible reasons may explain the smaller than expected differences in ablation following dust addition. The first possibility is that the added dust did not significantly change the energy balance of the snowpack relative to the control. Another possibility is that added dust had a smaller effect on snowpack energy balance than did variations in snowpack energy balance resulting from differences in canopy structure within our forest. A third possibility is that higher accumulation and/or sublimation rates at open-canopy locations in our forest compensated for faster ablation in the dust addition treatment. These three explanations are discussed below.

Our snowpack manipulation increased the dust load relative to the control, but may have had a smaller than expected effect on albedo. When we measured the mass of particulate matter in our snowpacks near the close of each ablation season, the mass in the dust addition treatment exceeded the control by a factor of two (Table 1). The control snowpack, however, had roughly double the particulate matter found in a nearby clearing. A

large percentage of the total particulate matter in the control and dust addition treatments was composed of forest litter in 2011 (24–32% litter) and 2012 (64–70% litter), indicating that particles other than our added dust probably impacted the snow surface albedo in both treatments. Snowpack albedo is often lower in forests when compared to clearings (Melloh *et al.*, 2002), and a number of prior studies have indicated that forest litter is highly effective at reducing the albedo and increasing the ablation of subcanopy snowpacks (Hardy *et al.*, 2000; Melloh *et al.*, 2001; Winkler *et al.*, 2010; Pugh and Small, 2012). The spectral characteristics and influence on albedo were not quantified, so it is difficult to judge the relative importance of dust versus forest litter in this study.

Significant variation in ablation was explained by canopy structure and its effect on radiative energy balance. In alpine or other snowpacks without overstory vegetation, net shortwave radiation is commonly the most significant component of snowpack radiative energy balance during the spring ablation season (Marks and Dozier, 1992). In forested areas, incoming shortwave radiation is intercepted by the canopy (shading), and a portion of this absorbed energy is re-emitted down to the snowpack as thermal radiation (longwave irradiance). The relative importance of shading and longwave irradiance to subcanopy snowpack energy balance depends greatly on canopy structure and solar angle. In forests with open or discontinuous canopies, such as an aspen forest in winter, there is less longwave irradiance to the snowpack from the canopy, but greater transmission of shortwave radiation through the canopy. This is particularly true in late spring as sun angle increases (Pomeroy and Dion, 1996; Hardy *et al.*, 2004; Pomeroy *et al.*, 2008; Lawler and Link, 2011). Accordingly, we found faster ablation under open canopy locations in our forest during the spring melt (Figure 4). As canopy closure increases, longwave irradiance also increases, and under some conditions, higher canopy longwave irradiance compensates for declines in shortwave transmission and becomes the major contributor of snowpack ablation energy (Link and Marks, 1999a; Sicart *et al.*, 2004). Our study forest had a heterogeneous and fairly open canopy structure, and it is probable that this led to high variability in the radiative energy balance of the snowpack. The albedo effect of dust acts primarily in the solar portion of the spectrum. If a large portion of the energy available for snowpack ablation in this forest was canopy longwave irradiance, the dust addition treatment would have been less effective in perturbing snowpack energy balance.

The potential for snow interception, sublimation, and redistribution also varied with canopy structure in our forest. Forest canopies intercept snowfall and facilitate water loss through redistribution and sublimation (Hedstrom and Pomeroy, 1998). Consequently, it is common to find greater snow accumulation beneath forest canopy openings relative to closed canopies (Hardy *et al.*, 1997; Koivusalo and Kokkonen, 2002). Our data clearly showed that more SWE accumulated beneath an open canopy (Figure 3d, 3e, and 3f), indicating less snowfall interception, sublimation, and/or redistribution in these areas. If we assume that dust addition lowered snowpack albedo and thus hastened ablation in our study forest, the effect would be highest in these same open areas where greater shortwave radiation was available to melt snow. It is possible that higher accumulation rates compensated for faster ablation in dust addition locations, making differences between treatments difficult to observe. Similar compensatory effects have occurred in other forest snowpack studies. Biederman *et al.* (2012) found lower snow interception during the grey phase in a mountain pine beetle impacted forest stand (presumably more open), but this was compensated for by higher sublimation rates in these stands.

Our empirical model results support the idea that canopy structure had a similar, or greater effect on snowpack ablation and accumulation than dust. Though our empirical model was not a full energy balance model, it successfully reproduced changes in SWE in our study forest. Snow accumulation was slightly higher in the control plots than in dust addition plots during the accumulation phase of each year (Figure 4). Given that, on average, control locations had a slightly more open canopy than the dust addition treatment (Table 2), it is unclear

whether this occurred due to the effects of dust or canopy structure. Later in the spring of 2011 and 2012, the control and dust addition treatments showed a similar rate of ablation, indicating that dust had a small effect on snowpack energy balance between treatments (Figure 4). In both years, however, there were significant differences in snowpack ablation below high and low transmission canopies, indicating that differences in canopy structure led to differences in snowpack energy balance. Snowpacks below more open canopies also had significantly greater snow accumulation during early spring, probably due to low canopy interception. These two effects together resulted in similar timing in the disappearance of snow below these contrasting canopy types (Figure 4). This is in agreement with other studies showing greater accumulation and more rapid snow ablation beneath openings in conifer forest canopies (Hardy *et al.*, 1997; Koivusalo and Kokkonen, 2002; Musselman *et al.*, 2012a).

Our results indicate a high dependence of snow accumulation and ablation on canopy structure, and highlight the need for more detailed study of subcanopy dust-on-snow effects. Though this is the first such dust manipulation in a forested area, scientists have applied distributed hydrological models to calculate the effect of dust deposition on snowpack dynamics and spring runoff across large areas of the western U.S. (Painter *et al.*, 2007, 2010). Models used in these studies employ realistic, full energy balance calculations for forested areas, but the driving data for overstory vegetation, subcanopy albedo, and their effects on snowpack energy balance tend to be coarsely defined. The VIC model, for example, uses a 1 km vegetation grid, with leaf area index (LAI) specified for the vegetated fraction of each grid cell using a global LAI database derived from 1981–1994 averages values (Liang *et al.*, 1994; Myneni *et al.*, 1997; Gao *et al.*, 2010). Solar radiation attenuation, longwave irradiance, snow interception and redistribution, and other canopy-dependent snowpack energy and mass balance parameters are calculated based on this gridded data. With realistic estimates of subcanopy solar and thermal radiation, accurate estimates of snowpack dynamics can be made at point or distributed scales (Link and Marks, 1999a, 1999b; Musselman *et al.*, 2012b), but obtaining or estimating this data at or beyond the watershed scale is not an easy task. Our results suggest that even under open, heterogeneous canopy cover, which is common in western U.S. mountains, the forest canopy mediates the effect of dust on snowpack ablation.

The shortwave albedo of subcanopy snowpack has an underappreciated role in determining snowpack radiative energy balance. A sensitivity study by Sicart *et al.* (2004) found that when subcanopy snow albedo was high, the radiative energy balance of the snowpack changed little in response to variation in canopy density. At low albedo (< 0.5), however, the radiative energy balance of the snowpack was sensitive to increases in shortwave transmission through a canopy. Thus, aeolian dust deposition should be expected to alter the radiative energy balance of some forests. A number of studies provide interesting context, but many of these have taken place in disturbed forests. In the western U.S., where the mountain pine beetle is currently impacting forests at a large scale, Pugh and Small (2012) found that high rates of litter deposition in beetle impacted conifer forests lowered snowpack albedo. They estimated that this increased snowpack ablation to a greater extent than other radiative or atmospheric effects resulting from tree death in the forest. Gleason *et al.* (2013) found a 200% increase in net shortwave radiation at the snowpack surface in a recently burned conifer forest. This change was due to the combined effects of higher solar radiation transmission by the canopy and lower snowpack albedo due to the deposition of burned woody debris. So, though it is established that changes in albedo impact the energy balance of a subcanopy snowpack, the conditions under which this results in faster ablation are not documented in a broad number of forest types, with notably few studies in undisturbed forests. Without more detailed, spatially explicit data on canopy structure and subcanopy snowpack albedo, it remains challenging to predict the effect of aeolian dust deposition on subcanopy snowpacks at a large spatial scale.

Impacts on the soil biophysical environment

Our snowpack manipulation had few effects on the soil environment. Differences in the overall seasonal pattern of mean T_{soil} and θ in the control and dust addition treatments were not significant (Figure 5 and 6, panels a & b), which is consistent with the small effects our treatment had on snowpack dynamics during the spring. Differences between the seasonal pattern of mean T_{soil} and θ in open and closed canopy groups were also insignificant (Figure 5 and 6, panels c & d). Despite this, there was an interesting difference in seasonal T_{soil} patterns between treatment and canopy groups. Surface T_{soil} began to increase from a near-zero level below the snowpack at or near the time snowcover disappeared, consistent with other observations in snow-covered ecosystems (Lundquist and Lott, 2008). This occurred a few days earlier in the dust addition plots (compared to the control) and open canopy locations (compared to closed) during 2011 and 2012 (Figure 5), perhaps indicating an earlier completion of ablation, on average, in these groups. Open canopy areas had greater radiative exposure that may have led to greater evapotranspiration (Molotch *et al.*, 2009; Bales *et al.*, 2011) and earlier decline in surface θ during the spring (Figure 6c, 6d).

When we examined T_{soil} and θ at discrete time periods (concomitant with below-snowpack or warm season R_s measurements; see Appendix A for details) there were some significant differences between treatment and canopy groups. Dust addition plots and open canopy locations had wetter soil and lower temperature below the snowpack in some years (Figure A.3 and A.4, perhaps indicating that lower snowpack albedo or greater radiation transmission led to more frequent winter melt events delivered cold melt water to the soil profile. We view this as somewhat unlikely in our high-elevation forest, though such events might be common where snowpacks are at or near an isothermal state during winter (Bales *et al.*, 2011). In the warm season, T_{soil} beneath open canopy was higher than beneath closed canopy (2012 only, Figure A.2), again suggesting greater radiation exposure in these areas. There were few consistent differences in warm season θ between treatment or canopy groups.

Interannual variability in T_{soil} and θ was larger than any difference due to dust treatment or canopy structure. The large snowpack year, 2011, had the highest below-snowpack T_{soil} (Figure A.1), indicating that the large snowpack effectively insulated the soil from the temperature and radiative environment at the snow surface [Zhang (2005); Maurer and Bowling, *in review*]. Below-snowpack and warm season θ were also higher in 2011 (Figure A.3 and A.6), suggesting that there was greater infiltration of snowmelt water into the soil in this year. Warm season θ was lowest during 2012, the year with the smallest snowpack. These patterns held at most soil depths.

Impacts on ecosystem processes

In alpine areas, earlier snowmelt has a marked effect on plant and animal phenology (Inouye *et al.*, 2000; Steltzer *et al.*, 2009), and based on present understanding of ecosystem processes we anticipated similar impacts to carbon and water cycling in our study. Differences in ecosystem carbon and water cycle processes between control and dust addition plots were not significant in the majority of cases (Figure 8 and 9). We attribute this to the small differences in T_{soil} and θ between these treatments. Litter decomposition rate was slightly slower in the dust addition treatment (Figure 10), but there were no consistent differences in T_{soil} or θ between the treatments that explained this.

There were significant differences in ecosystem processes between years. Interannual variability in snowpack and the soil environment appeared to be linked, and we interpret this to mean that differences in θ and T_{soil} led to different R_s and xylem ψ between years. Of the three winters observed in our experiment, soils were warmest

and wettest below the 2011 snowpack, and the highest below-snow R_s occurred in this year. A number of studies have highlighted that significant amounts of CO₂ are respired from soil below seasonal snowpacks and that these fluxes may vary significantly in response to changes in the below-snowpack soil environment (Monson *et al.*, 2006a, 2006b; Liptzin *et al.*, 2009; Aanderud *et al.*, 2013). Snow-molds, for example, are a group of fungi that colonize forest litter below Rocky Mountain (and probably other) snowpacks in the spring and are highly sensitive to small fluctuations in temperature (Schmidt *et al.*, 2009). Soil microbial physiology such as this may explain the higher below-snowpack respiration rate we observed in 2011.

Of the warm seasons observed in our experiment, soils were driest after the 2012 snowpack. This did not impact R_s , but did influence water availability for trees. Low θ in the warm season of 2012 resulted in predawn and midday sapling ψ that was significantly lower in 2012. This result agrees with other studies in our region indicating that years with lower SWE and earlier snow melt result in diminished soil water availability for vegetation (Molotch *et al.*, 2009; Hu *et al.*, 2010)

Conclusions

We artificially increased the load of aeolian dust in a subcanopy mountain snowpack. This dust addition treatment did not substantially alter snow accumulation, snowpack ablation, or the timing of snowmelt in our study forest. The influence of the canopy, through the combined effects of snow interception and shading, overwhelmed the effects of dust on snowpack albedo and radiative energy balance. Both SWE amount and ablation were significantly greater beneath open as compared to closed canopy areas in our study forest.

Dust addition produced few significant effects on the soil environment or on ecosystem processes. There were, however, significant differences in ecosystem processes between years, and this interannual variability was larger than any within-year effect of dust or canopy. Interannual differences in soil temperature and soil water content were in the direction expected given the year's snowpack size and melt timing. The resulting variation in the soil environment appeared to drive the differences in ecosystem processes we observed.

The limited impact of our dust manipulation in this forest suggests that the impacts of aeolian dust on snowpack energy balance are complex and likely to be site specific. In this system, within-forest and interannual variation in snowpack mass and energy balance were larger than the effect of dust. Both field and modeling studies of the influence of aeolian dust on snowpack ablation would benefit from better representation of canopy and its influence over snowpack energy balance. Future research on this topic should target interactions between canopy structure and snowpack albedo to better understand the conditions under which dust deposition may influence ecohydrological processes.

TEMPORARY NOTES

- Add a photo of the site, and or canopy hemi shots? Also, Tim thought a map of the plots and canopy density layer might be helpful *Appendix B*
- Based on Steenburghs comments, it would be good to discuss the spectral characteristics of our dust, and especially the contrast between colorado plateau dust and milford flats dust. *have sort of done this, but not with tons of detail*

- Hardy et al. (2004) used a similar method of characterizing canopy with hemispherical photos.
- Pugh and Small 2012: SWE was different in living and red/grey phase beetle affected stands in spring of 2009 and 2010. Needles lower albedo, but were there quantitative measurements of needle litter in snowpack?
- Musselman 2012: Ablation rate higher in stands, and in years, with greater direct beam solar transmissivity. Data may not have been corrected for differences in accumulation between years or between stands
- Lawler and Link: “Snowmelt dynamics in forested areas are largely driven by net radiation, which is controlled by solar elevation angle and spatial variations in canopy structure”
- Good descriptions of SNOBAL and its use in point simulation is in Link and Marks 1999. They also adjust inputs to model subcanopy energy balance.

Acknowledgments

The authors wish to thank Mark Blonquist, Andrew Moyes, Allison Chan, Raili Taylor, LaShaye Ervin, Tara Trammel, Meghan Avolio, Ryan Bares, Ryan Dillingham, Dave Eiriksson, Laurel LeGate, and Michael Bernard for donating valuable time to fieldwork. Thanks to Tom Painter for help with experimental design and thoughtful discussions. Thanks to Jim Steenburgh and Tim Bardsley for providing helpful comments on early versions of this manuscript. Randy Doyle (Brighton Mountain Resort), Park City Mountain Resort, and Royal Street Holdings permitted and facilitated access to the Hidden Canyon study site. Ed Grote, Paul Gettings, Kevin Hultine, and Evan Pugh assisted with technical matters. Mark Miller (NPS), Lisa Bryant, Dave Whitaker, and Randy Beckstrand (BLM) were helpful in sourcing the dust used in this experiment. The U.S. Department of Energy Terrestrial Ecosystem Science program (grant DE-SC0005236) and the University of Utah Global Change and Sustainability Center each provided partial support for this research. # Tables

Table 1: Snowpack particulate loading for 2011 and 2012 in a nearby clearing (no canopy) and in control and dust-addition treatments (with canopy). Mean total loading in g/m² and standard errors are given, along with the mean forest litter (in g/m²) extracted from the total. Three full-snowpack core samples were taken for each location/year, except in 2011 (explained in the text)

	Clearing		Control		+ Dust	
	Total (SE)	Litter (SE)	Total (SE)	Litter (SE)	Total (SE)	Litter (SE)
2011	18.3 (NA)	NA	32.7 (8.5)	10.5 (5.1)	64.2 (20.2)	15.8 (8.0)
2012	19.1 (6.8)	13.3 (7.5)	38.5 (2.0)	24.9 (4.3)	73.4 (11.6)	49.8 (13.1)

Table 2: Means of the canopy structure measurements derived from hemispherical photographs, including the percentage of sky view not occupied by canopy (% Open) and the percentage of incoming solar radiation transmitted by the canopy (% Transmitted) in control and dust-addition treatments. Locations were photographed during time periods with overstory deciduous leaves present, without deciduous leaves present, or both. Standard deviations of the means are in parentheses.

Meas.	Location	Control		+Dust	
		% Open	% Transmitted	% Open	% Transmitted
With leaves	Litterbags	19.4 (5.9)	30.8 (11.7)	21.8 (4.4)	34.8 (11.2)
	Soil respiration	19.6 (6.4)	31.8 (12.5)	20.9 (4.4)	32.5 (11.0)
	Soil profiles	19.6 (4.9)	33.1 (10.1)	22.5 (3.9)	34.9 (8.4)
Without leaves	SWE locations	30.2 (8.8)	45.0 (14.2)	27.7 (5.9)	40.6 (12.6)
	Soil profiles	22.9 (4.5)	34.1 (13.0)	24.4 (7.7)	35.7 (17.3)

Figures

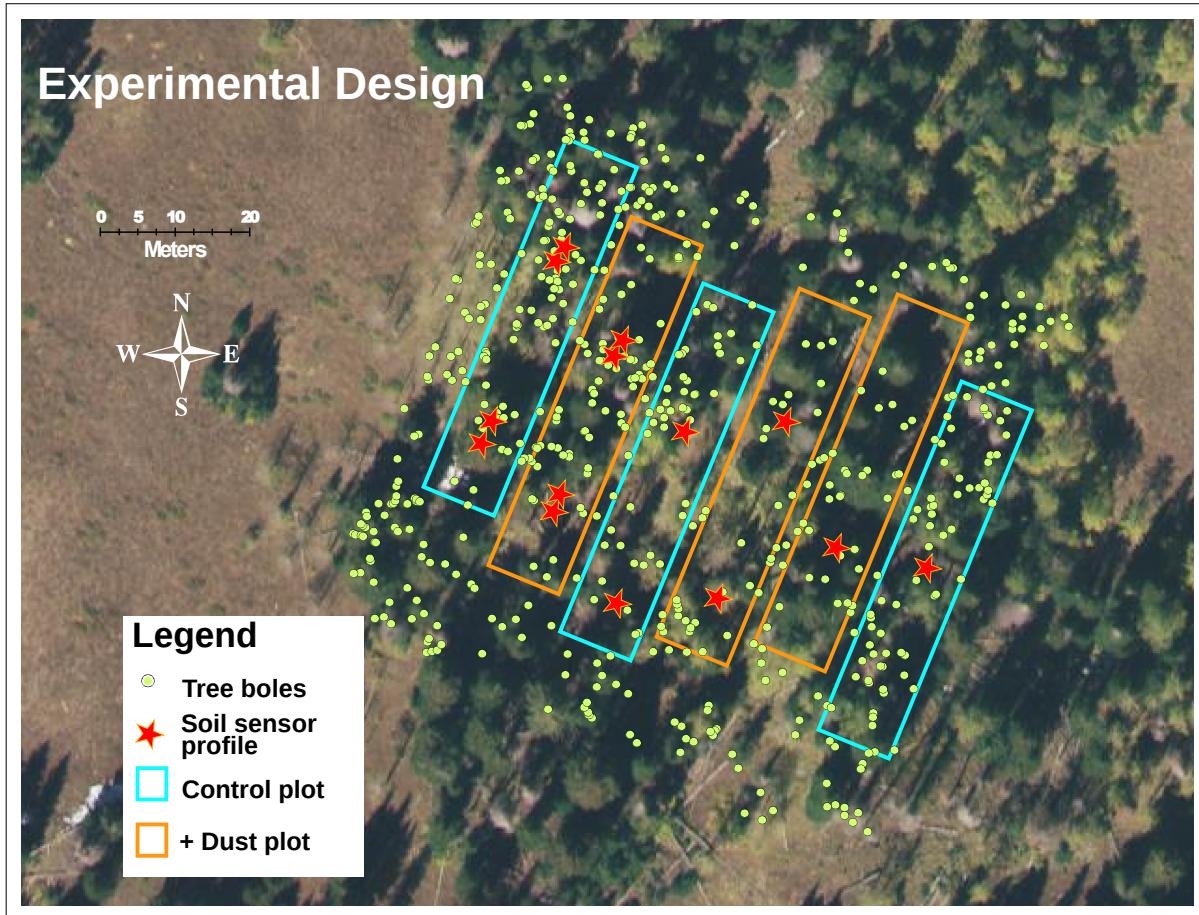


Figure 1: Schematic of the study forest, including the location of all snowpack manipulation plots. The weather station was located in the clearing to the northwest of the plots.

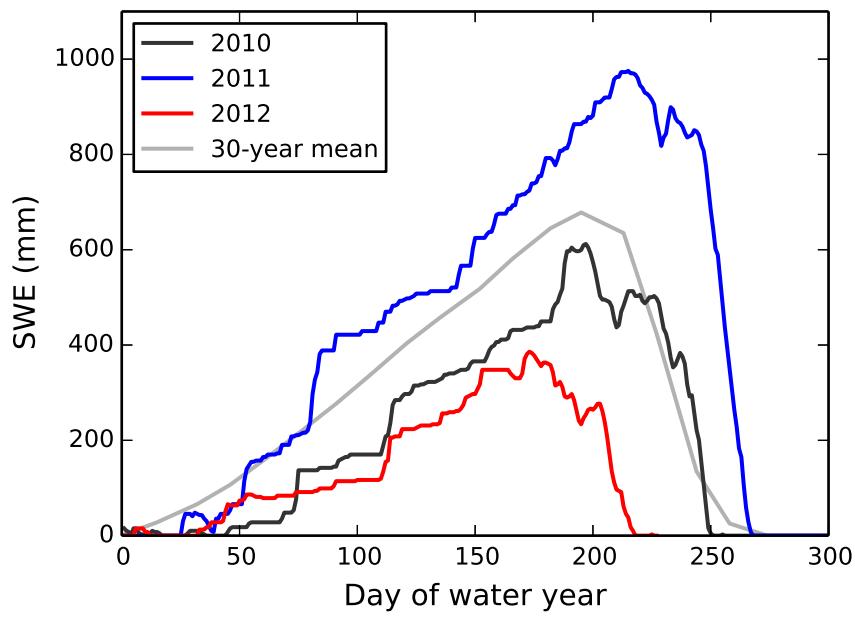


Figure 2: Snow water equivalent at the Brighton SNOTEL site, located about 2 km from our study forest, for the study years 2010 to 2012. The long-term mean for the site was calculated at 2-week intervals for the years 1971–2000 is plotted for reference in gray.

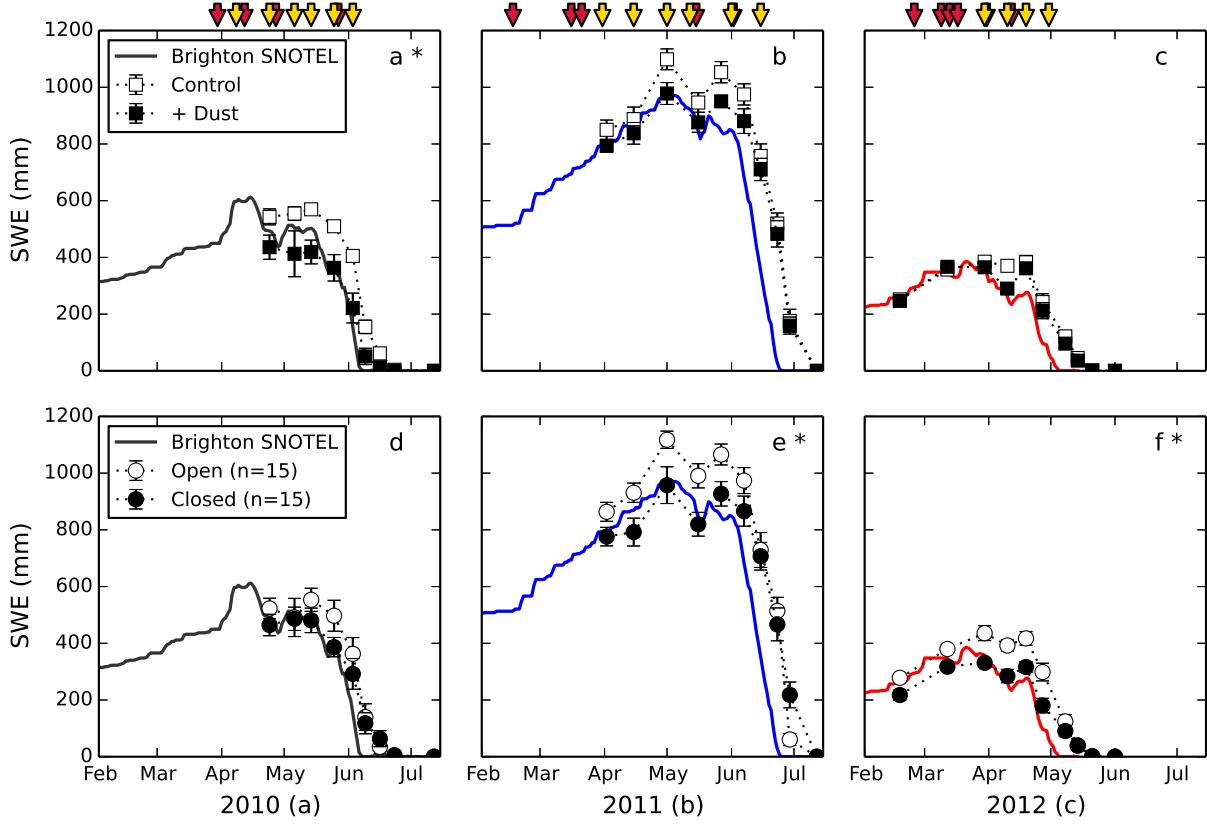


Figure 3: Snow water equivalent at the study plots. Observations were grouped and averaged in two ways in this figure. Panels (a), (b), and (c) compare the means of measurements made in control versus dust addition treatment plots ($n = 18$ per treatment). Panels (d), (e), and (f) compare the means of measurements made in open versus closed canopy locations in the forest ($n = 15$ per group, 6 median locations were excluded). Red arrows indicate the timing of natural dust events and yellow arrows indicate experimental dust additions. Asterisks denote significant differences ($p < 0.05$) between control and dust addition SWE accumulation prior to the start of snowmelt (first 4 observations in each year). Letters in the x-axis labels denote significant pairwise differences in SWE accumulation between years ($p < 0.05$). SWE observations from the Brighton SNOTEL site are shown for reference (as in Figure 2).

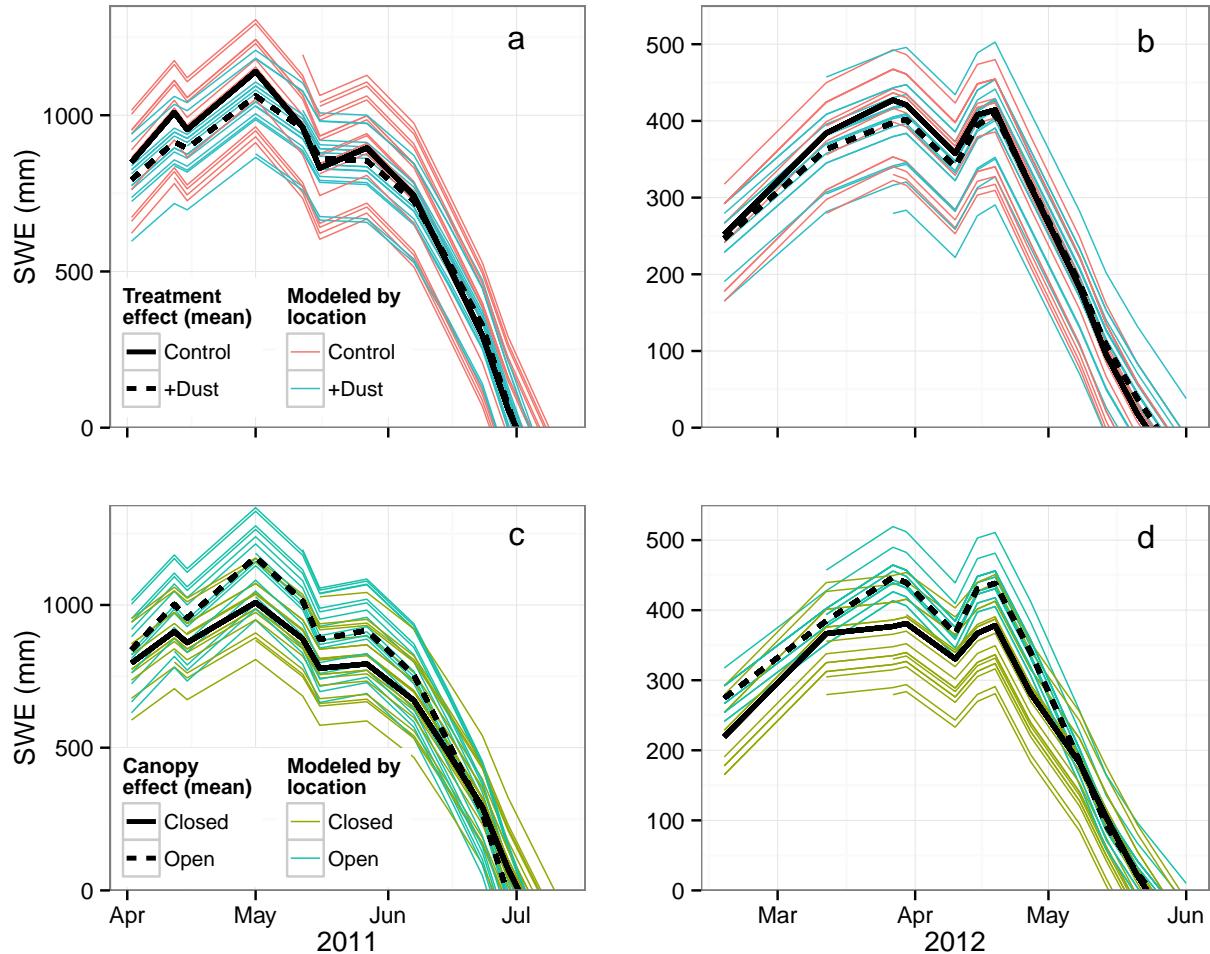


Figure 4: Modeled SWE during the spring of 2011 in panels (a) and (c), and the spring of 2012 in panels (b) and (d). Modeled SWE values were based on measured SWE during at the start of the experiment and linear model estimates of $dSWE$ fit using measured SWE and climate data from the site. The model start day was different in 2011 and 2012, and two variations of the model were tested in each year. The model used in panels (a) and (b) includes a treatment interaction effect, and in the panels (c) and (d) includes a canopy transmission interaction effect. Thick black lines represent mean SWE of all locations in each treatment or canopy group, beginning at each group's mean SWE on the starting day. Finer colored lines are modeled for individual locations, beginning at each location's measured SWE on the starting day.

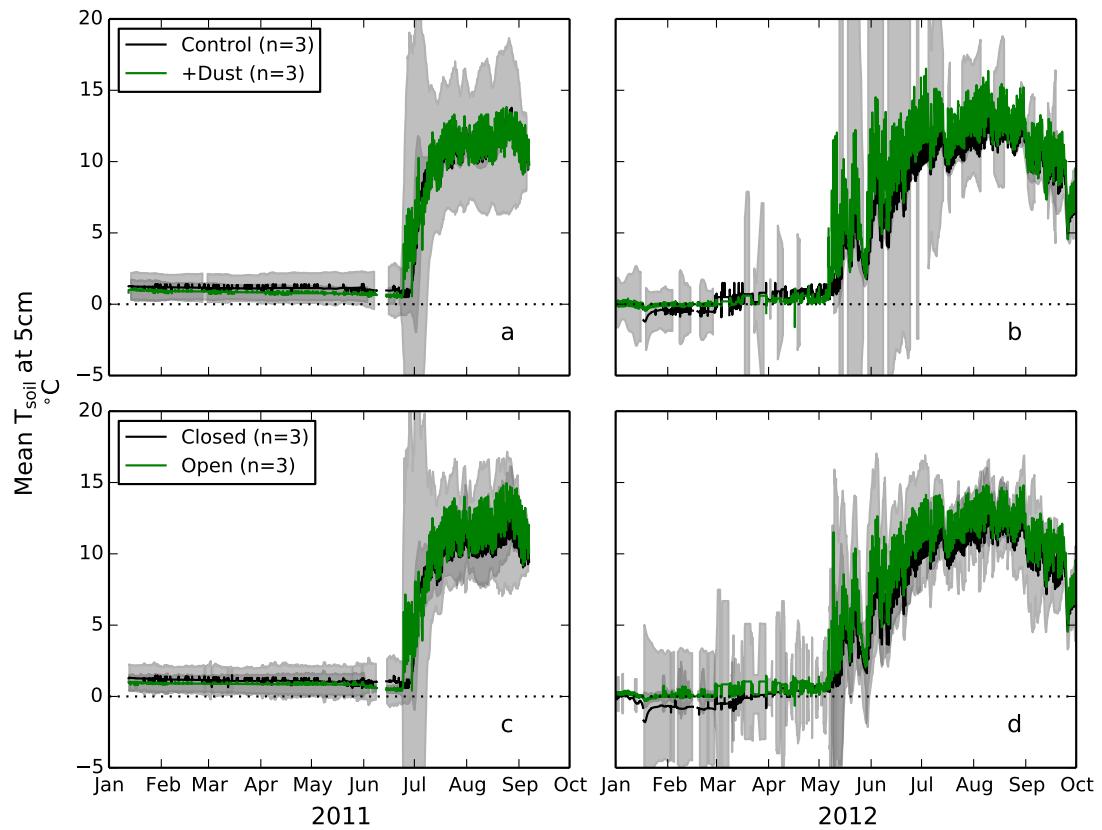


Figure 5: Comparison of mean soil temperature at 5 cm depth in the study plots. Lines represent the mean value of all sensors grouped by treatment in panels (a) and (b) or by canopy openness in panels (c) and (d). Shading represents the 95% confidence interval for data from all sensors used to calculate each mean. A dotted line at 0°C is plotted for reference.

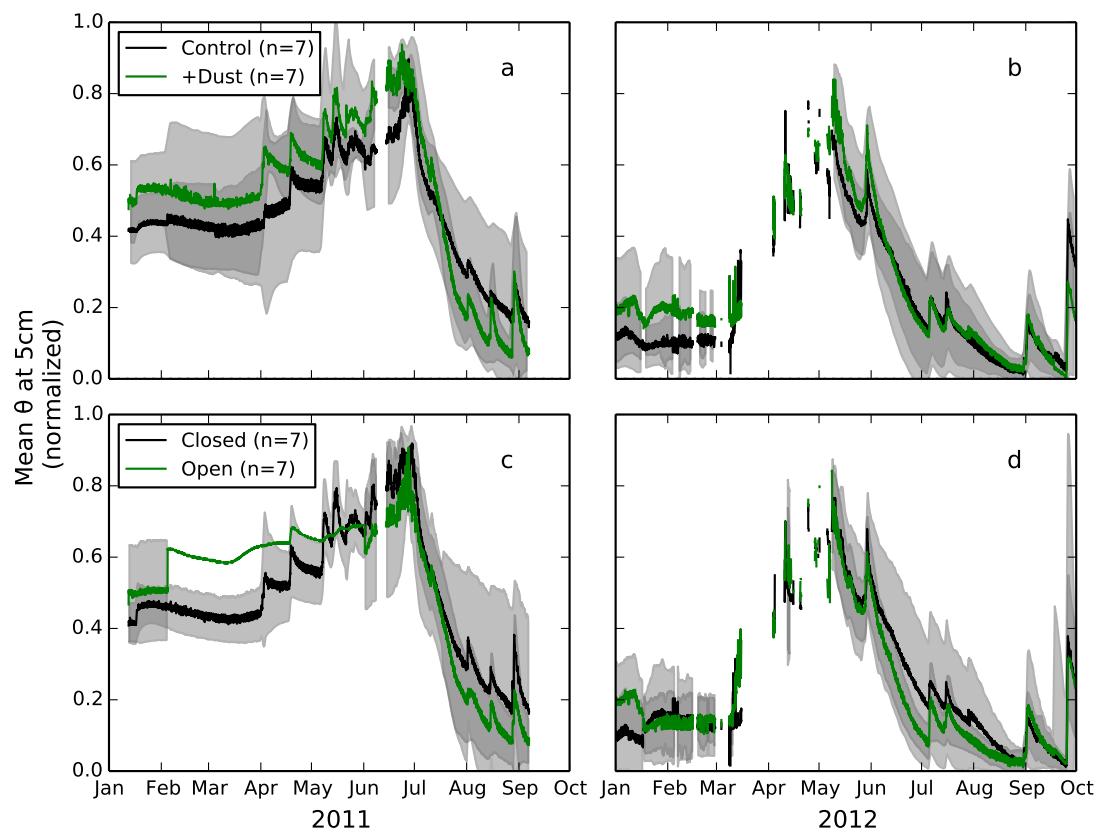


Figure 6: Comparison of mean volumetric soil water content (θ , normalized) at 5 cm depth in the study plots. Lines represent the mean value of all sensors grouped by treatment in panels (a) and (b) or by canopy openness in panels (c) and (d). Shading represents the 95% confidence interval for data from all sensors used to calculate each mean.

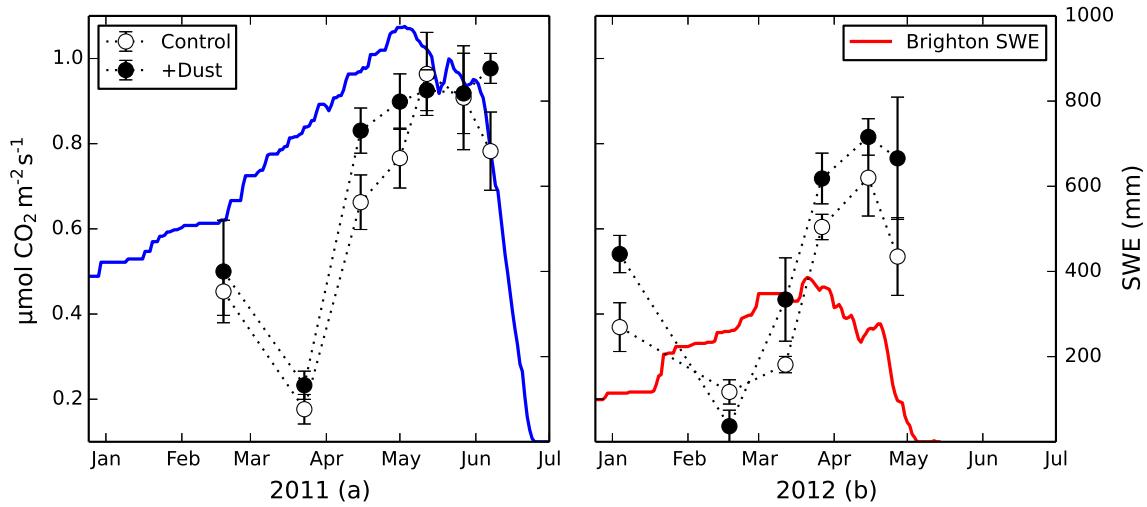


Figure 7: Mean values and standard errors of below-snowpack soil respiration measured in control and dust addition treatment plots ($n = 9$ for each treatment, left axis) during sampling dates in 2011 and 2012. Letters in the x-axis labels denote significant pairwise overall seasonal differences in below-snowpack R_s between years ($p < 0.05$). There were no significant treatment differences. The Brighton SNOTEL SWE observations during the corresponding time period are shown with colored lines for reference (right axis).

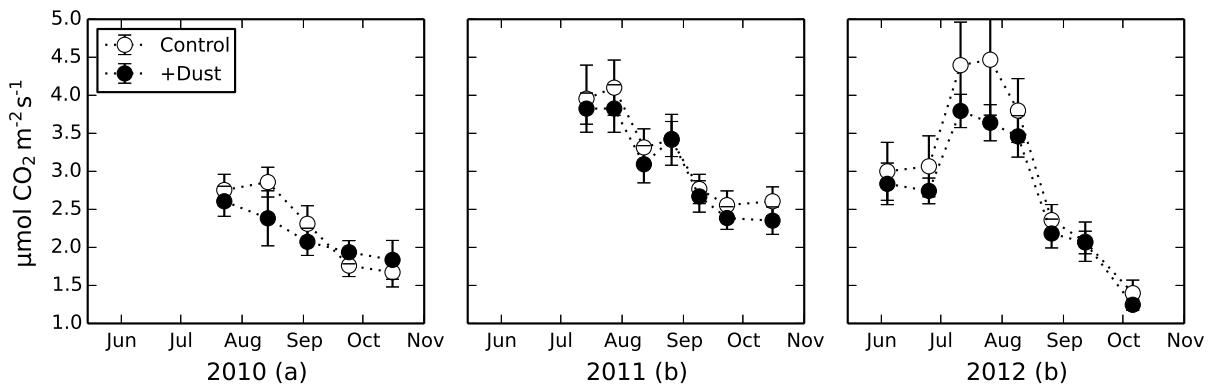


Figure 8: Mean values and standard errors of warm season soil respiration measured in control and dust addition treatments ($n = 18$ for each treatment). Letters in the x-axis labels denote significant pairwise overall seasonal differences in warm season R_s between years ($p < 0.05$). There were no significant treatment differences. Note the difference in scale with Figure 7.

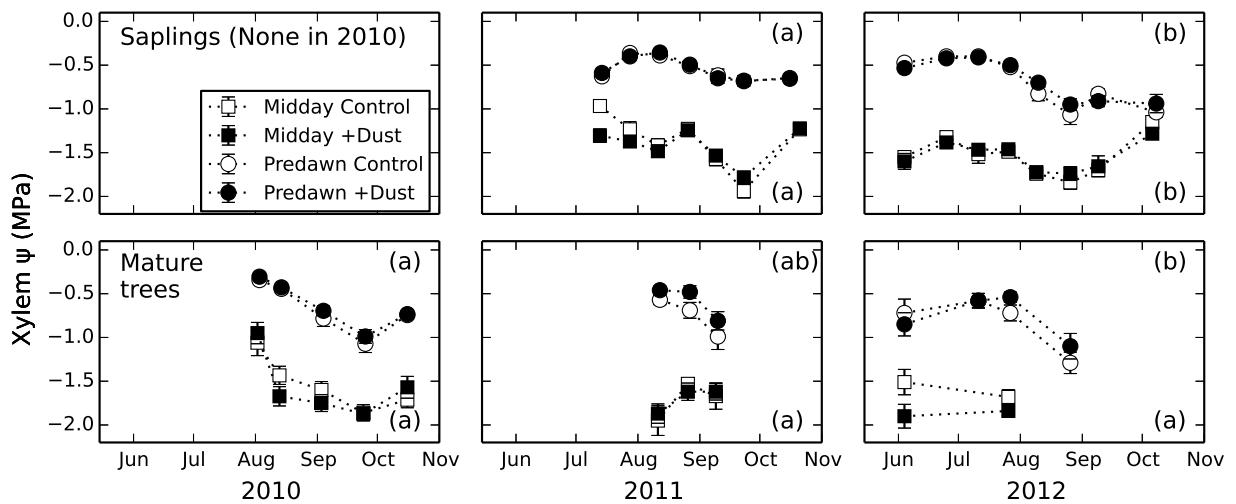


Figure 9: Mean values of xylem water potential in juvenile and mature subalpine fir measured in control and dust addition treatments ($n = 9$ for each treatment). No saplings were measured in 2010. Means and standard error bars, which are smaller than the symbols in many cases, are shown. Letters in the right corners of each panel indicate significant pairwise differences in xylem ψ between years ($p < 0.05$). Top corner letters correspond to predawn ψ and lower corner letters to midday ψ . There were no significant treatment differences.

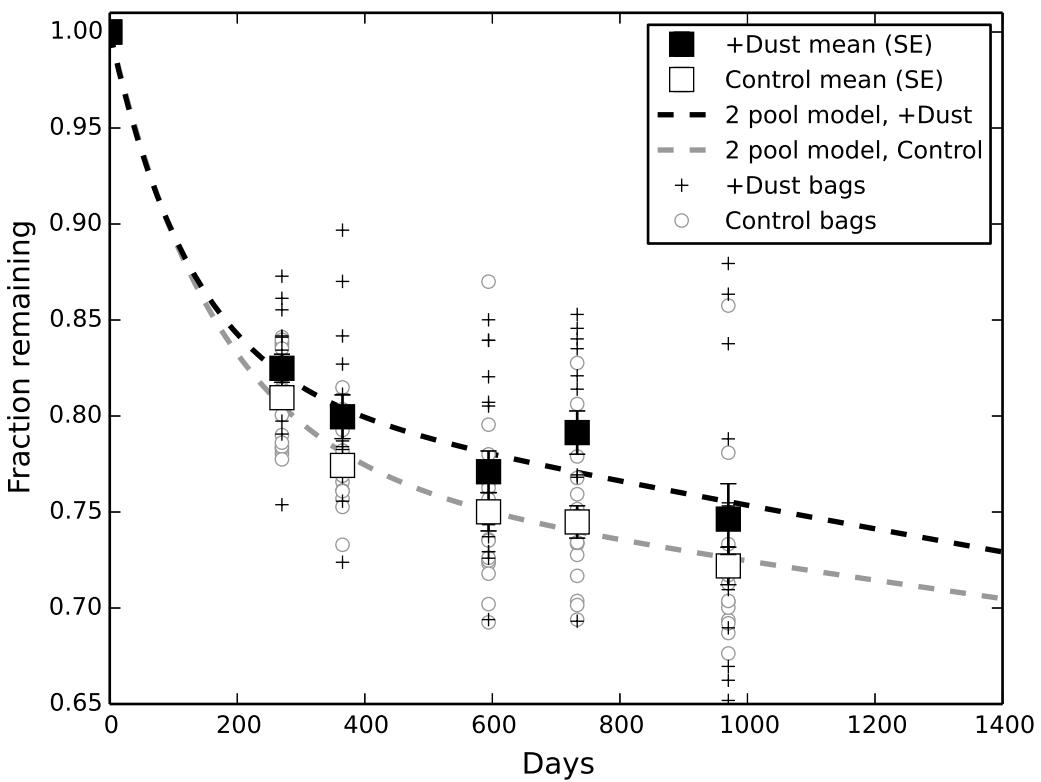


Figure 10: Litter bag mass loss between fall 2010 and spring 2013. Individual litter bag samples are shown (small circles or crosses), along with the mean and standard error of control and dust addition treatments for each collection date ($n = 18$ per treatment per date). The dashed lines were calculated using a 2-pool exponential decay function fit using non-linear least-squares. Decay constants for each pool (λ_f and λ_s) in each treatment are given in the text.

Appendix A: Treatment and canopy effects on soil temperature and water content

In our examination of multisensor mean time series (Figure 5 and 6) we found few differences between dust addition treatment and canopy groups. We also examined T_{soil} and θ during the discrete time periods used for sampling R_s below the snowpack and in the warm season. To compare treatment, canopy, and interannual differences in below-snowpack T_{soil} and θ we calculated 24 hour average T_{soil} and θ values from soil profile sensor data on each below_snowpack R_s sampling date (Jan.–Jun. 2011 and 2012). For comparison of warm season T_{soil} and θ , we calculated 24 hour average T_{soil} and θ values from soil profile sensors and collected handheld T_{soil} and θ measurements for each warm season respiration measurement date (Jun.–Oct. 2010, 2011, and 2012). Handheld measurements were made at all R_s collars. T_{soil} was measured at 5 and 15 cm depths using a thermocouple soil probe and θ measurements were integrated across the top 10 cm of the soil profile using a time-domain measurement soil water content probe (see Methods for instrumentation details). We tested for treatment and canopy differences in mean T_{soil} and θ data using a multilevel linear model with sample date as a random variable (a repeated measures design). To test for interannual differences in mean T_{soil} and θ , measurement location was the random variable since the same locations were measured in all years.

Soil differences between treatment and canopy groups

There were a number of significant differences in T_{soil} and θ between treatment and canopy groups during the below-snowpack period. In 2011, control plots were significantly warmer (higher T_{soil}) than dust addition plots ($p < 0.05$ – 0.0001 , depending on depth), but we found no significant difference between treatments in 2012 (Figure A.1). There were not consistent differences in mean T_{soil} between the canopy groups, though open and closed canopy mean T_{soil} were significantly different in some years and at some depths ($p < 0.05$ – 0.01 ; Figure A.2). Dust addition plots had significantly wetter soil (higher mean θ) than control plots below the snowpack in 2011 ($p < 0.001$), but there were no significant θ differences in 2012 (Figure A.3). Open canopy locations was also significantly wetter at 5 and 60 cm depths below the snowpack during both years ($p < 0.05$ – 0.0001 ; Figure A.4).

During the warm season, T_{soil} and θ were also significantly different in some treatment and canopy group contrasts. In 2012, 5 cm soil sensors indicated warmer T_{soil} in the dust addition plots ($p < 0.01$; Figure A.1), but there were no other significant treatment effects observed using soil profile sensors or handheld measurements (5 & 15 cm measurements; Figure A.5). Open canopy locations had significantly warmer soils in 2012 ($p < 0.05$ – 0.0001 , depending on depth), but handheld T_{soil} measurements did not corroborate these differences (Figure A.2 and A.5). In 2012, deep soil profile sensors (20 and 60 cm) had higher θ in the dust addition plots compared to the controls ($p < 0.05$ – 0.01 depending on depth; Figure A.3). Mean 20 cm θ was slightly lower in open canopy locations in 2010, but otherwise there were no other canopy or treatment differences in warm season θ observed in profiles or handheld measurements (Figure A.4 and A.6).

Soil differences between years

We found larger and more statistically significant differences in T_{soil} and θ between years, and it is likely that this was driven by the large interannual variation in snowpack size during our study (Figure 2). In the largest snowpack year, 2011, below-snowpack T_{soil} and θ were significantly higher than in other years ($p < 0.05$ – 0.0001

depending on depth), and these patterns held at all depths (Figure A.1 and A.3). During the warm season, soils were wettest in 2011 (large snowpack year) and significantly drier in the lowest snowpack year, 2012 ($p < 0.01$ – 0.0001) , and this pattern held at all depths and was significant with soil profile and handheld probe data (Figure A.3 and A.6). There were not, however, significant differences in warm season T_{soil} between years, whether measured by soil profile sensors or the handheld probe (Figure A.1 and A.5).

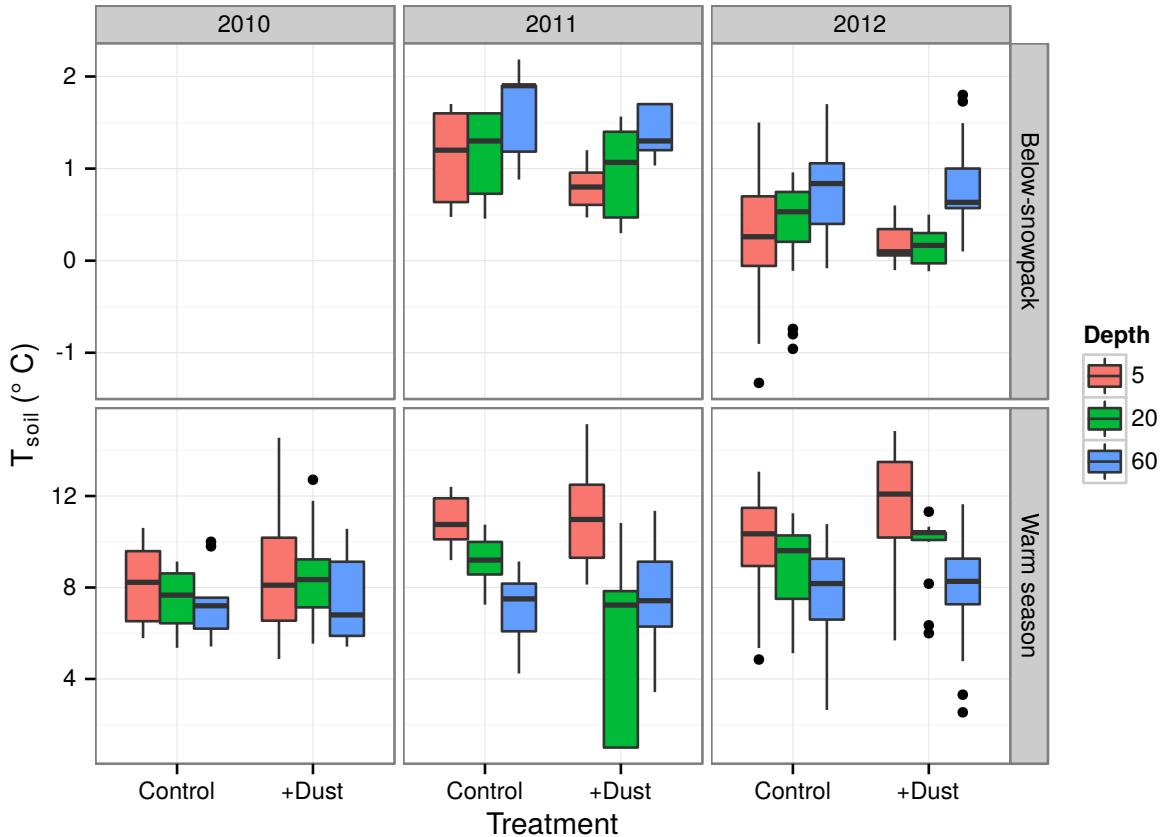


Figure A.1: Comparison of 24 hour mean T_{soil} taken from soil sensor profile data collected during the below-snowpack (top panels) and warm season (lower panels) R_s measurement periods in 2010, 2011, and 2012. The three soil sensor depths are shown, and sensor means are split into +Dust and Control treatments. Boxplots show the range (bars), first and third quartile (top and bottom of box), and median (line within box) of the data in each group. There were no below-snowpack respiration measurements made in 2010.

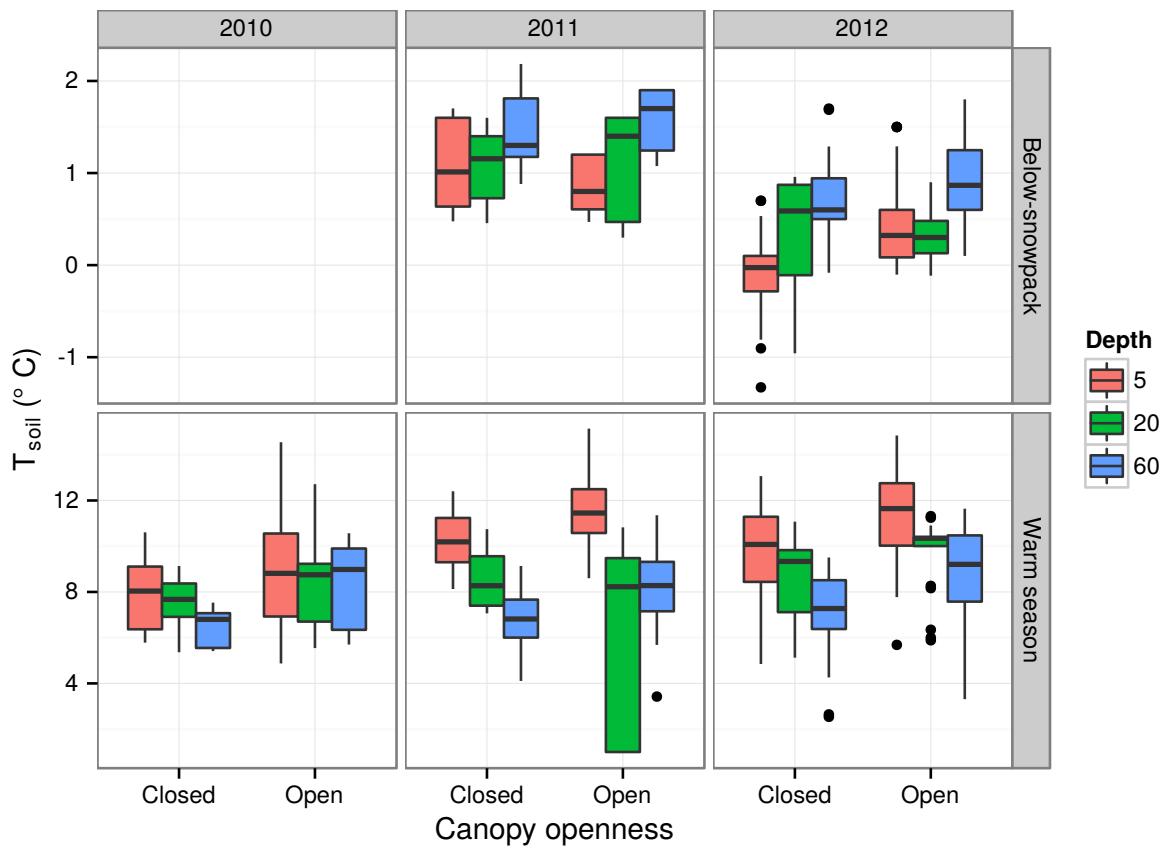


Figure A.2: Comparison of 24 hour mean T_{soil} from soil sensor profiles as in Figure A.1. In this figure, sensor means are split into Open and Closed canopy structure groups.

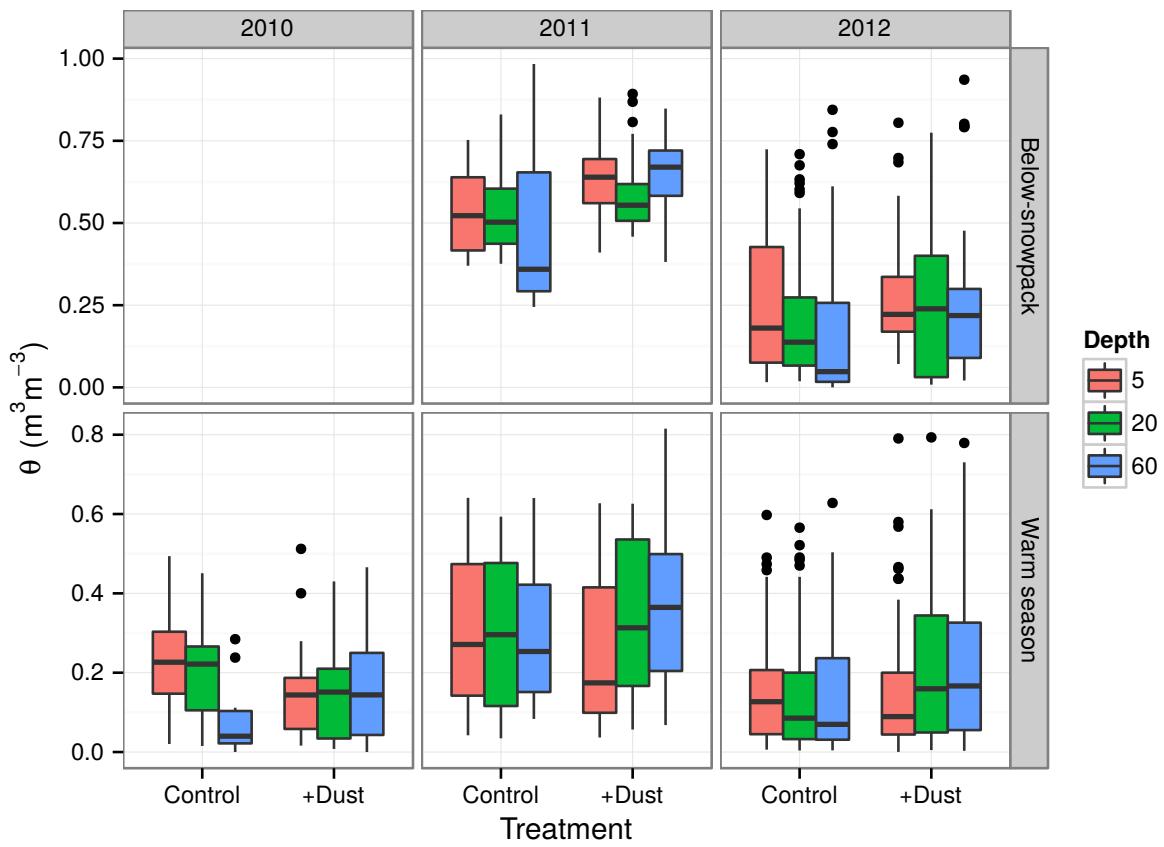


Figure A.3: Comparison of 24 hour mean θ taken from soil sensor profiles as in Figures A.1 and A.2. In this figure sensor means are split into +Dust and Control treatments.

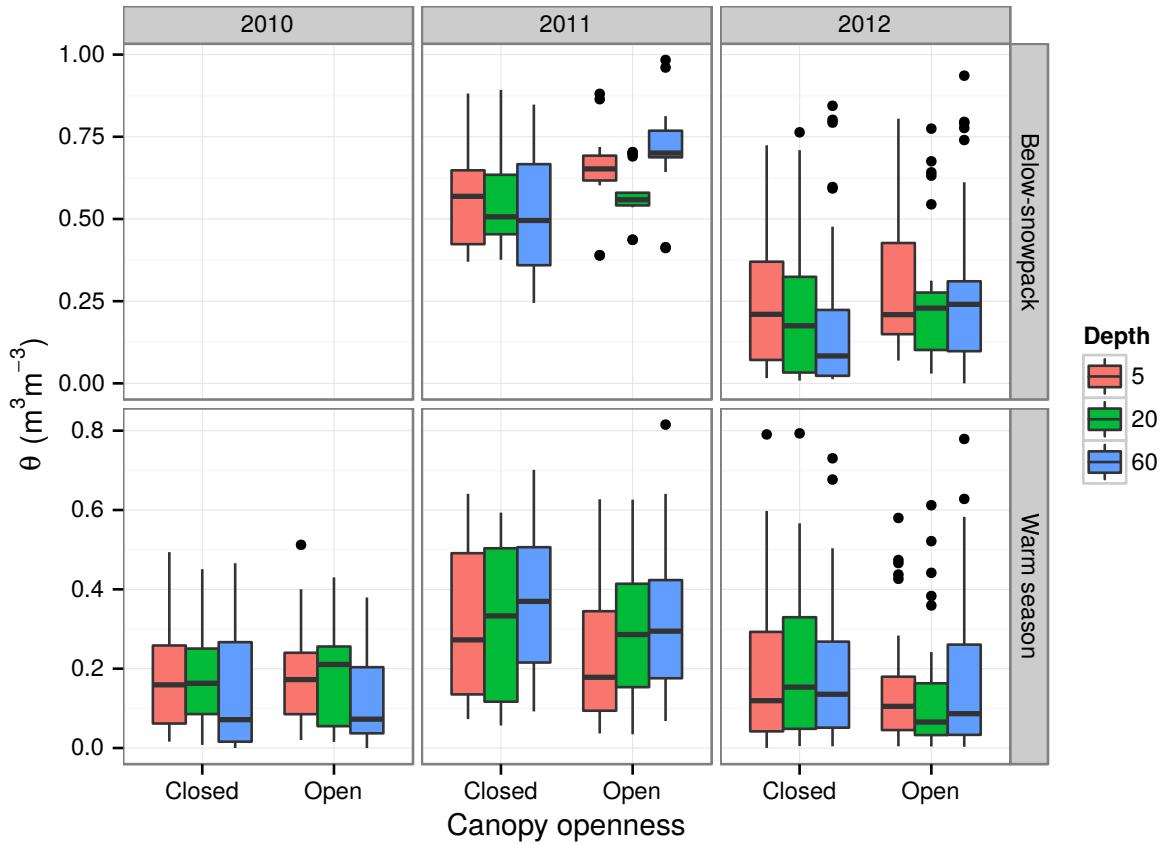


Figure A.4: Comparison of 24 hour mean θ from soil sensor profiles as in Figures A.1, A.2, and A.3. In this figure, sensor means are split into Open and Closed canopy structure groups.

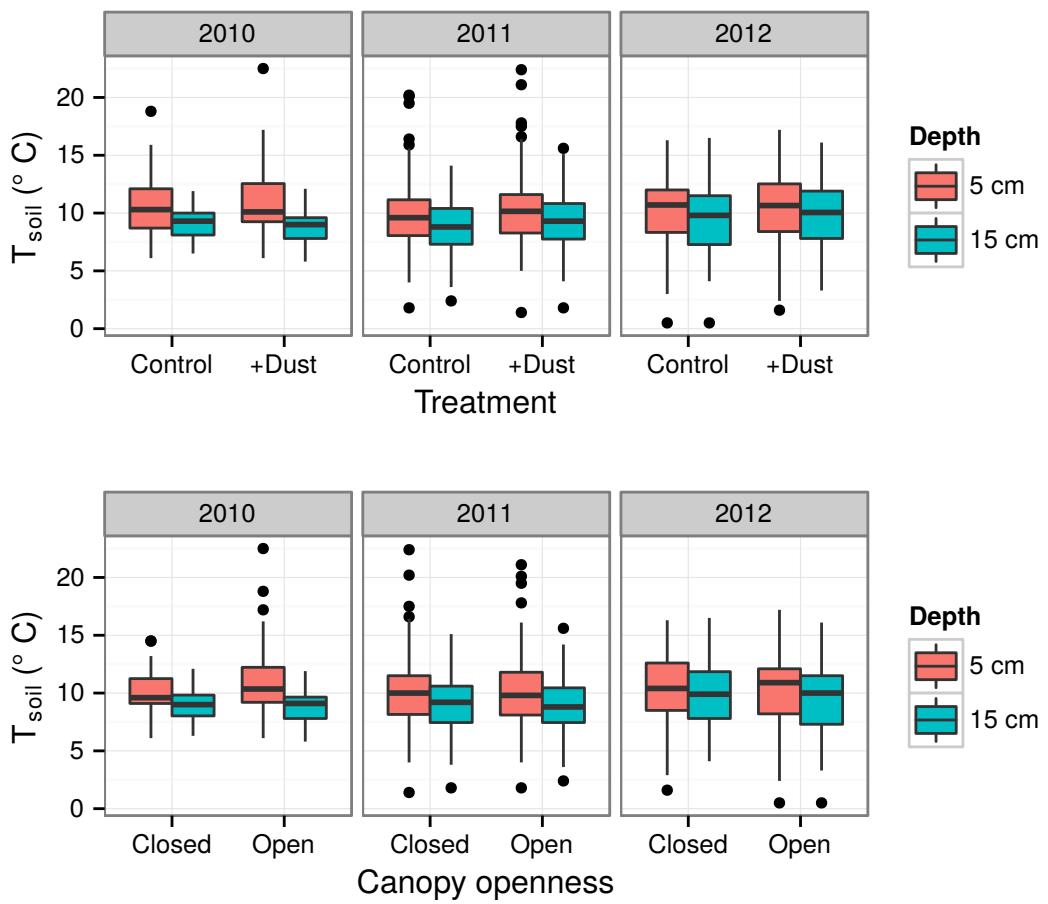


Figure A.5: Comparison of mean T_{soil} measurements made with a handheld probe during warm season R_s measurements (2010–2012). Means are split into +Dust and Control treatments in the top panels and Open and Closed canopy structure groups in the lower panels.

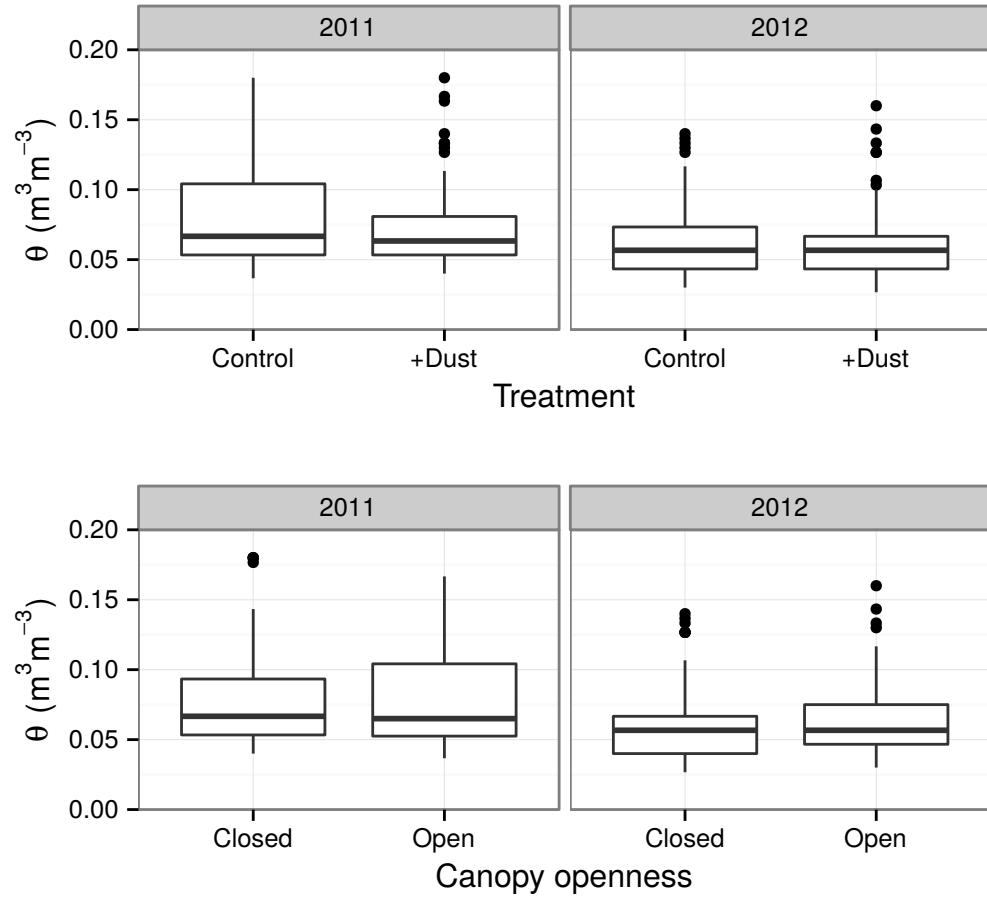


Figure A.6: Comparison of mean θ measurements made with a handheld probe during warm season R_s measurements (2011 & 2012). Means are split into groups as in Figure A.5.

References

- Aanderud ZT, Jones SE, Schoolmaster Jr. DR, Fierer N, Lennon JT. 2013. Sensitivity of soil respiration and microbial communities to altered snowfall. *Soil Biology and Biochemistry* **57** : 217–227.
- Adair EC, Hobbie SE, Hobbie RK. 2010. Single-pool exponential decomposition models: potential pitfalls in their use in ecological studies. *Ecology* **91** : 1225–1236.
- Adair EC, Parton WJ, Del Grosso SJ, Silver WL, Harmon ME, Hall SA, Burke IC, Hart SC. 2008. Simple three-pool model accurately describes patterns of long-term litter decomposition in diverse climates. *Global Change Biology* **14** : 2636–2660.
- Anderegg WRL, Berry JA, Smith DD, Sperry JS, Anderegg LDL, Field CB. 2011. The roles of hydraulic and carbon stress in a widespread climate-induced forest die-off. *Proceedings of the National Academy of Sciences* : 201107891.
- Bales RC, Hopmans JW, O'Geen AT, Meadows M, Hartsough PC, Kirchner P, Hunsaker CT, Beaudette D. 2011. Soil moisture response to snowmelt and rainfall in a sierra nevada mixed-conifer forest. *Vadose Zone Journal* **10** : 786.
- Ballantyne AP, Brahney J, Fernandez D, Lawrence CL, Saros J, Neff JC. 2011. Biogeochemical response of alpine lakes to a recent increase in dust deposition in the southwestern, US. *Biogeosciences* **8** : 2689–2706.
- Biederman JA, Brooks PD, Harpold AA, Gochis DJ, Gutmann E, Reed DE, Pendall E, Ewers BE. 2012. Multiscale observations of snow accumulation and peak snowpack following widespread, insect-induced lodgepole pine mortality. *Ecohydrology* **7** : 150–162.
- Bowling DR, Massman WJ. 2011. Persistent wind-induced enhancement of diffusive CO₂ transport in a mountain forest snowpack. *Journal of Geophysical Research* **116**.
- Brooks P, Williams M, Schmidt S. 1998. Inorganic nitrogen and microbial biomass dynamics before and during spring snowmelt. *Biogeochemistry* **43** : 1–15.
- Brown RD, Mote PW. 2009. The response of northern hemisphere snow cover to a changing climate*. *Journal of Climate* **22** : 2124–2145.
- Brown-Mitic C, Shuttleworth W, Chawn Harlow R, Petti J, Burke E, Bales R. 2007. Seasonal water dynamics of a sky island subalpine forest in semi-arid southwestern united states. *Journal of Arid Environments* **69** : 237–258.
- Clow DW. 2010. Changes in the timing of snowmelt and streamflow in colorado: a response to recent warming. *Journal of Climate* **23** : 2293–2306.
- Conway H, Gades A, Raymond CF. 1996. Albedo of dirty snow during conditions of melt. *Water Resources Research* **32** : 1713–1718.
- Day TA, DeLucia EH, Smith WK. 1989. Influence of cold soil and snowcover on photosynthesis and leaf conductance in two rocky mountain conifers. *Oecologia* **80** : 546–552.
- Dettinger MD, Cayan DR. 1995. Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in california. *Journal of Climate* **8** : 606–623.
- Dyer JL, Mote TL. 2007. Trends in snow ablation over north america. *International Journal of Climatology* **27** : 739–748.

- Ellis CR, Pomeroy JW, Essery RL, Link TE. 2011. Effects of needleleaf forest cover on radiation and snowmelt dynamics in the canadian rocky mountains. *Canadian Journal of Forest Research* **41** : 608–620.
- Fassnacht S, Williams M, Corrao M. 2009. Changes in the surface roughness of snow from millimetre to metre scales. *Ecological Complexity* **6** : 221–229.
- Frazer GW, Canham C, Lertzman K. 1999. Gap light analyzer (GLA), version 2.0: imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs, users manual and program documentation. Simon Fraser University, Burnaby, B.C.; the Institute of Ecosystem Studies, Millbrook, New York.
- Gao H, Tang Q, Shi X, Zhu C, Bohn T, Su F, Sheffield J, Pan M, Lettenmaier D, Wood E. 2010. Water budget record from variable infiltration capacity (VIC) model algorithm theoretical basis document. *Algorithm Theoretical Basis Document for Terrestrial Water Cycle Data Records (in review)*.
- Gleason KE, Nolin AW, Roth TR. 2013. Charred forests increase snowmelt: effects of burned woody debris and incoming solar radiation on snow ablation. *Geophysical Research Letters* **40** : 4654–4661.
- Hahnenberger M, Nicoll K. 2012. Meteorological characteristics of dust storm events in the eastern great basin of utah, U.S.A. *Atmospheric Environment* **60** : 601–612.
- Hamlet AF, Mote PW, Clark MP, Lettenmaier DP. 2005. Effects of temperature and precipitation variability on snowpack trends in the western united states. *Journal of Climate* **18** : 4545–4561.
- Hamlet AF, Mote PW, Clark MP, Lettenmaier DP. 2007. Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western united states. *Journal of Climate* **20** : 1468–1486.
- Hansen J, Nazarenko L. 2004. Soot climate forcing via snow and ice albedos. *Proceedings of the National Academy of Sciences of the United States of America* **101** : 423–428.
- Hardy J, Melloh R, Koenig G, Marks D, Winstral A, Pomeroy J, Link T. 2004. Solar radiation transmission through conifer canopies. *Agricultural and Forest Meteorology* **126** : 257–270.
- Hardy JP, Davis RE, Jordan R, Li X, Woodcock C, Ni W, McKenzie JC. 1997. Snow ablation modeling at the stand scale in a boreal jack pine forest. *Journal of Geophysical Research: Atmospheres* **102** : 29397–29405.
- Hardy JP, Melloh R, Robinson P, Jordan R. 2000. Incorporating effects of forest litter in a snow process model. *Hydrological Processes* **14** : 3227–3237.
- Harmon ME, Silver WL, Fasth B, Chen HUA, Burke IC, Parton WJ, Hart SC, Currie WS. 2009. Long-term patterns of mass loss during the decomposition of leaf and fine root litter: an intersite comparison. *Global Change Biology* **15** : 1320–1338.
- Harpold A, Brooks P, Rajagopal S, Heidbuchel I, Jardine A, Stielstra C. 2012. Changes in snowpack accumulation and ablation in the intermountain west. *Water Resources Research* **48**.
- Hedstrom NR, Pomeroy JW. 1998. Measurements and modelling of snow interception in the boreal forest. *Hydrological Processes* **12** : 1611–1625.
- Hu J, Moore DJP, Burns SP, Monson RK. 2010. Longer growing seasons lead to less carbon sequestration by a subalpine forest. *Global Change Biology* **16** : 771–783.
- Inouye DW, Barr B, Armitage KB, Inouye BD. 2000. Climate change is affecting altitudinal migrants and hibernating species. *Proceedings of the National Academy of Sciences of the United States of America* **97** : 1630–1633.

- Jaeger III CH, Monson RK, Fisk MC, Schmidt SK. 1999. Seasonal partitioning of nitrogen by plants and soil microorganisms in an alpine ecosystem. *Ecology* **80** : 1883–1891.
- Kapnick S, Hall A. 2012. Causes of recent changes in western north american snowpack. *Climate Dynamics* **38** : 1885–1899.
- Koivusalo H, Kokkonen T. 2002. Snow processes in a forest clearing and in a coniferous forest. *Journal of Hydrology* **262** : 145–164.
- Lawler RR, Link TE. 2011. Quantification of incoming all-wave radiation in discontinuous forest canopies with application to snowmelt prediction. *Hydrological Processes* **25** : 3322–3331.
- Lawrence CR, Neff JC. 2009. The contemporary physical and chemical flux of aeolian dust: a synthesis of direct measurements of dust deposition. *Chemical Geology* **267** : 46–63.
- Lawrence CR, Painter TH, Landry CC, Neff JC. 2010. Contemporary geochemical composition and flux of aeolian dust to the san juan mountains, colorado, united states. *Journal of Geophysical Research* **115**.
- Liang X, Lettenmaier DP, Wood EF, Burges SJ. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research: Atmospheres* **99** : 14415–14428.
- Link TE, Marks D. 1999a. Point simulation of seasonal snow cover dynamics beneath boreal forest canopies. *Journal of Geophysical Research: Atmospheres* **104** : 27841–27857.
- Link TE, Marks D. 1999b. Distributed simulation of snowcover mass- and energy-balance in the boreal forest. *Hydrological Processes* **13** : 2439–2452.
- Link TE, Marks D, Hardy JP. 2004. A deterministic method to characterize canopy radiative transfer properties. *Hydrological Processes* **18** : 3583–3594.
- Lipson DA, Schmidt SK, Monson RK. 1999. Links between microbial population dynamics and nitrogen availability in an alpine ecosystem. *Ecology* **80** : 1623–1631.
- Liptzin D, Williams MW, Helmig D, Seok B, Filippa G, Chowanski K, Hueber J. 2009. Process-level controls on CO₂ fluxes from a seasonally snow-covered subalpine meadow soil, niwot ridge, colorado. *Biogeochemistry* **95** : 151–166.
- Litaor MI, Williams M, Seastedt TR. 2008. Topographic controls on snow distribution, soil moisture, and species diversity of herbaceous alpine vegetation, niwot ridge, colorado. *Journal of Geophysical Research-Biogeosciences* **113** : 10.
- Logan JA, Macfarlane WW, Willcox L. 2010. Whitebark pine vulnerability to climate-driven mountain pine beetle disturbance in the greater yellowstone ecosystem. *Ecological Applications* **20** : 895–902.
- Lundquist JD, Lott F. 2008. Using inexpensive temperature sensors to monitor the duration and heterogeneity of snow-covered areas. *Water Resources Research* **44**.
- Marks D, Dozier J. 1992. Climate and energy exchange at the snow surface in the alpine region of the sierra nevada: 2. snow cover energy balance. *Water Resources Research* **28** : 3043–3054.
- Massman W. 1998. A review of the molecular diffusivities of H₂O, CO₂, CH₄, CO, o₃, SO₂, NH₃, N₂O, NO, and NO₂ in air, o₂ and n₂ near STP. *Atmospheric Environment* **32** : 1111–1127.

- McCabe GJ, Clark MP. 2005. Trends and variability in snowmelt runoff in the western united states. *Journal of Hydrometeorology* **6** : 476–482.
- Melloh RA, Hardy JP, Bailey RN, Hall TJ. 2002. An efficient snow albedo model for the open and sub-canopy. *Hydrological Processes* **16** : 3571–3584.
- Melloh RA, Hardy JP, Davis RE, Robinson PB. 2001. Spectral albedo/reflectance of littered forest snow during the melt season. *Hydrological Processes* **15** : 3409–3422.
- Miller ME, Bowker MA, Reynolds RL, Goldstein HL. 2012. Post-fire land treatments and wind erosion – lessons from the milford flat fire, UT, USA. *Aeolian Research* **7** : 29–44.
- Molotch N, Brooks P, Burns S, Litvak M, Monson R, McConnell J, Musselman K. 2009. Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests. *Ecohydrology* **2** : 129–142.
- Monson RK, Burns SP, Williams MW, Delany AC, Weintraub M, Lipson DA. 2006a. The contribution of beneath-snow soil respiration to total ecosystem respiration in a high-elevation, subalpine forest. *Global Biogeochemical Cycles* **20** : GB3030, doi:10.1029/2005GB002684, 2006.
- Monson RK, Lipson DL, Burns SP, Turnipseed AA, Delany AC, Williams MW, Schmidt SK. 2006b. Winter forest soil respiration controlled by climate and microbial community composition. *Nature* **439** : 711–714.
- Mote PW. 2006. Climate-driven variability and trends in mountain snowpack in western north america. *Journal of Climate* **19** : 6209–6220.
- Mote PW, Hamlet AF, Clark MP, Lettenmaier DP. 2005. Declining mountain snowpack in western north america. *Bulletin of the American Meteorological Society* **86** : 39–49.
- Moyes AB, Schauer AJ, Siegwolf RTW, Bowling DR. 2010. An injection method for measuring the carbon isotope content of soil carbon dioxide and soil respiration with a tunable diode laser absorption spectrometer. *Rapid Communications in Mass Spectrometry* **24** : 894–900.
- Munson SM, Belnap J, Okin GS. 2011. Responses of wind erosion to climate-induced vegetation changes on the colorado plateau. *Proceedings of the National Academy of Sciences* **108** : 3854–3859.
- Musselman KN, Molotch NP, Margulis SA, Kirchner PB, Bales RC. 2012a. Influence of canopy structure and direct beam solar irradiance on snowmelt rates in a mixed conifer forest. *Agricultural and Forest Meteorology* **161** : 46–56.
- Musselman KN, Molotch NP, Margulis SA, Lehning M, Gustafsson D. 2012b. Improved snowmelt simulations with a canopy model forced with photo-derived direct beam canopy transmissivity. *Water Resources Research* **48**.
- Myneni R, Ramakrishna R, Nemani R, Running S. 1997. Estimation of global leaf area index and absorbed par using radiative transfer models. *IEEE Transactions on Geoscience and Remote Sensing* **35** : 1380–1393.
- Nayak A, Marks D, Chandler DG, Seyfried M. 2010. Long-term snow, climate, and streamflow trends at the reynolds creek experimental watershed, owyhee mountains, idaho, united states. *Water Resources Research* **46** : W06519.
- Neff JC, Ballantyne AP, Farmer GL, Mahowald NM, Conroy JL, Landry CC, Overpeck JT, Painter TH, Lawrence CR, Reynolds RL. 2008. Increasing eolian dust deposition in the western united states linked to human activity. *Nature Geoscience* **1** : 189–195.

- Ozgul A, Childs DZ, Oli MK, Armitage KB, Blumstein DT, Olson LE, Tuljapurkar S, Coulson T. 2010. Coupled dynamics of body mass and population growth in response to environmental change. *Nature* **466** : 482–485.
- Painter TH, Barrett AP, Landry CC, Neff JC, Cassidy MP, Lawrence CR, McBride KE, Farmer GL. 2007. Impact of disturbed desert soils on duration of mountain snow cover. *Geophysical Research Letters* **34**.
- Painter TH, Deems JS, Belnap J, Hamlet AF, Landry CC, Udall B. 2010. Response of colorado river runoff to dust radiative forcing in snow. *Proceedings of the National Academy of Sciences* **107** : 17125–17130.
- Pomeroy J, Rowlands A, Hardy J, Link T, Marks D, Essery R, Sicart J, Ellis C. 2008. Spatial variability of short wave irradiance for snowmelt in forests. *Journal of Hydrometeorology* **9** : 1482–1490.
- Pomeroy JW, Dion K. 1996. Winter radiation extinction and reflection in a boreal pine canopy: measurements and modelling. *Hydrological Processes* **10** : 1591–1608.
- Pomeroy JW, Marks D, Link T, Ellis C, Hardy J, Rowlands A, Granger R. 2009. The impact of coniferous forest temperature on incoming longwave radiation to melting snow. *Hydrological Processes* **23** : 2513–2525.
- Pugh E, Small E. 2012. The impact of pine beetle infestation on snow accumulation and melt in the headwaters of the colorado river. *Ecohydrology* **5** : 467–477.
- Regonda SK, Rajagopalan B, Clark M, Pitlick J. 2005. Seasonal cycle shifts in hydroclimatology over the western united states. *Journal of Climate* **18** : 372–384.
- Riveros-Iregui DA, McGlynn BL. 2009. Landscape structure control on soil CO₂ efflux variability in complex terrain: scaling from point observations to watershed scale fluxes. *Journal of Geophysical Research* **114** : G02010–G02010.
- Schmidt S, Wilson K, Monson R, Lipson D. 2009. Exponential growth of “snow molds” at sub-zero temperatures: an explanation for high beneath-snow respiration rates and q 10 values. *Biogeochemistry* **95** : 13–21.
- Seager R, Vecchi GA. 2010. Greenhouse warming and the 21st century hydroclimate of southwestern north america. *Proceedings of the National Academy of Sciences* **107** : 21277–21282.
- Sicart JE, Essery RLH, Pomeroy JW, Hardy J, Link T, Marks D. 2004. A sensitivity study of daytime net radiation during snowmelt to forest canopy and atmospheric conditions. *Journal of Hydrometeorology* **5** : 774–784.
- Skiles SM, Painter TH, Deems JS, Bryant AC, Landry CC. 2012. Dust radiative forcing in snow of the upper colorado river basin: 2. interannual variability in radiative forcing and snowmelt rates. *Water Resources Research* **48** : W07522.
- Sommerfeld RA, Massman WJ, Musselman RC, Mosier AR. 1996. Diffusional flux of CO₂ through snow: spatial and temporal variability among alpine-subalpine sites. *Global Biogeochemical Cycles* **10** : 473–482.
- Steenburgh WJ, Massey JD, Painter TH. 2012. Episodic dust events of utah’s wasatch front and adjoining region. *Journal of Applied Meteorology and Climatology* **51** : 1654–1669.
- Steltzer H, Landry C, Painter T, Anderson J, Ayres E. 2009. Biological consequences of earlier snowmelt from desert dust deposition in alpine landscapes. *Proceedings of the National Academy of Sciences of the United States of America* **106** : 11629–11634.
- Stewart IT, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western north america. *Journal of Climate* **18** : 1136–1155.

- Tague C, Heyn K, Christensen L. 2009. Topographic controls on spatial patterns of conifer transpiration and net primary productivity under climate warming in mountain ecosystems. *Ecohydrology* **2** : 541–554.
- Warren SG, Wiscombe WJ. 1980. A model for the spectral albedo of snow. II: snow containing atmospheric aerosols. *Journal of the Atmospheric Sciences* **37** : 2734–2745.
- Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. 2006. Warming and earlier spring increase western US forest wildfire activity. *Science* **313** : 940–943.
- Winkler R, Boon S, Zimonick B, Baleshta K. 2010. Assessing the effects of post-pine beetle forest litter on snow albedo. *Hydrological Processes* **24** : 803–812.
- Zhang T. 2005. Influence of the seasonal snow cover on the ground thermal regime: an overview. *Reviews of Geophysics* **43** : 23.