FOREST CANOPIES INFLUENCE THE DEPOSITION AND CONCENTRATION OF DEBRIS, LIGHT-ABSORBING IMPURITIES, AND POLLUTANTS IN THE SIERRA NEVADA SNOWPACK

Kelly E. Gleason[1], Joseph R. McConnell[2], Monica M. Arienzo[2], Nathan Chellman[2], Christine Hedge[2], and Adrian Harpold[3]

ABSTRACT

Forests are typically warmer than surrounding open areas, particularly in warm mid-latitude climates, and forest canopies radiate longwave radiation throughout the winter, driving mid-winter snowmelt throughout the snow accumulation period. During winter, forest canopies shed organic debris onto the snowpack below, which concentrates on the snow surface during snowmelt, and may further accelerate snowmelt due to reduced snow albedo. Snowpack, as long as it remains frozen, serves not only as a reservoir of water, but also as a time-resolved repository of local and regionally-sourced particles, including black carbon (BC), dust, organic debris, and pollutants. We evaluated how forests may alter the depositional process of particles and pollutants into the snowpack beneath forest canopies, as well as how warm conditions in forests influence the redistribution of particles and pollutants in the snowpack. We measured BC, dust, organic debris, and the elemental composition of pollutants throughout snowpacks in an open meadow and beneath a nearby pine forest each month during winter and early spring of 2017 at the Sagehen Experimental Forest in the Northern Sierra Nevada Mountains.

Overall, snowpacks under the forest canopy had much greater concentrations of organic and inorganic debris, which concentrated on the snowpack surface throughout the snow season. While concentrations of BC, dust, and pollutants were similar under the forest canopy and in the open meadow during winter. During spring snowmelt, BC and dust became concentrated on the snowpack surface under the forest canopy and in the open meadow. Phosphorus and sulfur concentrations were greater under the forest canopy, while bismuth was greater in the open meadow during spring snowmelt. Nitrate concentrations on the snowpack surface were similar between sites, but reduced earlier in the meadow likely due to enhanced photodegradation. Throughout the snowpack season, debris, BC, dust and pollutants were much more variable under the forest canopy than the open meadow. Forest canopies serve as a source of large debris to the snowpack, but have little influence over the deposition and concentration of more regionally sourced light absorbing particles in the snowpack, and differential influence on the deposition and concentration of pollutants in the snowpack. (KEYWORDS: canopy debris, snow albedo, accelerated snowmelt, pollutant concentrations, black carbon, Sagehen Experimental Forest)

INTRODUCTION

Mountain snowpack serves as an important water subsidy for forests, fish, agriculture, recreation, and human consumption across the western US and beyond (Trujillo et al., 2012; Buytaert et al.; 2011, Tague and Grant; 2009). Warm snow, where average winter temperatures are above -1ºC dominates much of the mountainous maritime western US, while much of the western headwater regions are forested (Figure 1). With warming air temperatures, warm snow is increasingly vulnerable, melting earlier and faster, reducing this water storage capacity of seasonal snowpack (Pederson et al.; 2013, Abatzoglou, 2011). While simultaneously, and at least in part due to fire suppression, forested regions may be expanding and becoming denser over time.

Forest canopies influence the volume of snowpack water storage and the timing of snowmelt in different ways during the snow accumulation and snow ablation periods during the winter season (Varhola et al., 2010). Forest canopies influence snow accumulation by intercepting falling snow which can be blown away and/or lost through sublimation (Musselman et al., 2008; Pomeroy et al., 2002). Depending on the elevation and forest structure, less snow can accumulate beneath forest canopies than in open meadows, particularly in warmer snow environments where the snow is sticky and gets caught in the canopy (Roth and Nolin, 2017). However, much of this snow in warmer climates, may melt in the canopy and refreeze as it drips into the snowpack.

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Forest canopies influence snow ablation by altering the snowpack energy balance both directly and indirectly (Lundquist et al., 2013; Musselman et al. 2012). Forest canopies block incoming solar radiation through shading, reducing the sunlight energy available to the snowpack energy balance. Forest canopies increase longwave radiation absorbed by the snowpack due to reemission of heat energy from the tree trunks branches and needles. Forest canopies also reduce the turbulent fluxes due to sheltering and reduction of wind speeds within the forest.

Forests canopies also shed organic debris (i.e. needles, branches, epiphytes, etc) onto the snowpack, which concentrates during snowmelt, visibly darkening the snow surface, and reducing the snow surface albedo or reflectivity of the snowpack (Gleason et al., 2013; Hardy et al., 2004; Melloh et al., 2002). This reduction in snow surface albedo which may or may not influence the overall snowpack energy balance because insolation is reduced beneath the forest canopy, and snow albedo is not a critical in the longwave emission of snowpack.

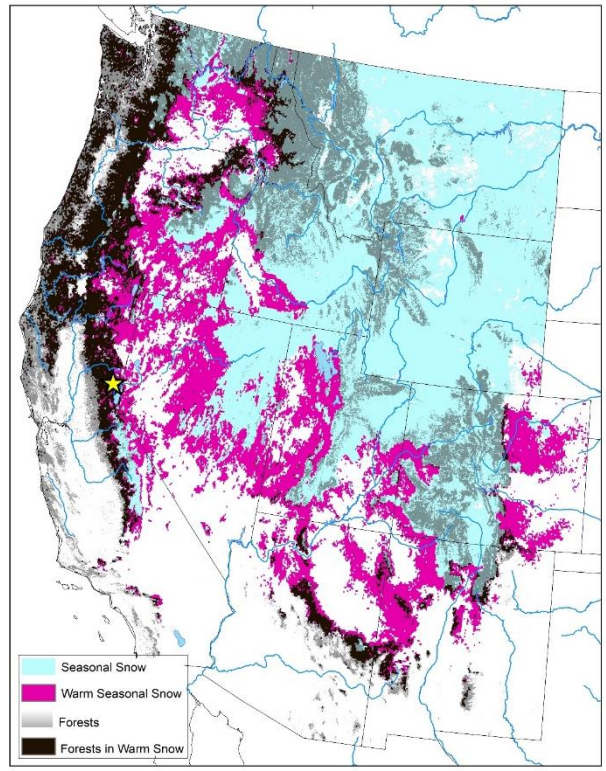

Figure 1. Forests in warm seasonal snow (black in magenta) across the Western US.

Snowpack, as long as it remains frozen, serves not only as a reservoir of water, but also as a time-resolved repository of local and regionally sourced particles, including black carbon (BC), dust, organic debris, and pollutants, transported to snow-covered mountains during winter. Many of these are light absorbing (such as BC and dust) and result in regional-scale darkening of snow surface albedo, which accelerates snowmelt, and advances the timing of snow disappearance (Painter et al., 2012; Skiles et al., 2012; Painter et al., 2010; Flanner et al., 2009). While other regionally-sourced particles (such as heavy metals and pollutants) may result in widespread contamination of seasonal snowpack, which ultimately melts and becomes a downstream water resource such as drinking water. As the snowpack melts, large and hydrophobic particles may concentrate on the snowpack surface, while others are entrained in meltwater and immediately flushed from the snowpack during melt (Doherty et al., 2013). Warm forested snowpacks are known to experience periodic mid-winter melt events in addition to rain-on-snow events, however we do not understand how these forests in warm snow climates may influence the redistribution of particles throughout the snow season and hence our ability to accurately measure particle and pollutant concentrations in the snowpack.

In order to evaluate the influence of the forest canopy on the concentration and redistribution of particles in warm snowpacks, we measured BC, dust, organic debris, and the elemental composition of pollutants in snowpack in an open meadow and beneath a nearby pine forest each month during winter and early spring of 2017 at the Sagehen Experimental Forest in the Northern Sierra Nevada Mountains. Our research was driven by the question: Do forest canopies in warm snow climates influence the deposition, surface concentration, and total concentration of organic and inorganic debris, light-absorbing particles, and pollutants in the snowpack throughout the winter and early spring?

METHODS

At the Sagehen Creek Field Station located on the eastern slope of the Sierra Nevada Mountains, we sampled snow in the forest and the nearby open meadow each month including February, March, April, and May until the end of the 2017 snow season. Each month in these two nearby sites, we collected snow surface samples, snow cores of the entire snowpack, and snow pits samples of the complete snowpack. A long-running micro-meteorological station in the open meadow site provides temperature data for the period of record. Snow water

equivalent data was obtained from the nearby Independence Lake SNOTEL station. During the winter of 2017, snowpack was deep in the Sagehen Experimental Research Station, although there were multiple strong rain-on-snow events during February and March (Figure 2).

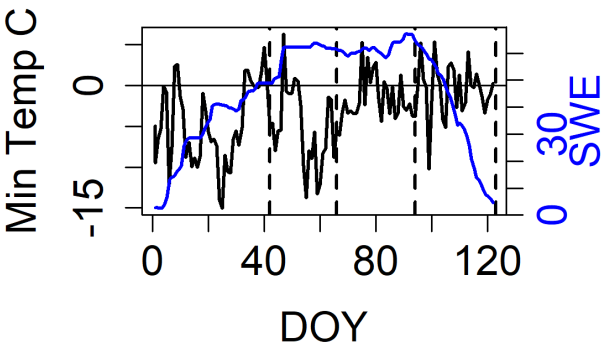

Figure 2. Four snow sampling times (dashed lines), air temperature, and snow water equivalent from Sagehen during winter of 2017.

Snow samples were brought back to the lab, where they were cleaned and prepared for analysis in a freezer at -15º C. Snow cores were cut into 10-cm increments to match the sampling protocol of snow pit sampling, and then cut into three subsamples to evaluate three size classes of particulates in the snow throughout the snowpack. One subsample was filtered using the gravimetric method to measure large organic and inorganic debris particles in the snow using loss-on-ignition. The second subsample was evaluated for BC, dust, stable isotopes, and NO3 using the continuous flow analysis system at the McConnell Ice Core Laboratory at the Desert Research Institute (McConnell et al., 2007a, McConnell et al., 2007b). The third subsamples was evaluated for the elemental geochemical composition of heavy metals and other pollutants including (P, S, Bi) using an Inductively Coupled Plasma Mass Spectrometer.

RESULTS

Total whole snowpack concentrations of organic and inorganic debris indicated consistent deposition rates through the snow season, but much greater concentrations overall in the snowpack beneath the forest canopy than in the open meadow. Total whole snowpack concentrations of light absorbing particles indicated consistent deposition rates of BC and dust which accumulated in the snowpack through the winter and early spring, and were not different beneath the forest canopy and in the open meadow. Total whole snowpack concentrations of pollutants indicated consistent deposition rates of phosphorus, sulfur, and bismuth through the winter and early spring, and were not different beneath the forest canopy and in the open meadow. Nitrate behaved differently than the other pollutants, and concentrations in the entire snowpack decreased significantly throughout the season, but particularly in April and May indicating that nitrate likely photodegraded and was flushed from the snowpack during initial snowmelt beneath the forest canopy and in the open meadow.

The forest canopy shed large quantities of organic and inorganic debris which accumulated in the snowpack and concentrated on the snowpack surface during snowmelt in April and May (Figure 3). Organic debris concentrations on the snowpack surface in the forest site were twelve times the concentrations measured in the open meadow site ($p<0.001$). Inorganic debris concentrations on the snowpack surface in the forest site were five times the concentrations measured in the open meadow site ($p<0.001$). The variability of the organic and inorganic debris concentrations was also much greater in the forest than in the meadow.

In snow surface samples collected in February and March, d18O values were enriched in the forest compared to the open meadow ($p=0.01$), indicating sublimation of intercepted snow likely occurred from within the forest canopy before unloading into snowpack. No difference in d18O values was observed during April and May between the forest and open

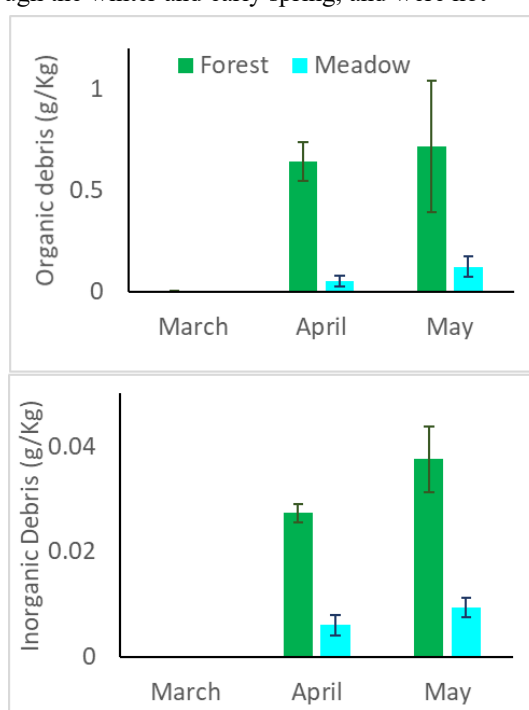

Figure 3. Organic and inorganic debris concentrated on snowpack surface in forest and open meadow during 2017.

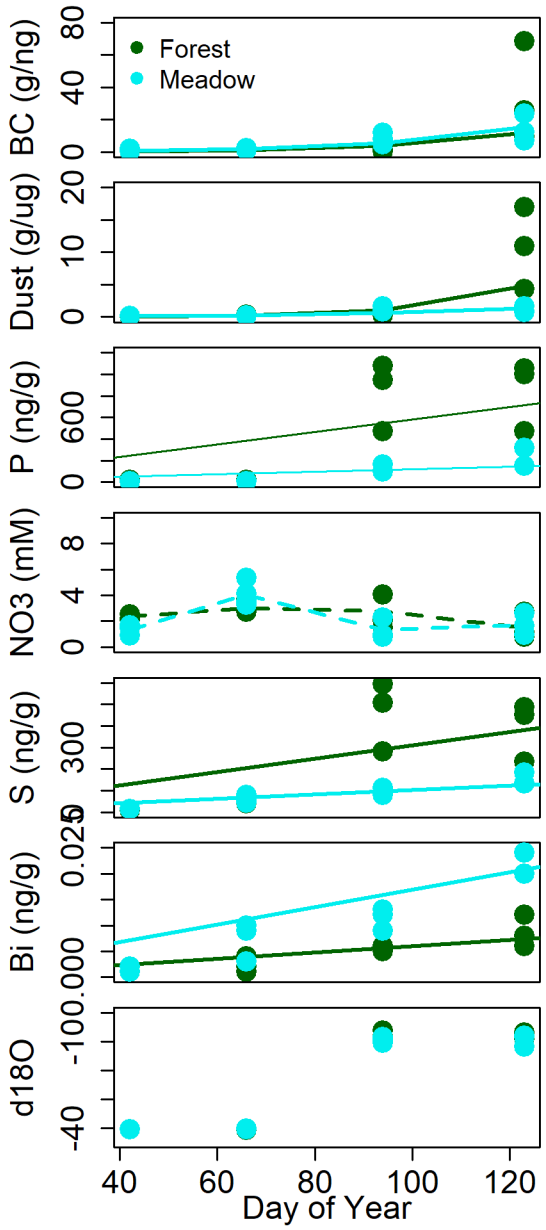

Figure 4. Black carbon, dust, phosphorus, nitrate, sulfur, bismuth, and d18O isotopes measured in snow surface samples.

meadow sites. Between the March and April sampling periods, a profound shift in the d18O values measured in samples collected from the snowpack surface was observed, indicating snowmelt was likely occurring and preferentially removing the heavier d18O from the snowpack in the forest and the open meadow site. The course temporal resolution of our sampling does not distinguish the influence of melt or rain on the isotopic concentrations. We were surprised there was no difference in the isotopic signatures of the snowpack beneath the forest canopy and in the open meadow during April and May.

The snow surface concentrations of BC and dust were similar beneath the forest canopy and in the open meadow, indicating minimal local forest effects on the deposition and concentration of these light absorbing particles overall (Figure 4). Although the variability of BC and dust was much greater on the snowpack surface in the forest than in the open meadow. Snow surface concentrations of BC and dust increased logarithmically throughout the winter and spring, indicating these hydrophobic particles were not entrained in melt water, but concentrated on the snowpack surface particularly during spring (BC: Forest (R2=0.52, p-value=0.004), Open (R2=0.86, p-value=0.001), dust: Forest (R2=0.52, p-value=0.004), Open (R2=0.81, p-value=0.001).

Snow surface concentrations of phosphorus were two times greater during winter, and four times greater during spring under the forest canopy than in the open meadow (Figure 4). There was no difference in the snow surface concentrations of sulfur between sites during winter, but during spring sulfur concentrations on the snow surface were four times greater under the forest canopy. Despite the anticipated loss of pollutants during snowmelt phosphorus and sulfur concentrated on the snow surface throughout the winter and particularly during spring (P: Forest (R2=0.33, p-value=0.03), Open (R2=0.86, p-value<0.001), S: Forest (R2=0.75, p-value<0.001), Open (R2=0.91, p-value<0.001).

Snow surface concentrations of bismuth were similar between sites during winter, but were two times greater in the open meadow than beneath the forest canopy during spring snowmelt (Figure 4). In both sites, but particularly in the forest, the concentrations of bismuth on the snow surface increased throughout winter and spring (B: Forest (R2=0.89, p-value<0.001), Open (R2=0.33, p-value=0.04). Nitrate concentrations on the snowpack surface demonstrated a cubic pattern over time indicating a slight increase in concentrations during the cloudy winter months. While during spring, concentrations decreased particularly in the open meadow, likely due to photodegradation as solar irradiance increased as well as flushing from the snowpack during snowmelt (N: Forest (R2=0.39, p-value=0.07), Open (R2=0.76, p-value=0.003).

DISCUSSION

Forest canopies in warm snow climates influenced the deposition, surface concentration, and total concentration of impurities in snowpack particularly during the snowmelt period, and differently depending on the chemical and structural characteristics of the individual impurities. Forest canopies shed organic and inorganic

debris which accumulates in the snowpack and concentrates on the snowpack surface during snowmelt within the forest canopy, with little influence to the nearby open meadow. The size and mass of this debris likely prevented it being transported far from the forest canopy by wind redistribution so remains primarily within the forest perimeter.

Forest canopies had no influence on the deposition of BC and dust into the snowpack or the concentration of the light-absorbing particles on the snowpack surface. BC and dust concentrated on the snowpack surface similarly throughout the winter and spring in both the forest and open meadow. These particles are typically hydrophobic and unlikely to get entrained in meltwater and therefore concentrate on the snowpack surface during snowmelt. Concentration of these light absorbing particles on the snowpack surface during snowmelt likely darkens the snow surface albedo, increasing net shortwave radiation of the snowpack where solar radiation not shaded from the snowpack surface. Pollutant concentrations were similar in snowpacks beneath the forest canopy and in the open meadow during the winter accumulation period, however during the spring ablation period, phosphorus and sulfur were greater in the forest, but bismuth was greater in the meadow. Nitrate concentrations decreased over time in snowpacks under the forest canopy and in the open meadow.

Forest canopies are known to decrease the net shortwave radiation and increase the net longwave radiation of snow, although the gross impact to the overall snowpack energy budget varies depending on the forest structure, the snow climate, and the seasonal and interannual variability in weather conditions. Therefore we were surprised by these results that the concentration of BC, dust, and pollutants was similar in snowpacks beneath the forest canopy and in the open meadow. Forest canopies serve primarily as a source of large debris, but have little influence over the deposition and concentration of more regionally-sourced light absorbing impurities in snowpack, and differential influence on the deposition and concentration of pollutants in snowpack.

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