**Variable effects of forest canopies on snow processes in a
valley of the central Spanish Pyrenees**

Running head: Variability in the snow responses to forest.

Alba Sanmiguel-Vallelado¹, Juan Ignacio López-Moreno¹, Enrique Morán-Tejeda²,
Esteban Alonso-González¹, Francisco M. Navarro-Serrano¹, Ibai Rico³, J. Julio
Camarero¹

¹ Pyrenean Institute of Ecology, IPE-CSIC, Avda. Montañana 1005, 50059 Zaragoza,
Spain

² Department of Geography, University of the Balearic Islands, Carr. de Valldemossa km
7.5, 07122 Palma de Mallorca, Spain

³ Department of Geography, Prehistory and Archaeology, University of the Basque
Country, Tomás y Valiente s/n, 01006 Vitoria-Gasteiz, Spain

Acknowledgements

This study was supported by the projects: “*Bosque, nieve y recursos hídricos en el Pirineo ante el cambio global*” funded by Fundación Iberdrola, and IBERNIEVE [CGL2014-52599-P] and HIDROIBERNIEVE [CGL2017-82216-R] funded by the Spanish Ministry of Economy and Competitiveness. A. Sanmiguel-Vallelado and F. Navarro-Serrano were supported by pre-doctoral University Professor Training grants [FPU16/00902, FPU15/00742] funded by the Spanish Ministry of Education, Culture and Sports. E. Alonso-González was supported by a pre-doctoral FPI grant [BES-2015-071466] funded by the Spanish Ministry of Economy and Competitiveness. We thank Dr. Maite Gartzia for kindly providing the potential solar radiation data series. We also sincerely thank colleagues, friends and relatives who helped during the field surveys.

Variable effects of forest canopies on snow processes in a valley of the central Spanish Pyrenees

Abstract

Snowpacks and forests have complex interactions throughout the large range of altitudes where they co-occur. However, there are no reliable data on the spatial and temporal interactions of forests with snowpacks, such as those that occur in nearby areas that have different environmental conditions and those that occur during different snow seasons. This study monitored the interactions of forests with snowpacks in four forest stands in a single valley of the central Spanish Pyrenees during three consecutive snow seasons (2015/16, 2016/17, 2017/18). Daily snow depth data from time-lapse cameras were compared with snow data from field surveys that were performed every 10 to 15 days. These data thus provided information on the spatial and temporal changes of snow-water equivalent (SWE). The results indicated that forest had the same general effects on snowpack in each forest stand and during each snow season. On average, forest cover reduced the duration of snowpack by 17 days, reduced the cumulative SWE of the snowpack by about 60%, and increased the spatial heterogeneity of snowpack (coefficient of variation: 190%). Overall, forest cover reduced SWE total accumulation by 40% and the rate of SWE accumulation by 25%. The forest-mediated reduction of the accumulation rate, in combination with the occasional forest-mediated enhancement of melting rate, explained the reduced duration of snowpacks beneath forest canopies. However, the magnitude and timing of certain forest effects on snowpack had significant spatial and temporal variations. This variability must be considered when selecting the location of an experimental site in a mountainous area, because the study site should be representative

of surrounding areas. The same considerations apply when selecting a time period for study.

Keywords: mountain forest, snowpack, spatial and temporal variability, SWE.

For Peer Review

1. Introduction

The snowpack of a mountain plays a fundamental role in several ecological and hydrological processes, in that it provides water for forest growth, and it also affects the water cycles and economies of mid-latitude mountainous regions (Barnett, Adam, & Lettenmaier, 2005; Beniston, 2012; Jones, Pomeroy, Walker, & Hoham, 2001; Pulliainen et al., 2017). Such is the case in the Mediterranean basin, in which winter snow dynamics influence the streamflow of many rivers (Darwish et al., 2015; Gil'ad & Bonne, 1990; López & Justríbó, 2010; López-Moreno & García-Ruiz, 2004; Morán-Tejeda, Lorenzo-Lacruz, López-Moreno, Rahman, & Beniston, 2014; N'da et al., 2016; Sanmiguel-Valladolid, Morán-Tejeda, Alonso-González, & López-Moreno, 2017), and water from spring snowmelt is an essential resource in the lower watersheds, which are drought-prone regions (Ceballos-Barbancho, Morán-Tejeda, Luengo-Ugidos, & Llorente-Pinto, 2008; García-Ruiz, López-Moreno, Vicente-Serrano, Lasanta-Martínez, & Beguería, 2011; López-Moreno et al., 2014).

The variable climate of the mountainous headwaters induces high inter- and intra-annual variability in snowpack characteristics (i.e., distribution, depth, density, and snow-water equivalent [SWE]) (Fayad et al., 2017). The characteristics of the snowpack also depend on interactions between topography and forest cover (Huerta, Molotch, & McPhee, 2019; Jenicek, Pevna, & Matejka, 2018; Jost, Weiler, Gluns, & Alila, 2007). Forest cover reduces snow accumulation on the ground because the tree canopies intercept some of the snowfall (Storck, Lettenmaier, & Bolton, 2002). Thus, the snowpack is smaller in forested areas than open sites (Moeser, Stähli, & Jonas, 2015; Veatch, Brooks, Gustafson, & Molotch, 2009). Snow that is intercepted by the forest canopy may return to the atmosphere by sublimation or may reach the ground as it melts or by direct mass release (Storck, 2000). The efficiencies of canopy interception and

subsequent process depend on local climate and forest structure (Varhola, Coops, Weiler, & Moore, 2010). Furthermore, forest cover influences snow melt by altering the energy balance (Nakai, Sakamoto, Terajima, Kitamura, & Shirai, 1999). For example, forested areas have reduced turbulent heat transfer because of their reduced wind speeds (Marks, Kimball, Tingey, & Link, 1998; Yamazaki & Kondo, 1992). The forest canopy can also reduce energy inputs by shading the snowpack from solar radiation (Ellis, 2011; Musselman, Molotch, & Brooks, 2008) and the snowpack beneath a canopy receives increased long-wave radiation from trees (Pomeroy et al., 2009), which have higher rates of emissivity than the atmosphere (Essery, Pomeroy, Ellis, & Link, 2008; Lawler & Link, 2011). In addition, litter on the snow surface (needles, leaves, etc.) can increase the net radiation during the melting period due to a reduction in the snow albedo (Hardy, Melloh, Robinson, & Jordan, 2000).

The Pyrenees, a mountain range located in the transition of the temperate-continental Atlantic-Eurosiberian and mild-dry Mediterranean climate, has a snowpack above 1600 m a.s.l. that usually lasts until late spring (López-Moreno et al., 2010). In the central Spanish part of this range, the dominant trees in the subalpine forests are mountain pine (*Pinus uncinata* Ram.) from 1600 to 2500 m a.s.l. and Scots pine (*Pinus sylvestris* L.) from 1200 to 1900 m a.s.l. (Ruiz de la Torre & Ceballos, 1979). Therefore, snowpack and forests interact at altitudes of 1600 to 2500 m a.s.l. Most of the Pyrenees are in this altitudinal band, and elevations only occasionally exceed 3000 m a.s.l. However, few studies have examined the impact of forest on snow in the Spanish Pyrenees, despite the climatically transitional nature of this range, which could make it vulnerable to dry conditions in a warmer future (López-Moreno & Latron, 2008a; López-Moreno & Latron, 2008b; Revuelto, López-Moreno, Azorín-Molina, Alonso-González, & Sanmiguel-Valladolid, 2016). Examination of the impact of the forest canopy on snow processes in

the Pyrenees will improve our understanding of hydrological responses to future hydroclimatic changes (climate warming) in this region (El Kenawy, López-Moreno, & Vicente-Serrano, 2012; López-Moreno et al., 2010; Morán-Tejeda et al., 2014).

Previous studies have documented the different ways that snowpacks and forests interact at different altitudinal ranges in mid-latitude mountain ranges (Huerta et al., 2019; Jenicek et al., 2018; Lundquist, Dickerson-Lange, Lutz, & Cristea, 2013). However, there is uncertainty on the magnitude of these interactions among nearby areas and during different years, and this can affect the representativeness of a study site and study period that is used for research. Thus, the location of the experimental site and time-span of the study are key considerations when undertaking research on a mountain area and designing the experimental set-up. To account for this uncertainty, it is necessary to have reliable data on the spatial and temporal variability of snow-forest interactions under contrasting environmental conditions.

This study assessed the sources of uncertainty in the magnitude of interactions among nearby areas and during different years by determining which characteristics of the forest-snow interactions remained constant and which varied among different nearby areas and during different consecutive snow seasons. Our purpose was to highlight the similarities and differences in the spatial and temporal effects of forest on snowpack. Thus, we used a snow monitoring initiative based on ground data that was developed in the central Spanish Pyrenees to compare forest openings (O) and areas beneath forest canopy (F). The specific objectives of this study were to: (i) identify and quantify the influences of forest canopies on the duration of snowpacks, amount of snow-water equivalent (SWE), SWE distribution, and SWE accumulation and melting rates in the study area; (ii) identify similarities and differences in the effects of forest canopies on the snowpacks of 4 nearby forest stands and during 3 consecutive snow seasons, in which

there were different snow and climatic characteristics; and (iii) determine the representativeness of the selected experimental set-up, based on results from localized daily estimations of SWE and spatially distributed SWE measurements across each plot every 10 to 15 days.

2. Data and methods

2.1. Experimental setting

This study was performed in the central Spanish Pyrenees, in the northeastern Iberian Peninsula (Figure 1a). The selected valley is Balneario de Panticosa, which constitutes the headwaters of the Caldarés River, a Pyrenean tributary. The experimental area consists of 4 forest stands that have different elevations (1674 to 2104 m a.s.l.), exposure, forest structure, and climatology because of the abrupt topography in this area (Figure 1b). There was 1 plot of approximately 450 m² in each of the 4 forest stands. The plots were designated based on their locations in the valley (from NE to SW) as plot 1, plot 2, plot 3, and plot 4 (Figure 1a). The studied forest stands mainly consisted of *P. uncinata*, although plot 3 also contained *P. sylvestris*.

2.2. Meteorological data

Global solar irradiance (GSI) and wind speed series were obtained from an automatic weather station (AWS; HOBO U30 NRC, Onset Co., Bourne, MA, USA) that was located at forest openings within each plot. These were installed in November 2016, so GSI and wind speed data were not available during the first snow season (2015/16), but they were available during the other two snow seasons (2016/17 and 2017/18). Measurements were recorded every 15 min. Potential irradiation received by each plot was calculated using the Points Solar Radiation tool implemented in ArcGIS 9.3 software

(ESRI, USA). This tool allows calculation of the amount of radiant energy for specific time periods (monthly) and specific locations (plots). These calculations were performed under clear-sky conditions (transmissivity: 0.5) and were based on a 20 m resolution digital elevation model (DEM; source: IDE Aragón - Infraestructura de Datos Espaciales de Aragón, <https://idearagon.aragon.es/>). Air temperature and humidity series were obtained using autonomous self-recording data-loggers (Tinytag-Plus-2; model TGP-4017, Gemini DataLoggers UK Ltd., Chichester, West Sussex, UK) that were equipped with naturally ventilated radiation shields (Datamate ACS-5050 Weather Shield; Gemini DataLoggers UK Ltd., Chichester, West Sussex, UK). One data-logger was installed at each forest stand, and measurements were recorded every 15 min during the three snow seasons.

2.3. Forest structure

The structure of the forest stand of each plot was characterized by measuring the following variables in representative subplots of 15×15 m (1 subplot per study plot):

- Canopy cover (%): Canopy cover refers to the proportion of the forest floor covered by the vertical projection of the tree crowns (Korhonen, Korhonen, Rautiainen, & Stenberg, 2006). For estimation, two crown projections (one perpendicular and one parallel to the slope line) were measured in each pine. Two area values were calculated from these measurements, and were then averaged for each pine. The cover area of each pine was expressed as a percentage of the subplot area. Finally, all individual canopy cover percentages were aggregated. Because the canopies of different individuals may overlap, the total cover may exceed 100%.
- Density (trees per ha): Number of pines per unit area.

- Basal area (m² per ha): Proportion of the ground occupied by the pine stems. The diameter of each tree was measured at 1.3 m above the bare ground surface, the area was calculated, and the individual basal areas were then summed and divided by the subplot area.

2.4. *Snow monitoring*

Snow data were collected during three snow seasons (2015/16, 2016/17, and 2017/18), from the onset of snow accumulation (November) to the end of melting (May/June). This provided the following data series:

- Snowpack density: SWE was manually surveyed every 10 to 15 days using a snow cylinder and scale (ETH core sampler, Swiss Federal Institute of Technology, Zurich) at snow pits dug at two single locations in each plot, one in a forest opening (O) and one below the forest canopy (F). Two replicates per F-O site were collected. Snow density was calculated from the collected data using the equation:

$$\rho_s = \frac{SWE \cdot \rho_w}{H}$$

where ρ_s is snowpack density (kg·m⁻³), SWE is the measured equivalent water of the snowpack (m), H is measured snowpack depth (m), and ρ_w is water density (kg·m⁻³). Daily snow density series were estimated by linear interpolation between each pair of density measurements from consecutive surveys.

- Spatially distributed SWE series: Snow depth was manually measured every 10 to 15 days. In total, 200 depth measurements were taken using a snow depth probe (Snowmetrics Inc., Fort Collins, CO) that covered the entire area of each plot (about 450 m²), clustered in 10 forest openings (O) and 10 sites beneath forest canopy (F), with 10 replicates per F-O site. The samples consisted of 10 replicates

(about 1 m apart) that had homogeneous distributions in each F-O site. Within F sites, effort was made to collect most of the snowpack spatial variability caused by canopy cover. Thus, measurements were taken from the tree trunks to the edge of the projections of the tree canopies to the ground, covering all aspects. Spatially distributed SWE series for F-O sites (Figure S1) were inferred from spatially distributed snow depth measurements and density values (described above).

- Daily SWE series: Eight fixed snow poles and time-lapse cameras were used to measure snow depth each day at several spots in a single representative location of each plot (Bushnell, Trophy Cam, Kansas, USA) (Figure 1c). Three poles were placed in a forest opening, and 5 were placed beneath the forest canopy. Daily snow depth series for each pole were manually extracted from collected photographs using ImageJ software (Rasband, 1997). Missing data were estimated at each pole using the missForest method (Stekhoven and Bühlmann, 2012), which is implemented in the MissForest R package (Stekhoven, 2013). This is a nonparametric iterative imputation method that accounts for missing data based on Random Forests (Breiman, 2001). For each variable, the missForest method fits a Random Forest regression to the observed part, and then predicts the missing parts of the input data. The algorithm proceeds iteratively until a stopping criterion is met or a user-specified maximum number of iterations are achieved. Average daily snow depth series for the F-O poles at each experimental plot were calculated. The estimated daily SWE series for the F-O poles at each experimental plot (Figure 2) were inferred from data on daily snow depth and estimated daily snow density (described above).

Daily records provided high temporal resolution data, but were restricted to small areas; spatially distributed measurements had low temporal resolution, but provided an

overview of snowpack characteristics for the whole plot and allow quantification of spatial variability. Use of both data sources allowed determination of whether continuous local data is representative of a larger neighboring area at the plot scale.

2.5. Statistical analyses

Some derived variables were calculated from the SWE series (Table 1). The Wilcoxon test, was used to detect the significance of differences in the cumulative SWE and derived variables between forest canopy areas (F) and forest openings (O). Comparisons were only performed when snowpack was present in both areas. When a forest effect was detected (i.e., statistically significant differences in the variables at F and O areas), the increase or decrease of a variable associated with the forest canopy relative to the original variable was calculated as a percentage. The Kruskal-Wallis test and then the Wilcoxon test were used to assess whether there were statistically significant differences in the detected effects of forests among plots, snow seasons, main accumulation periods, and main melting periods.

The Mann-Kendall test was used to detect trends of the effects of forests during each snow season, and the Theil-Sen slope estimator was used to compute the magnitude of this trend. Trend analyses were carried out using the zyp package (Bronaugh & Consortium, 2019), which includes a trend-free pre-whitening method for removing serial autocorrelation. Spearman correlations were calculated to determine the influence of environmental variables on the detected effects of forests.

None of the analyzed variables had normal distributions (Shapiro-Wilk test: $p < 0.05$), so non-parametric methods were used in all analyses. The criteria considered for statistical analysis are in Table 1. The results commented below are all statistically significant ($p < 0.05$). Both significant and insignificant results can be seen in the

respective tables. All analyses were performed using R statistical software (R Core Team, 2018).

3. Results

3.1. Characteristics of the plots

Table 2 shows the major topographic and climatic characteristics of the forests in each plot. Plot 1 had the greatest tree density, canopy cover, and basal area per ha, and its forest openings were rather small. Plot 1 was also the steepest plot and mostly faced southward, so it could potentially receive the greatest amount of solar radiation. However, actual measurements indicated that the forest openings in plot 1 received the least radiation and also had the lowest wind speed values (close to 0) because of the sheltering effects of trees. Plot 2 had a relatively dense forest and the smallest basal area per ha. Its exposure was mostly eastward, and its winter temperatures and March snow depth were similar to those of plot 1 (intermediate among all plots). Plot 3 had the lowest elevation, was the flattest plot, and it faced westward. This plot had a relatively high canopy-cover and received a relatively high irradiance. Plot 3 also had the highest winter temperatures and the thinnest snowpacks. Plot 4 had the highest elevation and faced northeastward. This plot had the lowest tree density and amount of canopy-covered forest, so it could potentially receive the least amount of solar irradiation. However, measurements indicated this plot had the largest irradiance, as well as the greatest wind speeds, the coldest winter temperatures, and the deepest snowpacks.

3.2. Characteristics of the snow seasons

The study area had notable interannual variability in snow accumulation and melting from 2015 to 2018 (Table 3, Figure 2). The longest snow season was 2017/18,

and this season had the largest SWE peak values. Snow accumulation started much earlier and ended much later during this snow season, and the shortest melt period occurred afterwards. In contrast, the 2016/17 snow season was the shortest. Heavy snowfalls occurred, as indicated by the magnitude of the SWE peak, but snow accumulation occurred over a short period of time, and was followed by a long melt period. In 2015/16, a smaller snow accumulation was recorded but the duration of snow cover was longer than in 2016/17.

3.3. *Effects of forest on snowpack duration*

Snow disappeared an average of 17 ± 10 days earlier when it was beneath forest canopies than in forest openings (Table 4). Plot 3 had the greatest forest-mediated reduction in snow duration, and plot 1 had the least. Plot 4 had the greatest interannual variability in forest-mediated reduction of snow duration. The 2016/17 snow season had the strongest forest-mediated reduction of snow duration.

3.4. *Effects of forest on snowpack distribution: cumulative SWE*

Daily measurements showed there was significantly less SWE beneath forest canopies than in forest openings (Figure 3a). Forest reduced the cumulative SWE by an average of $64.2 \pm 10.8\%$ (Figure 3b). The magnitude of this forest effect varied significantly among snow seasons and among plots (Table 4). Forest had the greatest effect in plot 3, and the smallest effect in plot 1. This forest effect was significantly stronger during 2015/16 and significantly weaker during 2017/18, and was also greater during the main melting period than the main accumulation period ($73.8 \pm 15.4\%$ vs. $59.4 \pm 13.1\%$). In most cases, this forest effect significantly decreased when near the SWE peak, but increased towards the end of the melting period (Table 5, Figure 4).

Spatially distributed measurements also showed a significantly lower SWE beneath forest canopies than in forest openings (Figure S2a). Similarly, the overall forest-mediated reduction in cumulative SWE was $56.9 \pm 11.8\%$ (Figure S2b). The magnitude of this forest effect varied significantly among snow seasons and among plots (Table 4). This forest effect was significantly greater in plot 3 than in the other plots, and was also significantly greater during the main melting periods than the main accumulation periods ($68.3 \pm 11.2\%$ vs. $51.2 \pm 16.1\%$).

3.5. Effect of forest on snowpack distribution: SWE coefficient of variation

Spatially distributed measurements showed that the SWE spatial coefficient of variation (CV) was significantly greater beneath the forest canopies than in forest openings (0.5 ± 0.2 vs. 0.2 ± 0.1 ; Figure 5a). On average, forest increased the SWE CV by $190.0 \pm 118.0\%$ (Figure 5b). The magnitude of this effect varied significantly among snow seasons and among plots (Table 4). Thus, the forest in plot 2 had the smallest effect on the SWE CV, and forests during the 2017/18 snow season had the greatest effect on the SWE CV.

The absolute CV values in O-F areas were 0.2 ± 0.1 and 0.4 ± 0.3 in 2015/16, 0.2 ± 0.1 and 0.4 ± 0.2 in 2016/17, and 0.1 ± 0.0 and 0.6 ± 0.2 in 2017/18. The absolute CV values in O-F areas among plots were: 0.2 ± 0.1 and 0.5 ± 0.2 in plot 1, 0.2 ± 0.1 and 0.4 ± 0.2 in plot 2, 0.2 ± 0.1 and 0.7 ± 0.4 in plot 3, and 0.1 ± 0.0 and 0.3 ± 0.1 in plot 4.

There were no statistically significant differences in the effects of forest on the SWE CV between the main accumulation and melting periods.

3.6. Effect of forest on accumulation and melting rates of SWE

Based on daily series, there was a significantly lower accumulation rate of SWE beneath the canopies relative to forest openings (Figure 6a). Overall, forest reduced SWE

1
2
3 accumulation by $40.3 \pm 13.5\%$ when considering all accumulation days. Analysis of
4
5 snowmelt indicated there were significantly lower melting rates of SWE beneath the
6
7 canopies than in forest openings (Figure 6b). Overall, forest also reduced SWE melting
8
9 by $25.1 \pm 9.9\%$ when considering all melting days. On average, a forest had a $70.4 \pm$
10
11 59.8% greater effect on accumulation than melting (Figure 6c). This imbalance was
12
13 greatest in plot 3 and smallest in plot 1.
14
15

16
17 Forest cover reduced the SWE accumulation rate on 84.5% of the days when
18
19 accumulation occurred. If only these days were considered, forest reduced the SWE
20
21 accumulation rate by $53.30 \pm 7.2\%$ (Figure 7a). The magnitude of this forest effect varied
22
23 significantly between snow seasons and among plots (Table 4). During the 2017/18 snow
24
25 season, this forest effect was significantly weaker. Plot 1 had the smallest forest-mediated
26
27 reduction in accumulation rate, and plot 3 had the greatest. The forest-mediated reduction
28
29 in accumulation rate was significantly greater after the SWE peak than before the SWE
30
31 peak ($59.7 \pm 13.6\%$ vs. $52.2 \pm 8.0\%$). There were no significant intra-annual trends in the
32
33 forest-mediated effect on accumulation rate (Table 6).
34
35
36
37

38
39 The rates of SWE accumulation were only occasionally greater beneath the forest
40
41 canopies (occurring on 15.5% of accumulation days), and the mean increase was $37.5 \pm$
42
43 21.2% (Figure S3a). However, the magnitude of this effect had no significant variations
44
45 among snow seasons, among plots, or within snow seasons (Table 4).
46
47

48
49 Forest canopies reduced the melting rates of SWE on 73.6% of the days when
50
51 melting occurred. When considering these days alone, forest canopies reduced the
52
53 melting rates of SWE by $52.7 \pm 6.8\%$ on average (Figure 7b). The magnitude of this forest
54
55 effect varied significantly between snow seasons and among plots (Table 4). During the
56
57 2016/17 snow season this forest effect was significantly weaker, and during the 2015/16
58
59 snow season it was significantly stronger. Plot 2 had the smallest forest-mediated
60

reduction in melting rate. There were no statistically significant differences in the forest-mediated reduction in melting rate during periods before and after the SWE peak. The effect of forest on melting rate significantly increased from the SWE peak towards the end of the snow depletion in three plots (Table 6).

The rate of SWE melting was greater beneath forest canopies on 26.4% of the days when melting occurred, and the mean increase on these days was $37.5 \pm 21.2\%$ (Figure S3b). The magnitude of this effect varied significantly among plots, but not between snow seasons (Table 4). The effect was significantly weaker in plot 4 than the other plots. The forest-mediated increase in melting rate was significantly larger after than before the SWE peak ($63.2 \pm 18.3\%$ vs. $47.5 \pm 17.7\%$).

3.7. Role of environmental variables on intra-annual variability of effects of forests on snowpack

Several environmental factors influenced the effects of forests on the rate of accumulation of SWE, melting, and the SWE CV (Table 7). The strongest effect was a reduction of SWE accumulation by forest canopies and snowfall magnitudes, with significant correlations in all plots. As a result, the reduced rate of SWE accumulation by forest canopy was greater during seasons with less snowfall. We also observed larger SWE CVs beneath the canopy generally occurred when the snowpack was thinner, with significant correlations in plot 1. Similarly, the forest-mediated reduction of melting rate of SWE was lower when the snowpack was thicker, with significant correlations in plots 1 and 3. Higher irradiance increased the forest-mediated reduction in melting rate, but this only occurred after the SWE peak, and these correlations were only significant in plots 3 and 4. Higher temperatures significantly reduced the forest-mediated reduction in melting rates in plots 1 and 2.

1
2
3 **4. Discussion**
4
5

6 This study examined the spatial and temporal changes of the interactions of forests
7
8 and snowpacks, and identified characteristics that varied and those that remained
9
10 constant. The results highlight the need to consider spatial and temporal sources of
11
12 uncertainty when undertaking research in a mountain area, in particular when designing
13
14 the experimental set-up and selecting the location and time-span of a study.
15
16

17
18 Topographic factors, such as elevation, aspect, and slope, can affect snowpack
19
20 accumulation, insolation, air and soil temperatures, and other important factors
21
22 (Hungerford, Nemani, Running, & Coughlan, 1989; Sartz, 1972). Consequently, the
23
24 different topography of the plots we studied meant they had different microclimates,
25
26 snowpack regimes, and forest characteristics (Table 2). However, our results indicated
27
28 the effects of forest on snow processes were generally the same in all plots. Local
29
30 topography and vegetation cover strongly affect snow accumulation, distribution, and
31
32 melting in forested areas (Duyar, 2018; Jost et al., 2007). We found significant spatial
33
34 variability among our 4 forest stands in terms of the magnitude of certain influences. On
35
36 the other hand, the typically high temporal variability of climate in mountainous
37
38 headwaters induces high inter- and intra-annual variability in snowpack characteristics
39
40 (Fayad et al., 2017). Consequently, the three snow seasons that we examined had different
41
42 snowpack regimes (Table 3). Forests had the same basic effects on snowpack during all
43
44 3 snow seasons, but the magnitude of certain effects varied among snow seasons. Previous
45
46 research indicated that such variability is related to differences in the intensity of
47
48 snowfall, accumulated snowpack, timing of accumulation and melting events, and other
49
50 climatic conditions (López-Moreno & Latron, 2008a; López-Moreno & Stähli, 2008;
51
52 Mellander, Laudon, & Bishop, 2005).
53
54
55
56
57
58
59
60

We found that forest canopies had a large effect in reducing the cumulative SWE of snowpack (average from daily records: 64.2%, average from spatially distributed measurements: 56.9%); in contrast, previous studies reported mean reductions in the range of 40 to 50% (Jenicek et al., 2018; Jost et al., 2007; López-Moreno & Latron, 2008b; Lundberg, Nakai, Thunehed, & Halldin, 2004; Musselman et al., 2008; Revuelto, López-Moreno, Azorin-Molina, & Vicente-Serrano, 2015; Winkler, Spittlehouse, & Holding, 2005). We found that the magnitude of the forest effect significantly varied among plots, and was greatest in plot 3 and weakest in plot 1. Plot 3 is at the lowest elevation, had the warmest temperatures, and the shallowest snowpacks, and therefore received the least amount of snow. Boon (2009) reported that when the amount of snow is small, forest usually has a greater impact on snow accumulation (Boon, 2009). This is consistent with our results (Table 7), which showed that forest had the greatest impact on cumulative SWE at plot 3. Plot 1 had a dense canopy with very small forest openings; consequently, its trees had a sheltering effect on the forest openings, and the forest cover had a greater influence than in other plots. This meant that the effect of forest on reducing cumulative SWE was smallest in plot 1.

The magnitude of the effects of forest also varied significantly among the snow seasons. As noted above, previous studies reported that the effect of forest cover increases as snowpack depth decreases (Boon, 2009; López-Moreno & Latron, 2008b; Revuelto et al., 2015). In agreement, we found that the 2015/16 snow season, when snow accumulation was lowest, forest had the greatest effect on reducing cumulative SWE; the 2017/18 snow season, when snow accumulation was greatest, forest had the weakest effects. The same reasoning explains the intra-annual variability for this effect: forest caused a significantly greater reduction in cumulative SWE after the SWE peak (main melting period) than before it, and this effect was greater toward the end of the snow

season. These results are similar to previous findings of studies in the Pyrenees (López-Moreno & Latron, 2008b; Revuelto et al., 2015).

Our study confirms the results of previous research (López-Moreno & Latron, 2008a; Talbot et al., 2006; Winkler & Moore, 2006), in that areas with forest cover had increased (190.0% on average) small-scale spatial variability of snowpack thickness compared to open areas. The magnitude of this effect of significantly varied among plots and snow seasons, but there was no significant intra-annual variability.

The interception of snow by forest canopies explains why daily accumulation rates were greater in forest openings (53.3% on average), consistent with previous research (Garvelmann, Pohl, & Weiler, 2013; Hedstrom & Pomeroy, 1998; Lundberg et al., 2004; Stähli, Jonas, & Gustafsson, 2009). The magnitude of the forest-mediated reduction in accumulation rate significantly varied among plots, among snow seasons, and within each snow season. This effect was significantly greater in plot 3, which had the least snowfall, and weaker during 2017/18 and during the main accumulation period of each year, periods that had greater snowfall. Thus, our observations indicated that the forest-mediated reduction in SWE accumulation rate was inversely related to the amount of snowfall (Table 7). This is because trees have a limited capacity of snow interception (Boon, 2009; Keller & Strobel, 1982; López-Moreno & Latron, 2008a; Mellander et al., 2005; Revuelto et al., 2016). Enhancement of the SWE accumulation rate beneath the forest canopy was infrequent (15.5% of accumulation days). This may be because there was a delayed snow loading from the forest canopy on days with no snowfall, or because wind released some of the intercepted snow. The magnitude of this unusual forest-mediated increase in the SWE accumulation rate did not vary significantly among plots, among snow seasons, or within snow seasons.

Our analysis of snow melting indicated that forest reduced the melting rate of SWE by 52.7% on average. Many previous studies also reported that forest canopies reduce the snow ablation rate by attenuating solar radiation, because they reflect incoming shortwave radiation back to the atmosphere (Ellis, 2011; Jenicek et al., 2018; López-Moreno & Stähli, 2008; Molotch et al., 2009; Musselman et al., 2008; Musselman, Pomeroy, & Link, 2015; Pomeroy, Fang, & Ellis, 2012; Revuelto et al., 2015; Schnorbus & Alila, 2013; Sicart et al., 2004). We found that the magnitude of this effect varied significantly among plots and snow seasons. The low irradiance in plot 2 may explain why the forest there had the weakest effect on melting rate, in agreement with the previous observations of Sicart et al. (2004) and Musselman et al. (2015). Although we did not find significant differences in the magnitude of this effect when comparing the main accumulation and main melting periods, it was greater near the end of the ablation period. This is likely because the level of incoming solar radiation is a function of the time of year (shortwave) and air temperature (longwave) (Lundquist et al., 2013).

In addition, during early summer, the solar angle is higher and the amount of incoming radiation blocked by the forest canopy is therefore greater relative to open areas. This is because of enhanced shading compared to earlier in the season (Lundquist et al., 2013; Schnorbus & Alila, 2013). Thus, toward the end of the snow season, when the irradiance is greater, the enhanced shading was responsible for the greater effect of forest on snow melting (Table 7). It is also worth mentioning that on 26.4% of days with SWE melting we observed higher ablation rates beneath forest canopies than in forest openings. Longwave emission from evergreen conifers, enhanced by warmer temperatures, can increase melting beneath a forest canopy (Davis et al., 1997; Essery et al., 2008; López-Moreno & Stähli, 2008; Lundquist et al., 2013; Sicart et al., 2004). The most common effect of forest that we observed was reduced melting rate, thus suggesting that the effect

of shadowing by the forest canopy exceeded the effect of release of longwave radiation from trees. The magnitude of this forest-mediated increase in the melting rate of SWE varied significantly among plots and within years, but not among snow seasons. The forest in plot 4, which had the lowest temperatures, had the weakest effect on SWE melting rate. Lundquist et al. (2013) reported similar observations.

We observed a shorter duration of snowpack beneath forest canopies (more than two weeks on average). This may be explained by forest variations among plots and among snow seasons. Lundquist et al. (2013) reported similar results for regions with warm winters; their average December-January-February temperatures were higher than -1°C , and this value was $-0.63 \pm 0.94^{\circ}\text{C}$ in our study area. These researchers argued that the forest canopy enhanced longwave radiation and this was the main driver for earlier snow depletion in forested areas, especially during winter. However, we only occasionally observed a forest-mediated increase in the melting rate in our forest stands, as mentioned above. Thus, our observations are consistent with those of Lundquist et al., but only to a limited extent. The shorter duration of snowpacks beneath forest canopies in our study can be mostly explained by the more intense forest-mediated reduction in accumulation (40.3% on average) than on melting (25.1% on average), when considering the overall effect of forest on all days of accumulation and melting together. Dickerson-Lange et al. (2017) also reported a greater effect of forest on accumulation than melting in several mountainous forests of the Pacific Northwest in the United States.

We only studied 4 forest stands over 3 snow seasons, thus limiting our ability to definitively identify the different roles of climate, topography, and forest characteristics on the observed variability in forest-snow interactions. It is difficult to increase the number of study plots when using manual or semi-automated measurements because of the significant manual labor required in the field. Thus, further research is needed to better

quantify the influence of these factors on the observed variability of forest-snow interactions. We also experienced technical difficulties when trying to increase the number of locations for measurements of snowpack density during field work by digging snow pits. Because snowpack density has spatial variation, this could contribute to uncertainty in these measurements.

We analyzed the effect of forest on the cumulative SWE using two sources of SWE data — SWE daily estimations and spatially distributed SWE measurements. The results from both data sources were similar in magnitude, and indicated similar spatial and temporal variability in the effect of forest on snow. Therefore, our experimental design, which employed intensive field work during three years, daily SWE estimations at snow poles, and bi-weekly spatially distributed measurements, confirmed that accurate local data could be representative of a larger area at the plot scale. The combination of such field measurements with spatially distributed modelling of energy and mass balance of snow (Bair, Davis, & Dozier, 2018; Liu et al., 2019) and emerging techniques of measurements based on airborne LIDAR or UAVs (Bühler, Adams, Bösch, & Stoffel, 2016; Currier et al., 2019; Painter et al., 2016; Mazzotti et al., 2019; Webster & Jonas, 2018) will be key to obtaining reliable large-scale results in the future.

5. Conclusions

1. We found that forest canopies reduced the duration and cumulative SWE of snowpacks, and increased small-scale spatial variability relative to forest openings. Forest canopies also reduced the accumulation rate and melting rate of the SWE. In addition, there was a more intense forest-mediated reduction of SWE accumulation than SWE melting and this, in combination with the

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

occasional enhancement of SWE melting, was responsible for the earlier snow depletion beneath forest canopies.

- 2. Forests had the same general effects on snowpacks in all 4 of our forest stands and during all 3 snow seasons. However, the magnitude of these effects varied significantly among the forest stands (despite their proximity) and among different snow seasons. We also observed an intensification during the main period of melting (from the SWE peak to complete snow depletion) for certain forest effects. Thus, the magnitude and timing of the effects of forest on snowpack had significant spatial and temporal variations among plots in the same valley. This finding highlights the need to consider the effects of forests as a source of uncertainty when undertaking research in mountain areas, when designing field experiments, and when selecting the location of the experimental site and time-span of a study.
- 3. Our experimental design provided localized daily estimations of SWE and spatially distributed measurements of SWE across each plot every 10 to 15 days. This approach allowed verification that local data was representative of a larger area at the plot scale.

References

- Bair, E. H., Davis, R. E., & Dozier, J. (2018). Hourly mass and snow energy balance measurements from Mammoth Mountain, CA USA, 2011–2017. *Earth System Science Data*, 10(1), 549–563. <https://doi.org/10.5194/essd-10-549-2018>
- Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438(7066), 303–309. <https://doi.org/10.1038/nature04141>
- Beniston, M. (2012). Impacts of climatic change on water and associated economic activities in the Swiss Alps. *Journal of Hydrology*, 412–413, 291–296. <https://doi.org/10.1016/j.jhydrol.2010.06.046>
- Boon, S. (2009). Snow ablation energy balance in a dead forest stand. *Hydrological Processes*, 23(18), 2600–2610. <https://doi.org/10.1002/hyp.7246>
- Breiman, L. (2001). Random Forests, *Machine learning*, 45(1), 5–32.
- Bronaugh, D., & Consortium, A. W. (2019). zyp: Zhang + Yue-Pilon Trends Package (Version 0.10-1.1). Available at <https://CRAN.R-project.org/package=zyp>
- Bühler, Y., Adams, M. S., Bösch, R., & Stoffel, A. (2016). Mapping snow depth in alpine terrain with unmanned aerial systems (UASs): Potential and limitations. *The Cryosphere*, 10(3), 1075–1088. <https://doi.org/10.5194/tc-10-1075-2016>
- Ceballos-Barbancho, A., Morán-Tejeda, E., Luengo-Ugidos, M. Á., & Llorente-Pinto, J. M. (2008). Water resources and environmental change in a Mediterranean environment: The south-west sector of the Duero river basin (Spain). *Journal of Hydrology*, 351(1), 126–138. <https://doi.org/10.1016/j.jhydrol.2007.12.004>
- Currier, W. R., Pflug, J., Mazzotti, G., Jonas, T., Deems, J. S., Bormann, K. J., ... Spaete, L. (2019). Comparing aerial lidar observations with terrestrial lidar and snow-probe transects from NASA's 2017 SnowEx campaign. *Water Resources Research*, 55, 6285–6294. <https://doi.org/10.1029/2018WR024533>
- Darwish, T., Shaban, A., Portoghesi, I., Vurro, M., Khadra, R., Saqallah, S., ... Amacha, N. (2015). Inducing Water Productivity from Snow Cover for Sustainable Water Management in Ibrahim River Basin, Lebanon. *British Journal of Applied Science & Technology*, 519. <https://doi.org/10.9734/BJAST/2015/13777>

- Davis, R. E., Hardy, J. P., Ni, W., Woodcock, C., McKenzie, J. C., Jordan, R., & Li, X. (1997). Variation of snow cover ablation in the boreal forest: A sensitivity study on the effects of conifer canopy. *Journal of Geophysical Research: Atmospheres*, 102(D24), 29389-29395. <https://doi.org/10.1029/97JD01335>
- Dickerson-Lange, S. E., Gersonde, R. F., Hubbart, J. A., Link, T. E., Nolin, A. W., Perry, G. H., ... Lundquist, J. D. (2017). Snow disappearance timing is dominated by forest effects on snow accumulation in warm winter climates of the Pacific Northwest, United States. *Hydrological Processes*, 31(10), 1846-1862. <https://doi.org/10.1002/hyp.11144>
- Duyar, A. (2018). The effects of forest canopy cover and altitude on snow accumulation and melting in the upper watersheds. *Fresenius Environmental Bulletin*, 27(12), 9642-9649.
- El Kenawy, A., López-Moreno, J. I., & Vicente-Serrano, S. M. (2012). Trend and variability of surface air temperature in northeastern Spain (1920–2006): Linkage to atmospheric circulation. *Atmospheric Research*, 106, 159-180. <https://doi.org/10.1016/j.atmosres.2011.12.006>
- Ellis, C. R. (2011). *Radiation and snowmelt dynamics in mountain forests*. Ph.D. thesis, University of Saskatchewan, Saskatchewan, Canada.
- Essery, R., Pomeroy, J., Ellis, C., & Link, T. (2008). Modelling longwave radiation to snow beneath forest canopies using hemispherical photography or linear regression. *Hydrological Processes*, 22(15), 2788-2800. <https://doi.org/10.1002/hyp.6930>
- Fayad, A., Gascoin, S., Faour, G., López-Moreno, J. I., Drapeau, L., Page, M. L., & Escadafal, R. (2017). Snow hydrology in Mediterranean mountain regions: A review. *Journal of Hydrology*, 551, 374-396. <https://doi.org/10.1016/j.jhydrol.2017.05.063>
- García-Ruiz, J. M., López-Moreno, J. I., Vicente-Serrano, S. M., Lasanta-Martínez, T., & Beguería, S. (2011). Mediterranean water resources in a global change scenario. *Earth-Science Reviews*, 105(3), 121-139. <https://doi.org/10.1016/j.earscirev.2011.01.006>
- Garvelmann, J., Pohl, S., & Weiler, M. (2013). From observation to the quantification of snow processes with a time-lapse camera network. *Hydrology and Earth System Sciences*, 17(4), 1415-1429. <https://doi.org/10.5194/hess-17-1415-2013>
- Gil'ad, D., & Bonne, J. (1990). The snowmelt of Mt. Hermon and its contribution to the sources of the Jordan River. *Journal of Hydrology*, 114(1), 1-15. [https://doi.org/10.1016/0022-1694\(90\)90072-6](https://doi.org/10.1016/0022-1694(90)90072-6)

- Grünewald, T., & Lehning, M. (2011). Altitudinal dependency of snow amounts in two small alpine catchments: Can catchment-wide snow amounts be estimated via single snow or precipitation stations? *Annals of Glaciology*, 52(58), 153-158. <https://doi.org/10.3189/172756411797252248>
- Hardy, J. P., Melloh, R., Robinson, P., & Jordan, R. (2000). Incorporating effects of forest litter in a snow process model. *Hydrological Processes*, 14(18), 3227-3237. [https://doi.org/10.1002/1099-1085\(20001230\)14:18<3227::AID-HYP198>3.0.CO;2-4](https://doi.org/10.1002/1099-1085(20001230)14:18<3227::AID-HYP198>3.0.CO;2-4)
- Hedstrom, N. R., & Pomeroy, J. W. (1998). Measurements and modelling of snow interception in the boreal forest. *Hydrological Processes*, 12(10-11), 1611-1625. [https://doi.org/10.1002/\(SICI\)1099-1085\(199808/09\)12:10/11<1611::AID-HYP684>3.0.CO;2-4](https://doi.org/10.1002/(SICI)1099-1085(199808/09)12:10/11<1611::AID-HYP684>3.0.CO;2-4)
- Huerta, M. L., Molotch, N. P., & McPhee, J. (2019). Snowfall interception in a deciduous Nothofagus forest and implications for spatial snowpack distribution. *Hydrological Processes*, 33(13), 1818-1834. <https://doi.org/10.1002/hyp.13439>
- Hungerford, R. D., Nemani, R. R., Running, S. W., & Coughlan, J. C. (1989). *MTCLIM: A mountain microclimate simulation model*. Research Paper INT-RP-414. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 52 pp. <https://doi.org/10.2737/INT-RP-414>
- Jenicek, M., Pevna, H., & Matejka, O. (2018). Canopy structure and topography effects on snow distribution at a catchment scale: Application of multivariate approaches. *Journal of Hydrology and Hydromechanics*, 66(1), 43-54. <https://doi.org/10.1515/johh-2017-0027>
- Jones, H. G., Pomeroy, J. W., Walker, D. A., & Hoham, R. W. (2001). *Snow Ecology: An Interdisciplinary Examination of Snow-Covered Ecosystems*. Cambridge University Press, Cambridge, UK..UK.
- Jost, G., Weiler, M., Gluns, D. R., & Alila, Y. (2007). The influence of forest and topography on snow accumulation and melt at the watershed-scale. *Journal of Hydrology*, 347(1), 101-115. <https://doi.org/10.1016/j.jhydrol.2007.09.006>
- Keller, H. M., & Strobel, T. (1982). Water and nutrient discharge during snowmelt in subalpine areas. *Hydrological Aspects of Alpine and High-Mountain Areas*, (Ed.) J.W. Glen.
- Korhonen, L., Korhonen, K. T., Rautiainen, M., & Stenberg, P. (2006). Estimation of forest canopy cover: a comparison of field measurement techniques. *Silva Fennica*, 40(4), 577-588. <https://doi.org/10.14214/sf.315>

- Lawler, R. R., & Link, T. E. (2011). Quantification of incoming all-wave radiation in discontinuous forest canopies with application to snowmelt prediction. *Hydrological Processes*, 25(21), 3322-3331. <https://doi.org/10.1002/hyp.8150>
- Liu, Y., Zhang, P., Nie, L., Xu, J., Lu, X., & Li, S. (2019). Exploration of the Snow Ablation Process in the Semiarid Region in China by Combining Site-Based Measurements and the Utah Energy Balance Model: A Case Study of the Manas River Basin. *Water*, 11(5), 1058. <https://doi.org/10.3390/w11051058>
- López, R., & Justribó, C. (2010). The hydrological significance of mountains: A regional case study, the Ebro River basin, northeast Iberian Peninsula. *Hydrological Sciences Journal*, 55(2), 223-233. <https://doi.org/10.1080/02626660903546126>
- López-Moreno, J. I., & García-Ruiz, J. M. (2004). Influence of snow accumulation and snowmelt on streamflow in the central Spanish Pyrenees. *Hydrological Sciences Journal*, 49(5), null-802. <https://doi.org/10.1623/hysj.49.5.787.55135>
- López-Moreno, J. I., & Latron, J. (2008a). Spatial heterogeneity in snow water equivalent induced by forest canopy in a mixed beech–fir stand in the Pyrenees. *Annals of Glaciology*, 49, 83-90. <https://doi.org/10.3189/172756408787814951>
- López-Moreno, J. I., & Latron, J. (2008b). Influence of canopy density on snow distribution in a temperate mountain range. *Hydrological Processes*, 22(1), 117-126. <https://doi.org/10.1002/hyp.6572>
- López-Moreno, J. I., & Stähli, M. (2008). Statistical analysis of the snow cover variability in a subalpine watershed: Assessing the role of topography and forest interactions. *Journal of Hydrology*, 348(3), 379-394. <https://doi.org/10.1016/j.jhydrol.2007.10.018>
- López-Moreno, J. I., Vicente-Serrano, S. M., Moran-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., & García-Ruiz, J. M. (2010). Impact of climate evolution and land use changes on water yield in the Ebro basin. *Hydrology and Earth System Sciences*, 15, 311–322. <https://doi.org/10.5194/hess-15-311-2011>
- López-Moreno, J. I., Zabalza, J., Vicente-Serrano, S. M., Revuelto, J., Gilaberte, M., Azorin-Molina, C., ... Tague, C. (2014). Impact of climate and land use change on water availability and reservoir management: Scenarios in the Upper Aragón River, Spanish Pyrenees. *Science of The Total Environment*, 493, 1222-1231. <https://doi.org/10.1016/j.scitotenv.2013.09.031>

- Lundberg, A., Nakai, Y., Thunehed, H., & Halldin, S. (2004). Snow accumulation in forests from ground and remote-sensing data. *Hydrological Processes*, 18(10), 1941-1955. <https://doi.org/10.1002/hyp.1459>
- Lundquist, J. D., Dickerson-Lange, S. E., Lutz, J. A., & Cristea, N. C. (2013). Lower forest density enhances snow retention in regions with warmer winters: A global framework developed from plot-scale observations and modeling: Forests and Snow Retention. *Water Resources Research*, 49(10), 6356-6370. <https://doi.org/10.1002/wrcr.20504>
- Marks, D., Kimball, J., Tingey, D., & Link, T. (1998). The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: A case study of the 1996 Pacific Northwest flood. *Hydrological Processes*, 12(10-11), 1569-1587. [https://doi.org/10.1002/\(SICI\)1099-1085\(199808/09\)12:10/11<1569::AID-HYP682>3.0.CO;2-L](https://doi.org/10.1002/(SICI)1099-1085(199808/09)12:10/11<1569::AID-HYP682>3.0.CO;2-L)
- Mazzotti, G., Currier, W. R., Deems, J.S., Pflug, J. M., Lundquist, J. D., & Jonas, T. (2019). Revisiting snow cover variability and canopy structure within forest stands: Insights from airborne lidar data. *Water Resources Research*, 55, 6198–6216. <https://doi.org/10.1029/2019WR024898>
- Mellander, P. E., Laudon, H., & Bishop, K. (2005). Modelling variability of snow depths and soil temperatures in Scots pine stands. *Agricultural and Forest Meteorology*, 133(1), 109-118. <https://doi.org/10.1016/j.agrformet.2005.08.008>
- Moeser, D., Stähli, M., & Jonas, T. (2015). Improved snow interception modeling using canopy parameters derived from airborne LiDAR data. *Water Resources Research*, 51(7), 5041-5059. <https://doi.org/10.1002/2014WR016724>
- Molotch, N. P., Brooks, P. D., Burns, S. P., Litvak, M., Monson, R. K., McConnell, J. R., & Musselman, K. N. (2009). Ecohydrological controls on snowmelt partitioning in mixed-conifer sub-alpine forests. *Ecohydrology*, 2(2), 129-142. <https://doi.org/10.1002/eco.48>
- Morán-Tejeda, E., Lorenzo-Lacruz, J., López-Moreno, J. I., Rahman, K., & Beniston, M. (2014). Streamflow timing of mountain rivers in Spain: Recent changes and future projections. *Journal of Hydrology*, 517, 1114-1127. <https://doi.org/10.1016/j.jhydrol.2014.06.053>
- Murray, C. D., & Buttle, J. M. (2003). Impacts of clearcut harvesting on snow accumulation and melt in a northern hardwood forest. *Journal of Hydrology*, 271(1), 197-212. [https://doi.org/10.1016/S0022-1694\(02\)000352-9](https://doi.org/10.1016/S0022-1694(02)000352-9)

- Musselman, K. N., Molotch, N. P., & Brooks, P. D. (2008). Effects of vegetation on snow accumulation and ablation in a mid-latitude sub-alpine forest. *Hydrological Processes*, 22(15), 2767-2776. <https://doi.org/10.1002/hyp.7050>
- Musselman, K. N., Pomeroy, J. W., & Link, T. E. (2015). Variability in shortwave irradiance caused by forest gaps: Measurements, modelling, and implications for snow energetics. *Agricultural and Forest Meteorology*, 207, 69-82. <https://doi.org/10.1016/j.agrformet.2015.03.014>
- N'da, A. B., Bouchaou, L., Reichert, B., Hanich, L., Ait Brahim, Y., Chehbouni, A., ... Michelot, J. L. (2016). Isotopic signatures for the assessment of snow water resources in the Moroccan high Atlas mountains: Contribution to surface and groundwater recharge. *Environmental Earth Sciences*, 75(9), 755. <https://doi.org/10.1007/s12665-016-5566-9>
- Nakai, Y., Sakamoto, T., Terajima, T., Kitamura, K., & Shirai, T. (1999). Energy balance above a boreal coniferous forest: A difference in turbulent fluxes between snow-covered and snow-free canopies. *Hydrological Processes*, 13(4), 515-529. [https://doi.org/10.1002/\(SICI\)1099-1085\(199903\)13:4<515::AID-HYP712>3.0.CO;2-J](https://doi.org/10.1002/(SICI)1099-1085(199903)13:4<515::AID-HYP712>3.0.CO;2-J)
- Painter, T. H., Berisford, D. F., Boardman, J. W., Bormann, K. J., Deems, J. S., Gehrke, F., ... Winstral, A. (2016). The Airborne Snow Observatory: Fusion of scanning lidar, imaging spectrometer, and physically-based modeling for mapping snow water equivalent and snow albedo. *Remote Sensing of Environment*, 184, 139-152. <https://doi.org/10.1016/j.rse.2016.06.018>
- Pomeroy, J. W., 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(17), 2513-2525. <https://doi.org/10.1002/hyp.7325>
- Pomeroy, J., Fang, X., & Ellis, C. (2012). Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance. *Hydrological Processes*, 26(12), 1891-1904. <https://doi.org/10.1002/hyp.9248>
- Pulliainen, J., Aurela, M., Laurila, T., Aalto, T., Takala, M., Salminen, M., ... Vesala, T. (2017). Early snowmelt significantly enhances boreal springtime carbon uptake. *Proceedings of the National Academy of Sciences*, 114(42), 11081-11086. <https://doi.org/10.1073/pnas.1707889114>
- R Core Team. (2018). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.
- Rasband, W. S. (1997). *ImageJ*. US National Institutes of Health, Bethesda, MD, USA.

- Revuelto, J., López-Moreno, J. I., Azorin-Molina, C., & Vicente-Serrano, S. M. (2015). Canopy influence on snow depth distribution in a pine stand determined from terrestrial laser data: Canopy influence on snow depth distribution. *Water Resources Research*, 51(5), 3476-3489. <https://doi.org/10.1002/2014WR016496>
- Revuelto, J., López-Moreno, J.I., Azorin-Molina, C., Alonso-González, E., & Sanmiguel-Vallelado, A. (2016). Small-Scale Effect of Pine Stand Pruning on Snowpack Distribution in the Pyrenees Observed with a Terrestrial Laser Scanner. *Forests*, 7(8), 166. <https://doi.org/10.3390/f7080166>
- Ruiz de la Torre, J., & Ceballos, L. (1979). *Árboles y Arbustos de la España Peninsular*. ETSI de Montes. Madrid. 512 pp. ISBN 84-600-84-600.
- Sanmiguel-Vallelado, A., Morán-Tejeda, E., Alonso-González, E., & López-Moreno, J. I. (2017). Effect of snow on mountain river regimes: An example from the Pyrenees. *Frontiers of Earth Science*, 11(3), 515-530. <https://doi.org/10.1007/s11707-016-0630-z>
- Sartz, R. S. (1972). *Effect of topography on microclimate in southwestern Wisconsin*. USDA Forest Service Research Paper NC-74, North Central Forest Experiment Station, St. Paul, MN.
- Schnorbus, M., & Alila, Y. (2013). Peak flow regime changes following forest harvesting in a snow-dominated basin: Effects of harvest area, elevation, and channel connectivity. *Water Resources Research*, 49(1), 517-535. <https://doi.org/10.1029/2012WR011901>
- Sicart, J. E., Essery, R. L. H., Pomeroy, J. W., 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(5), 774-784. [https://doi.org/10.1175/1525-7541\(2004\)005<0774:ASSODN>2.0.CO;2](https://doi.org/10.1175/1525-7541(2004)005<0774:ASSODN>2.0.CO;2)
- Stähli, M., Jonas, T., & Gustafsson, D. (2009). The role of snow interception in winter-time radiation processes of a coniferous sub-alpine forest. *Hydrological Processes*, 23(17), 2498-2512. <https://doi.org/10.1002/hyp.7180>
- Stekhoven, D. J. (2013). missForest: Nonparametric Missing Value Imputation using Random Forest (Version 1.4). Available at <https://CRAN.R-project.org/package=missForest>
- Stekhoven, D. J., Bühlmann, P. (2012). MissForest – Nonparametric Missing Value Imputation for Mixed-Type Data, *Bioinformatics*. 28(1), 112–118.
- Storck, P. (2000). *Trees, snow and flooding: An investigation of forest canopy effects on snow accumulation and melt at the plot and watershed scales in the Pacific Northwest*. Water Resources Series, Tech.

- Rep. 161, Department of Civil and Environmental Engineering, University of Washington, 176 pp.
- Storck, P., Lettenmaier, D. P., & Bolton, S. M. (2002). Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. *Water Resources Research*, 38(11), 5-1-5-16. <https://doi.org/10.1029/2002WR001281>
- Talbot, J., Plamondon, A. P., Lévesque, D., Aubé, D., Prévost, M., Chazalmartin, F., & Gnocchini, M. (2006). Relating snow dynamics and balsam fir stand characteristics, Montmorency Forest, Quebec. *Hydrological Processes*, 20(5), 1187-1199. <https://doi.org/10.1002/hyp.5938>
- Varhola, A., Coops, N. C., Weiler, M., & Moore, R. D. (2010). Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology*, 392(3), 219-233. <https://doi.org/10.1016/j.jhydrol.2010.08.009>
- Veatch, W., Brooks, P. D., Gustafson, J. R., & Molotch, N. P. (2009). Quantifying the effects of forest canopy cover on net snow accumulation at a continental, mid-latitude site. *Ecohydrology*, 2(2), 115-128. <https://doi.org/10.1002/eco.45>
- Webster, C., & Jonas, T. (2018). Influence of canopy shading and snow coverage on effective albedo in a snow-dominated evergreen needleleaf forest. *Remote Sensing of Environment*, 214, 48-58.
- Winkler, R. D., & Moore, R. D. (2006). Variability in snow accumulation patterns within forest stands on the interior plateau of British Columbia, Canada. *Hydrological Processes*, 20(17), 3683-3695. <https://doi.org/10.1002/hyp.6382>
- Winkler, R. D., Spittlehouse, D. L., & Golding, D. L. (2005). Measured differences in snow accumulation and melt among clearcut, juvenile, and mature forests in southern British Columbia. *Hydrological Processes*, 19(1), 51-62. <https://doi.org/10.1002/hyp.5757>
- Yamazaki, T., & Kondo, J. (1992). The Snowmelt and Heat Balance in Snow-covered Forested Areas. *Journal of Applied Meteorology*, 31(11), 1322-1327. [https://doi.org/10.1175/1520-0450\(1992\)031<1322:TSAHBI>2.0.CO;2](https://doi.org/10.1175/1520-0450(1992)031<1322:TSAHBI>2.0.CO;2)

Data Availability Statement

The data recorded during this study are available from the corresponding author upon reasonable request.

For Peer Review

Table 1. Criteria used for statistical analysis (top) and derived variables calculated from SWE series (bottom).

Criteria for statistical analysis		Description
Continuous snowpack †	Start	Date of the first day of 14 or more consecutive days with snow on the ground
	End	Last date with a snow record
	Duration	Time between the start and end dates
Main accumulation period		Date of peak SWE to the end of the continuous snowpack
Main melt period		Date of peak SWE to the end of the continuous snowpack
Days of accumulation ‡		SWE difference between consecutive days > 0
Days of melting ‡		SWE difference between consecutive days < 0
Derived variables		Description
Spatial coefficient of variation (CV)§	Spatially distributed series	SWERatio of the standard deviation to the mean value of SWE of each survey day.
Accumulation rates	Daily SWE series	Positive values obtained when performing first-order differencing, day-by-day. Units: mm·day ⁻¹
Melting rates	Daily SWE series	Negative values obtained when performing first-order differencing, day-by-day. Units: mm·day ⁻¹

(†) Only data in a continuous snowpack period were considered.
(‡) Assuming that the main processes in SWE gain and loss were snowfall and snow melting, although other processes may have contributed (e.g., snow redistribution by wind).
(§) For each area, CV shows the extent of spatial variability in relation to the SWE average.

Table 2. Average values of forest structure, topography, and climatology in the four plots.

Plot	Elevation (m a.s.l.)	Aspect	Slope (°)	Canopy cover (%)	Density (indiv·ha ⁻¹)	Basal area (m ² ·ha ⁻¹)	DJF T (°C)	March SD (cm)	RH (%)	Wind speed (m·s ⁻¹)	MAM potential irradiation (1000 W·h·m ⁻²)	MAM measured GSI (W·m ⁻²)
1	2008	S	29.4	156	1689	45.1	-0.44	101.4	70.0	0.04	165.3	154.4
2	1814	E	20.4	85	844	13.7	-0.43	113.9	69.3	0.40	129.6	167.6
3	1674	W	9.3	119	533	35.3	0.29	78.8	68.9	0.49	140.2	192.7
4	2104	NE	22.7	29	356	26.6	-1.95	246.5	66.9	0.78	122.6	195.1

DJF T: winter mean air temperature from December to February.

March SD: average snow depth in March.

RH: average relative humidity for the whole snow season (November to May).

Wind speed: average for the whole snow season (November to May).

MAM potential irradiation: average from March to May.

MAM measured GSI: average global solar irradiation from March to May.

The source of climate data is in section 2.2.

The methods used to obtain forest structure data are in section 2.3.

The methods used to obtain snow data are in section 2.4. Source of data: daily records in forest openings.

Table 3. Characteristics of the three snow seasons.

Snow season	Plot	Date of accumulation onset	Date of SWE peak	SWE peak (mm)	Date at end of melt	Days of SWE accumulation	Days of SWE melting	Continuous snowpack duration (days)
2015/16	1	2-Jan.	16-Feb.	388.7	24-Apr.	46	69	114
	2	21-Nov.	20-Mar.	436.2	26-Apr.	121	38	158
	3	2-Jan.	15-Mar.	247.0	20-Apr.	74	37	110
	4	21-Nov.	13-Apr.	1012.7	30-May.	145	48	192
2016/17	1	10-Jan.	14-Feb.	476.3	23-Mar.	36	38	73
	2	23-Nov.	13-Feb.	390.0	8-Apr.	83	55	137
	3	11-Jan.	7-Feb.	318.7	10-Apr.	28	63	90
	4	14-Nov.	25-Mar.	1113.7	25-May.	132	62	193
2017/18	1	1-Dec.	10-Apr.	645.4	7-May.	131	28	158
	2	1-Dec.	20-Mar.	738.8	5-May.	110	47	156
	3	1-Dec.	11-Apr.	578.3	5-May.	132	25	156
	4	5-Nov.	29-Apr.	1245.2	2-Jun.	176	35	210

The methods used to obtain snow data are in sections 2.4 and 2.5. Source of data: daily records in forest openings.

Table 4. Average effects of forests $\pm$ standard deviations among snow seasons (top) and among plots (bottom).

Season or Plot	Forest effects							
	Reduction in snow duration (days)	Decrease in snow SWE (%)	Decrease in cumulative SWE (%)	Increase in SWE (%)	CV of SWE accumulation (%)	Decrease in rate of SWE melting (%)	Increase in rate of SWE melting (%)	Increase in rate of SWE melting (%)
		DS	DM					
2015/16	11 $\pm$ 7	69.8 $\pm$ 12.0 ^a	61.6 $\pm$ 11.3 ^a	148.0 $\pm$ 93.3 ^a	$\pm$ 55.8 $\pm$ 7.6 ^a	31.7 $\pm$ 18.7	57.3 $\pm$ 2.5 ^a	54.9 $\pm$ 10.4
2016/17	26 $\pm$ 8	63.5 $\pm$ 6.5 ^a	46.8 $\pm$ 8.6 ^a	112.2 $\pm$ 60.2 ^b	$\pm$ 56.4 $\pm$ 4.2 ^b	30.3 $\pm$ 30.0	47.1 $\pm$ 1.8 ^a	47.1 $\pm$ 14.7
2017/18	14 $\pm$ 10	59.3 $\pm$ 12.9 ^a	62.3 $\pm$ 10.1	309.7 $\pm$ 95.7 ^{a,b}	$\pm$ 47.6 $\pm$ 7.3 ^{a,b}	48.7 $\pm$ 16.8	53.8 $\pm$ 9.5 ^a	54.3 $\pm$ 20.0
Plot 1	10 $\pm$ 8	56.8 $\pm$ 6.2 ^a	51.0 $\pm$ 11.0 ^a	215.2 $\pm$ 92.4 ^a	$\pm$ 48.6 $\pm$ 3.6 ^{a,c}	55.5 $\pm$ 17.7	52.2 $\pm$ 4.2	54.0 $\pm$ 3.4 ^a
Plot 2	15 $\pm$ 6	60.1 $\pm$ 7.5 ^a	55.9 $\pm$ 8.0 ^b	101.2 $\pm$ 114.5 ^{a,b,c}	$\pm$ 50.3 $\pm$ 6.7 ^b	24.6 $\pm$ 20.2	48.6 $\pm$ 6.3 ^{a,b}	51.6 $\pm$ 26.1 ^b
Plot 3	26 $\pm$ 5	73.4 $\pm$ 9.3 ^a	63.7 $\pm$ 20.2 ^{a,b,c}	274.4 $\pm$ 162.4 ^b	$\pm$ 59.3 $\pm$ 5.0 ^{a,b}	28.7 $\pm$ 34.6	57.6 $\pm$ 9.4 ^a	61.4 $\pm$ 9.0 ^c
Plot 4	18 $\pm$ 16	66.5 $\pm$ 14.6 ^a	56.9 $\pm$ 6.6 ^c	169.2 $\pm$ 66.4 ^c	$\pm$ 55.0 $\pm$ 10.0 ^c	38.2 $\pm$ 10.6	52.6 $\pm$ 6.9 ^b	41.4 $\pm$ 8.9 ^{a,b,c}

Daily SWE series (DS) were used to determine the effect of forest on snowpack duration and accumulation and melting rates of SWE. Spatially distributed SWE measurements (DM) were used to determine the effect of forest on the SWE CV. Both sources of data were used to determine the effect of forest on the cumulative SWE.

Identical superscript letters in the same column indicate significant differences for snow seasons or plots (Wilcoxon test, $p < 0.05$).

Table 5. Mann-Kendall linear trends in the intra-annual change of forest-mediated reduction in the cumulative SWE in each plot. Source of data: daily records.

Period	Snow season	Plot 1	Plot 2	Plot 3	Plot 4
Before SWE peak	2015/16	0.14*	0.11*	0.17*	-0.21*
	2016/17	-0.10	-0.15*	-0.40*	-0.03
	2017/18	-0.30*	-0.28*	-0.06	-0.24*
After SWE peak	2015/16	0.27*	0.54*	0.43*	0.55*
	2016/17	0.10	0.56*	0.60*	0.73*
	2017/18	0.22	0.51*	NA	0.60*

(*) $p < 0.05$

For Peer Review

Table 6. Mann-Kendall linear trends in the intra-annual changes of forest-mediated reduction in the SWE rates of accumulation and melting in each plot. Source of data: daily records.

Type of forest-mediated reduction	Period	Snow season	Plot 1	Plot 2	Plot 3	Plot 4
Accumulation rate	Before SWE peak	2015/16	-0.09	0.21	0.13	-0.09
		2016/17	-0.23	-0.10	-0.12	-0.16
		2017/18	-0.12	-0.16	0.03	-0.01
	After SWE peak	2015/16	-0.16	0.43	-0.40	0.20
		2016/17	0.06	0.51*	-0.03	<i>NA</i>
		2017/18	-0.33	-0.33	<i>NA</i>	<i>NA</i>
Melting rate	Before SWE peak	2015/16	<i>NA</i>	<i>NA</i>	<i>NA</i>	-0.17*
		2016/17	-0.21	-0.01	-0.04	0.12
		2017/18	-0.11	-0.10	-0.11	0.18*
	After SWE peak	2015/16	0.24	0.36*	-0.05	0.37*
		2016/17	0.17	0.05	0.20	0.46*
		2017/18	-0.27	0.08	-1.00	-0.12

(*) $p < 0.05$

Table 7. Spearman correlation coefficients for the relationships between forest variables and environmental variables in each plot.

Forest variables	Environmental variables	Plot 1	Plot 2	Plot 3	Plot 4
Forest increase SWE CV	Snow depth	-0.63*	0.01	-0.04	-0.26
Forest decrease accumulation rate	Daily snow accumulation	-0.57*	-0.54*	-0.62*	-0.42*
Forest decrease melting rate	Snow depth	-0.23*	-0.06	-0.26*	-0.05
Forest decrease melting rate	Global solar irradiance (†)	0.01	0.03	0.39*	0.33*
Forest decrease melting rate	Air temperature	-0.13*	-0.23*	0.05	0.10*

(*) $p < 0.01$

(†) Significant correlations only occurred during the main melting period (after SWE peak).

For Peer Review

Figure Legends

Figure 1. (a) Left: Study location (Balneario de Panticosa) in the Spanish Pyrenees. Right: Location of the experimental plots in the Balneario de Panticosa Valley (orthophoto source: PNOA 1:25000 n°145). (b) General view of the experimental plots *in situ*. (c) Example of the semi-automatic snow depth monitoring system in plot 2, based on time-lapse cameras and snow poles.

Figure 2. Daily snow-water equivalent (SWE) at each experimental plot and each snow season in areas beneath forest canopies (F, green lines) and in forest openings (O, blue lines).

Figure 3. (a) Cumulative SWE in areas beneath forest canopies (F) and in forest openings (O). (b) Reduction of SWE in forested areas. Box indicates 25% and 75% percentiles; central line represents the median; whiskers indicate $1.5 \times \text{interquartile range (IQR)}$; and points indicate outliers ($>1.5 \times \text{IQR}$ and $<3 \times \text{IQR}$). Dashed lines: averages of each plot during each snow season. Statistical differences between plots, snow seasons, and covers are indicated by same letters or an asterisk (Wilcoxon test, $p < 0.05$). Source of data: daily records.

Figure 4. Temporal changes in the effect of forest on reducing cumulative of SWE. Continuous lines: moving means for each plot over a 20-day period; dashed lines: general linear adjustments according to the main period of accumulation (A) and melting (B). Arrows indicate the date of peak of SWE. Statistically significant Mann-Kendall linear trends ($p < 0.05$) are indicated by asterisks. Table 5 provides related statistics. Source of data: daily records.

Figure 5. (a) SWE coefficients of variation in areas beneath forest canopies (F) and in forest openings (O). (b) Changes of SWE variability in forested areas. Box plots, dashed lines, and statistical differences are as described in Figure 3. Source of data: spatially distributed measurements from field surveys.

Figure 6. (a) Accumulation and (b) melting rates of SWE in areas beneath forest canopies (F) and in forest openings (O). Statistical differences are indicated by asterisks (Wilcoxon test, $p < 0.05$). (c) Effect of forest on accumulation rates and on melting rates. Dots: overall forest effect; whiskers: mean increase and mean decrease. Source of data: daily records.

Figure 7. Effect of forest on reducing the rate of accumulation (a) and melting (b). Significant differences among plots and snow seasons are indicated by the same letters (Wilcoxon test, $p < 0.05$). Boxes and dashed lines are as described in Figure 3. Source of data: daily records.

Figure 1. (a) Left: Study location (Balneario de Panticosa) in the Spanish Pyrenees. Right: Location of the experimental plots in the Balneario de Panticosa Valley (orthophoto source: PNOA 1:25000 n°145). (b) General view of the experimental plots in situ. (c) Example of the semi-automatic snow depth monitoring system in plot 2, based on time-lapse cameras and snow poles.

Figure 2. Daily snow-water equivalent (SWE) at each experimental plot and each snow season in areas beneath forest canopies (F, green lines) and in forest openings (O, blue lines).

101x84mm (600 x 600 DPI)

Figure 3. (a) Cumulative SWE in areas beneath forest canopies (F) and in forest openings (O). (b) Reduction of SWE in forested areas. Box indicates 25% and 75% percentiles; central line represents the median; whiskers indicate 1.5×interquartile range (IQR); and points indicate outliers (>1.5×IQR and <3×IQR). Dashed lines: averages of each plot during each snow season. Statistical differences between plots, snow seasons, and covers are indicated by same letters or an asterisk (Wilcoxon test, $p < 0.05$). Source of data: daily records.

105x50mm (600 x 600 DPI)

Figure 4. Temporal changes in the effect of forest on reducing cumulative of SWE. Continuous lines: moving means for each plot over a 20-day period; dashed lines: general linear adjustments according to the main period of accumulation (A) and melting (B). Arrows indicate the date of peak of SWE. Statistically significant Mann-Kendall linear trends ($p < 0.05$) are indicated by asterisks. Table 5 provides related statistics. Source of data: daily records.

2043x1264mm (96 x 96 DPI)

Figure 5. (a) SWE coefficients of variation in areas beneath forest canopies (F) and in forest openings (O). (b) Changes of SWE variability in forested areas. Box plots, dashed lines, and statistical differences are as described in Figure 3. Source of data: spatially distributed measurements from field surveys.

104x50mm (600 x 600 DPI)

Figure 6. (a) Accumulation and (b) melting rates of SWE in areas beneath forest canopies (F) and in forest openings (O). Statistical differences are indicated by asterisks (Wilcoxon test, $p < 0.05$). (c) Effect of forest on accumulation rates and on melting rates. Dots: overall forest effect; whiskers: mean increase and mean decrease. Source of data: daily records.

89x50mm (600 x 600 DPI)

Figure 7. Effect of forest on reducing the rate of accumulation (a) and melting (b). Significant differences among plots and snow seasons are indicated by the same letters (Wilcoxon test, $p < 0.05$). Boxes and dashed lines are as described in Figure 3. Source of data: daily records.

87x96mm (600 x 600 DPI)

Appendices

Figure S1. Snow-water equivalent (SWE) at each experimental plot and each snow season in areas beneath forest canopies (F, green lines) and in forest openings (O, blue lines). Confidence intervals: mean $\pm$ standard deviation. Source of data: spatially distributed measurements from field surveys.

Figure S2. (a) Cumulative SWE in areas beneath forest canopies (F) and in forest openings (O). (b) Reduction of SWE in forested areas. Box indicates 25% and 75% percentiles; central line represents the median; whiskers indicate 1.5×interquartile range (IQR); and points indicate outliers ($>1.5\times\text{IQR}$ and $<3\times\text{IQR}$). Dashed lines: averages of each plot during each snow season. Statistical differences between plots, snow seasons, and covers are indicated by same letters or an asterisk (Wilcoxon test, $p < 0.05$). Source of data: spatially distributed measurements from field surveys.

Figure S3. Effect of forest on reducing the rate of accumulation (a) and melting (b). Significant differences among plots and snow seasons are indicated by the same letters (Wilcoxon test, $p < 0.05$). Boxes and dashed lines are as described in Figure S2. Source of data: daily records.