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RESEARCH ARTICLE

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Snowtography quantifies effects of forest cover on net water input to soil at sites with ephemeral or stable seasonal snowpack in Arizona, USA

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Abstract

Forested, snow-dominated watersheds provide a range of ecosystem services including water supply, carbon sequestration, habitat and recreation. While hydrologic partitioning has been well-studied in watersheds with stable seasonal snowpack, less is known about watersheds with ephemeral snowpack. Furthermore, drought-related disturbances and/or management practices are altering vegetation cover in many forests, with unknown and potentially different, consequences for stable seasonal versus ephemeral snowpacks. This study quantifies net water input (NWI) to soil for two sites with contrasting stable seasonal and ephemeral snowpacks, respectively, for three water years in Arizona, USA. Observations include a network of automated cameras and graduated snow stakes (snowtography) deployed across gradients of forest structure, airborne lidar maps of topography and forests and SNOTEL station records. Given the importance of mixed-phase precipitation in ephemeral snowpack watersheds, an algorithm is developed to distinguish among snowfall and rainfall that does/does not contribute to snowpack mass. Finally, existing canopy interception and snowpack models are used to estimate how NWI varies with canopy cover. At the ephemeral snowpack site, increasing canopy cover reduces NWI amount and advances its seasonal timing less strongly than at the stable seasonal snowpack site. Interestingly, canopy reduces NWI duration at the ephemeral site but prolongs it at the stable seasonal snowpack site. These effects are more important in a cool/wet and average year than a warm/dry year. Understanding differences between canopy impacts on amount, timing and duration of NWI for areas with ephemeral versus stable seasonal snowpack is increasingly important as the number of watersheds with ephemeral snowpack grows.

KEYWORDS
forest, net water input to soil, precipitation partitioning, SNOTEL, snowmelt, Snowtography

1 | INTRODUCTION

Snowpacks in high-elevation forested areas are critical sources of water for forest health and for millions of people in water-limited regions such as the southwestern US (Bales et al., 2006; Barnett et al., 2005; Simpkins, 2018). While hydrologic partitioning has been well-studied in watersheds with stable seasonal snowpack, that is, a continuous winter-long snowpack, less is known about the growing number of watersheds with ephemeral snowpack. Characterization of snowpack dynamics and resulting impacts for soil moisture and streamflow are particularly challenging in forested environments with an ephemeral snowpack, where many processes affect snow partitioning (e.g., air temperature, humidity, hydrometeor size and temperature and fall rate; see also Harder and Pomeroy (2013); Harpold et al. (2017)) and the net water input to soils (e.g., canopy interception, sublimation, unloading and melt drip of the incepted snowfall; Bonner et al. (2022); Dickerson-Lange et al. (2015); Raleigh et al. (2022)). Furthermore, drought-related disturbances and/or management practices are altering vegetation cover in many forests, with unknown consequences for water balance. This is a critical knowledge gap in an era marked with droughts, forest die-offs due to drought-enhanced pests and pathogens, wildfires, heavily managed forested landscapes, human-caused global climate change and extreme-duration drought events (Gudmundsson et al., 2021; Hallema et al., 2018; IPCC, 2021; Williams et al., 2020). Therefore, the aim of this study is to improve our understanding of forest cover-snow-water interactions by quantifying net water input (NWI) to soil for sites with contrasting stable seasonal and ephemeral snowpacks.

At present, it is not clear how the relationships among forest cover, snowpack and NWI to soil vary between watersheds with stable seasonal versus ephemeral snowpacks. While significant research has been conducted for cold sites with seasonal snowpack (Barnhart et al., 2020; Harder & Pomeroy, 2013; Kittredge, 1953; Schmidt & Gluns, 1991), less is known about hydrologic partitioning at warm sites with an ephemeral snowpack. Ephemeral snowpack watersheds are also becoming more common as winter temperatures warm, and they present unique challenges to coherent, generalizable predictions (Koehn et al., 2021; Lundquist et al., 2013; Petersky et al., 2019). Some of the key challenges related to ephemeral snowpack include (i) the greater frequency of mixed-phase winter precipitation events; (ii) different importance of winter evaporative loss terms (owing to ephemerality of snowpacks) than at a stable seasonal snowpack site, a higher sensitivity of snowpack dynamics to relatively small changes in climate; (iii) breakdown of the traditional assumption that peak SWE can be considered as a proxy for total available water from a snowpack due to multiple mid-winter melt events or multiple SWE curves during winters; (iv) changing role of trees from retarding snowmelt rate due to shading and wind effects to accelerating melt as trees become radiative hotspots; and (v) complex interactions among climate, snow, topography and vegetation structure (Biederman et al., 2012; Broxton et al., 2020; Lundquist et al., 2013; Marks et al., 1999; Safa et al., 2021; Trujillo & Molotch, 2014). Thus, there is a need to develop a better understanding of forest-snow-water interactions and how such interactions differ between stable seasonal versus ephemeral snowpack sites.

Key Points

- The radius of canopy influence on interception is greater for a site with stable seasonal snowpack than for a site with ephemeral snowpack.
- The amount and timing of water inputs to soil are less sensitive to canopy cover at the site with ephemeral snowpack.
- A new method is developed to partition SNOTEL station precipitation data among snowfall and portions of rainfall that do/do not add to snowpack.

One challenging aspect for hydrological modelling of sites with ephemeral snowpack is difficulty partitioning between precipitation phase (Harpold et al., 2017; Jennings & Molotch, 2019; Wayand et al., 2016). While there are many techniques available to partition precipitation between rainfall and snowfall, most have difficulty when air temperature is close to freezing during storms, as is common in many areas with ephemeral snowpack (Jennings & Molotch, 2019; Wayand et al., 2016). Furthermore, these techniques generally do not consider rainfall falling on snow that contributes to SWE versus that which immediately contributes to soil moisture and/or streamflow (e.g., the 'two rains' concept of Kittredge (1953); see also Krogh et al. (2020); Marks et al. (1999)). While existing temperature- and humidity-based algorithms partition rain and snow precipitation, none of the existing algorithms separate rain into components that do/do not contribute to an existing snowpack (Auer, 1974; Harder & Pomeroy, 2013; Jennings et al., 2018; Wigmosta et al., 1994). This separation is more important for warmer, ephemeral snowpack sites, because they are more likely to experience winter rainfall.

Areas with ephemeral snowpack also experience repeated cycles of accumulation and ablation. Therefore, quantification of snowpack characteristics alone is not as effective for understanding hydrologic inputs to the soil as they are for areas with stable seasonal snowpacks (Harpold, 2016; Petersky & Harpold, 2018; Slater et al., 2017; Tyler et al., 2008). At ephemeral snowpack sites, neither peak seasonal SWE nor end-of-winter SWE is a reliable proxy for snowmelt water inputs, because melt occurs periodically during winter. It is important to be able to quantify the timing and amount of NWI (the water entering the soil either as rainfall or snowmelt), which is more challenging than characterizing SWE. The literature on forest cover-snow-water interactions is mostly focused on variability in snowpack depth, SWE and snow disappearance, with comparatively few studies explicitly linking snowpack to soil moisture dynamics (Harpold & Molotch, 2015; Kerhoulas et al., 2013; Kerhoulas & Kane, 2012), streamflow (Tarboton & Goeking, 2020) and subsurface microbiology and biogeochemistry (Brooks et al., 1996; Sorensen et al., 2020). Focusing on snowpack alone might obscure important differences between the impact of forest on snowpack and the impact of forest on NWI. While many studies suggest that decreasing forest cover leads to increased snowpack at many sites (Varhola et al., 2010), there may be mismatches between how snowpack is changed by forest cover and how NWI is consequently altered. Therefore, it is important to be able to characterize both snowpack and NWI together and to further understand their differences between sites with stable seasonal versus ephemeral snowpack.

In response to these pressing challenges, the present study addresses the following research questions: (1) How can SNOTEL station precipitation and SWE data be combined to partition snowfall and the components of rain that do/do not contribute mass to the snowpack? (2) How does canopy cover regulate the amount, timing and duration of NWI to soil from rain and/or snowmelt? (3) How do the amount, timing and duration of NWI differ between stable seasonal and ephemeral snowpack sites? These questions are addressed by developing a method to partition the three types of winter precipitation, quantifying snow dynamics at 46 locations across a gradient of forest structure and estimating the amount, timing and duration of NWI to soil. This is accomplished for two contrasting sites with stable seasonal versus ephemeral snowpack during three winters using snowtography (snow photography), SNOTEL station data and lidar maps of forest cover. We use simple, well-accepted snow and rain interception parameterizations and an existing one-dimensional snowmelt model in order to keep the focus on NWI to soils across gradients of forest cover at stable seasonal versus ephemeral snowpack sites.

2 | STUDY SITES AND DATA USED

2.1 | Site description

This study uses data from two forested field sites located in Central and Eastern Arizona near the headwaters of the economically vital Salt-Verde River Basin, which provides water supply to much of central Arizona (Demaria et al., 2017; Larson et al., 2005) (Figure 1). The Eastern Arizona field site (hereafter 'high-elevation' or 'stable seasonal snowpack' site) is located at an elevation of 2816 m a.s.l. (mean slope of 5° and a predominantly eastern aspect), and the Central Arizona site ('mid-elevation' or 'ephemeral snowpack' site) is located at an elevation of 2,217 m a.s.l. (mean slope of 3° and a predominantly southwestern aspect). Despite similar ranges in total winter

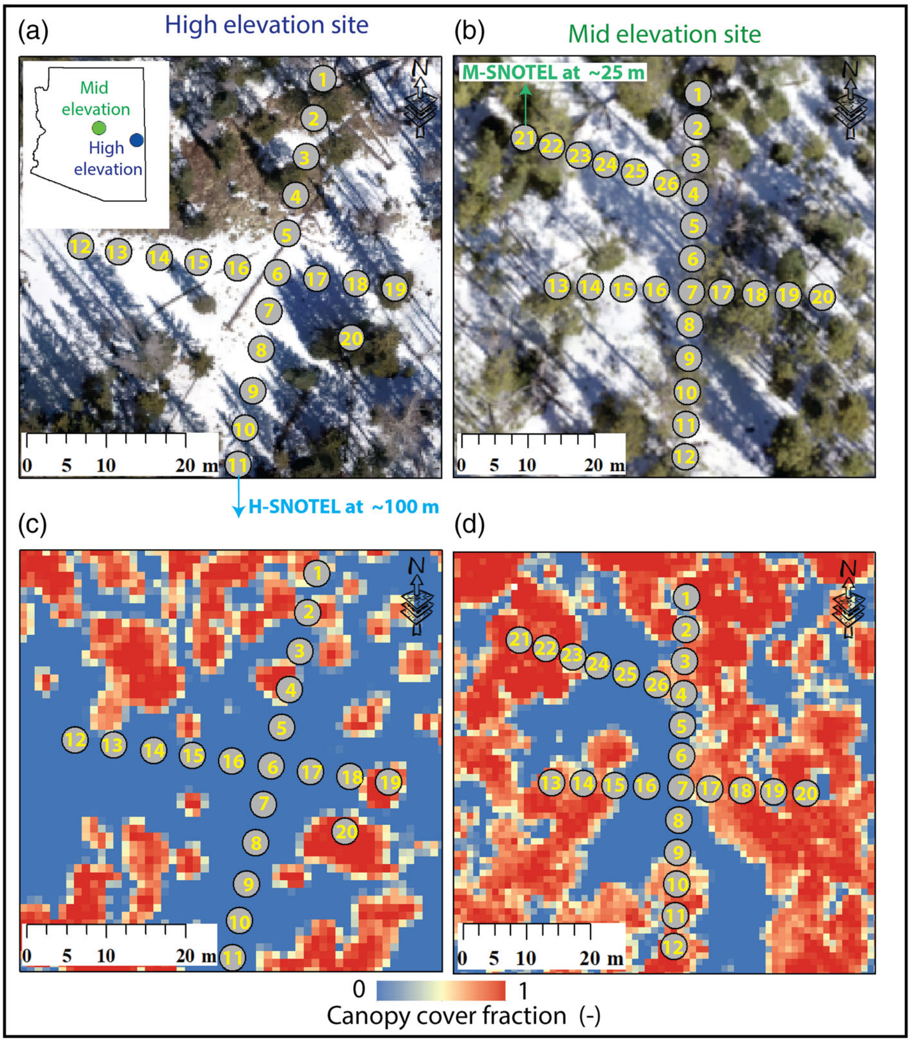

FIGURE 1 The location of the snowtography stakes along with the site orthoimage acquired using a drone (a) and *lidar*-derived canopy cover fraction (CC; C) at 1-m scale at the high-elevation site. (b) and (c) show the same information for the mid-elevation site. The location of the field sites in the regional map is shown in the inset plot in (d).

precipitation (Table 1), the high-elevation site experiences greater SWE and lower mean daily air temperature than the mid-elevation site (Table 1 and Figure S1). The high-elevation site often develops a stable seasonal snowpack typical of well-studied cold region snowpacks (e.g., see Trujillo and Molotch (2014)), while the mid-elevation site usually has an ephemeral snowpack with multiple mid-winter ablation events (Figure S1 in Supporting information) typical of highland areas in Arizona and the US Southwest that are generally not as well-studied (Petersky et al., 2019; Petersky & Harpold, 2018). At the mid-elevation site, where fire has been mostly excluded for >120 years, forest cover is denser (Table 1) and vegetation is mostly ponderosa pine (*Pinus ponderosa*) forest with lesser amounts of Douglas fir (*Pseudotsuga menziesii*) and Gambel oak (*Quercus gambelii*) (Broxton et al., 2020). At the high-elevation site, forest cover is less dense, and vegetation consists of mixed conifer forest interspersed with mountain meadows (Broxton et al., 2020). The high-elevation site experienced a forest fire (Wallow Fire) in 2011, resulting in a mixture of dead and live tree stands.

2.2 | SNOTEL station and snowtography data

Both study sites have SNOTEL stations (Maverick Fork SNOTEL, site ID: 617 at the high-elevation site and Baker Butte SNOTEL station, site ID: 308 at the mid-elevation site; Table S1), as well as a network of photographed snow depth measurement stakes (snowtography) at each site (Broxton et al., 2020). The SNOTEL station data at each site consist of hourly measurements of snow depth (using an ultrasonic snow depth sensor), SWE (using a snow pillow) and precipitation (using a shielded weighing bucket precipitation gauge) in sheltered clearings. The snowtography data consist of daily snow depth at snow stakes photographed by automated trail cameras (Payton et al., 2021). The stakes are arranged across forest clearings to capture the spatial variability of snow accumulation and ablation (sublimation and/or melt) across gradients of canopy, shading and wind exposure. There are 26 snowtography stakes at the mid-elevation site and 20 at the high-elevation site (Figure 1a,b), which provide daily snow depths for the study period: Winters 2018–2020. Snowtography images are also interpreted visually to estimate daily canopy snow content at three levels: 'none', 'partial' and 'abundant'. The resulting time series is used for evaluation of the precipitation partitioning and canopy snow models.

TABLE 1 Locations and meteorological characteristics of the high- and mid-elevation sites for water years 2018/2019/and 2020

Category	High elevation	Mid elevation
SNOTEL station—latitude (decimal degrees)	33.92122343	34.45654459
SNOTEL station—longitude (decimal degrees)	109.4587336	111.4065253
SNOTEL station elevation (m, asl)	2804	2225
Average percentage canopy coverage	35	58
Annual precipitation (mm)	373/787/594	465/790/706
Winter precipitation (mm)	104/429/391	160/516/622
Cumulative positive SWE increments (mm)	84/419/302	119/356/300
Peak annual SWE (mm)	53 /323/254	53/183/140
Winter mean daily air temperature (°C)	3.5/0.9/1.8	7.8/5.0/5.6
Peak SWE dates (mean date in dd/mm format/ standard deviation in days)	2nd of March/16th of March/2nd of March	1st of March/23rd of February/7th of March

Notes: (a) water year *n* is defined as the annual period from October 1st through September 30th of the following year, and (b) a winter season is defined as the November through April period.

2.3 | Lidar data

Multiple airborne lidar datasets collected by Quantum Spatial, Inc., are utilized to develop maps of forest canopy height and cover with average point densities of 10–15 points/m^2. More information about these datasets can be found in Broxton et al. (2020); Quantum Spatial Inc. (2013, 2014, 2019).

3 | METHOD DESCRIPTION

3.1 | Precipitation partitioning method (PPM)

A new PPM is developed using SNOTEL station data (Figure 2 and Table 2). Our PPM partitions daily precipitation into snowfall (S_s) and two rainfall terms: rain, which contributes to existing snowpack (R_s) and rain that is a same-day moisture input to soil (R_o). Specifically, when mean daily air temperature (T_a) is less than a critical value (T_c), precipitation is considered as snowfall or S_s. During days when $T_a > T_c$, three possible components S_s, R_s and R_o are computed according to the rules in Table 2. T_a is set to the average of hourly maximum and minimum air temperature for any given day, T_c is set to 1°C, following Jennings et al. (2018) and Rajagopal and Harpold (2016) and a maximum new snowfall density (ρ_{max}) is set to 0.25 g/cm^3, based on the maximum observed density of new snowfall at the study sites (Figure S2c and Figure S3c in Supporting information). Due to instrument noise and jitter in the observed SNOTEL station precipitation data, especially during low snowpack conditions, the daily observed precipitation on snow-covered days is adjusted such that if the difference P-ΔSWE is negative, then P is set to ΔSWE before applying the proposed PPM (see Figure S2c and Figure S3c in Supporting information).

3.2 | Canopy cover and canopy height models

The canopy cover (CC) and canopy height (CH) models are derived from lidar data (obtained in 2019) (Figure 1c,d). First, a 1-m resolution

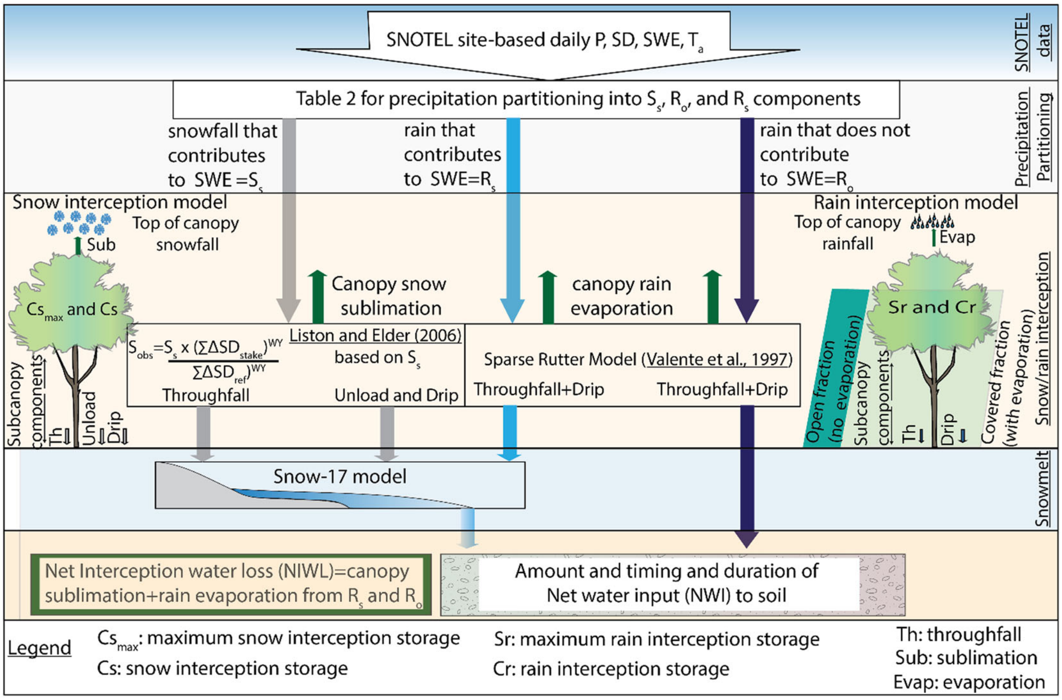

FIGURE 2 Flow chart for estimating net water input (NWI) to soil and net interception water loss (NIWL) at each snowtography stake location

TABLE 2 Rules for process-based precipitation partitioning on a daily time scale

Condition 1	Condition 2	Condition 3	Condition 4	S_s	R_s	R_o
$T_a <= T_c$				Max (0, ΔSWE)	0	0
$T_a > T_c$	SD = 0			Max (0, ΔSWE)	0	Max (0, P-S_s)
$T_a > T_c$	SD > 0	ΔSWE < =0		Max (0, ΔSWE)	0	P
$T_a > T_c$	SD > 0	ΔSWE > 0	ΔSD < =0	0	ΔSWE	Max (0, P-R_s)
$T_a > T_c$	SD > 0	ΔSWE > 0	ΔSD > 0	Min (ΔSWE, ΔSDxρ_{max})	ΔSWE-S_s	Max (0, P-S_s-R_s)

Note: S_s is snowfall, R_s and R_o are rain components that do and that do not contribute to an existing snowpack, respectively, T_c is the critical air temperature, T_a is the mean daily air temperature, SD and SWE are the latest snow depth and snow water equivalent, respectively, ΔSD and ΔSWE are daily changes, ρ_{max} is the maximum allowed new snow density (see also Figure S2 and S3 in Supporting information).

digital terrain model (DTM) is constructed from lidar collected under snow-free conditions using the US Forest service Fusion software (McGaughey, 2020). Then, CC and CH models are developed at 1-m spatial resolution using a height threshold of 2 m for trees. At each snowtography stake, values of CC and CH are quantified from the mean of all pixels within a variable radius ranging from 1 to 25 m with a step size of 2 m.

3.3 | Snow and rain interception models

Separate interception models are used to simulate canopy rain and snow interception, storage and ablation processes (Figure 2). For snow, the Liston and Elder (2006) model is used for estimating maximum canopy snow storage parameter and the effective radius of canopy influence using the observed daily throughfall rates (Th[t]; mm/day)—quantified at each stake by differences in accumulated snow depth on a snow event basis (see also Figure S1 in Supporting information for details). Specifically, daily throughfall rates are computed as the product of daily snowfall (S_s) from the PPM and the ratio of total snowfall depth at any stake to that at an open-condition reference stake (identified as the stake at each site with maximum total winter snowfall). This procedure assumes that (1) for each snow event, new snowfall density is constant across snowtography stake locations and (2) the reference stake snowfall is the same as at the SNOTEL station (from which S_s is computed), since both represent open canopy conditions.

When applying the Liston and Elder (2006) model, daily observed throughfall is utilized in two ways. First, the parameter governing maximum canopy snow storage capacity and the effective radius of canopy influence are estimated based on optimization with both observed daily throughfall rates and the natural logarithm of total

3-year snow throughfall. Second, the estimated parameters from the first step are used in conjunction with observed daily throughfall rates for keeping track of canopy snow storage and fluxes using the snow interception model.

A daily accounting is kept of canopy snow storage by computing the fluxes of interception, canopy sublimation, melt drip and snow unloading. Canopy snow storage is computed as:

$$C_s(t) = C_s(t-1) + \mathrm{Int}(t) \quad (1)$$

where $C_s(t)$ is the canopy snow storage at the current timestep, $C_s(t-1)$ is the canopy snow storage from the previous day and $\mathrm{Int}(t)$ is the daily interception rate given by:

$$\mathrm{Int}(t) = S_s(t) - \mathrm{Th}(t) = 0.7(C_{s,max} - C_s(t-1))\left(1 - e^{-\frac{S_s(t)}{C_{s,max}}}\right) \quad (2)$$

where $S_s(t)$ is the daily snowfall rate, $\mathrm{Th}(t)$ is the daily throughfall rate and $C_{s,max}$ is the maximum snow interception storage. Subsequently, the canopy snow ablation fluxes, sublimation ($\mathrm{Sub}(t)$), melt drip ($\mathrm{Drip}(t)$) and snow unloading ($\mathrm{Unload}(t)$) are computed on daily time steps using the current canopy storage conditions or $C_s(t)$. $\mathrm{Sub}(t)$ and $\mathrm{Drip}(t)$ components are computed from formulations in Liston and Elder (2006) (and are not reproduced here for). Following Broxton et al. (2014), snow unloading is computed as:

$$\mathrm{Unload}(t) = 0.083\ \mathrm{day}^{-1} \times C_s(t) \quad (3)$$

Following Liston and Elder (2006), $C_{s,max}$ is estimated as the product of an optimization parameter, f, and the effective leaf area index or LAI (Equation 4). The effective LAI is computed from CC Liston and Elder (2006) (Equation 5). For each possible effective radius of canopy influence (varying from 1 to 25 m), the optimal value of the parameter *f* is estimated globally for all stakes at a given site by minimizing residuals between simulated and observed throughfall. Subsequently, calibration of the sublimation, drip and unloading terms is done by comparing the simulated canopy snow storage, $C_s(t)$, and the observed canopy snow condition data obtained from snow photographs using a constant factor for each term. When daily rates of sublimation, unload and melt are reduced by 50%, 50% and 10% (applicable to both sites), respectively, simulated canopy snow storage is able to mimic observed conditions. These factors applied well across a variety of snowfall events across three winters with different degrees of sublimation, snow unload and melt drip (see also Figure S4 in Supporting information). Finally, the effective radius of canopy influence is estimated by including previously mentioned snow interception processes and by optimally matching global rates and amounts of throughfall for each site using the modified Kling-Gupta efficiency or KGE (Gupta et al., 2009; Kling et al., 2012).

$$C_{s,max} = f \text{ X } \mathrm{LAI} \quad (4)$$

$$\mathrm{LAI} = \exp\left(\frac{CC - 0.55}{0.29}\right) \quad (5)$$

Using the optimal values of the f parameter and radius of canopy influence and the corresponding CC and effective LAI values, the daily observed throughfall rates are used as model input for simulating daily fluxes of sublimation, unload and drip.

Rainfall interception is simulated using the CC at each stake and the sparse Rutter model (Valente et al., 1997) (Figure 2). Evaporation from wet canopies is modelled using the Penman-Monteith equation (Allen et al., 1998) by setting the canopy resistance to zero and using mean CH to estimate zero-plane displacement height and roughness length (Rutter & Morton, 1977). The storage capacity (S) for rain, when considering both covered and uncovered areas, is set to 1 mm for the mid-elevation site with ponderosa pine forest, following Johnson (1942) who used S between 0.8 and 1.3 mm for young ponderosa pine. For the high-elevation site with mixed conifer forest S is set to 1.5 mm, following (Rutter & Morton, 1977) who suggest S can vary between 1 and 2 mm for conifer stands. Canopy rain storage capacity (S_r) is set equal to the ratio of storage capacity S and CC (Valente et al., 1997).

3.4 | Snowpack model

The snowpack is simulated at each SNOTEL station and snowtography stake using the point-scale version of the SNOW-17 model at daily time steps (Figure 2). SNOW-17 is an index model that uses precipitation and air temperature to simulate snowpack dynamics and snowmelt outflow (Anderson, 2006) and requires eight parameters (see also He et al. (2011)). The model is calibrated separately at each SNOTEL station and snowtography stake for the period of November to April. In this study, model precipitation inputs are prescribed based on the observations described in prior sections. Therefore, only snow ablation parameters are calibrated. Specifically, UADJ (average wind function during rain on snow, mm/mb/°C), MBASE (base temperature above, which melt occurs, °C), MFMAX (maximum melt factor during non-rain period, mm/ °C) and MFMIN (minimum melt factor during non-rain period, mm/°C) parameters (see also Figure 1 in He et al. (2011)) are varied for model calibration, while all other parameters are provided values suggested by He et al. (2011). The model is calibrated to minimize KGE at each SNOTEL station using daily snow depth, SWE and snowpack density. Each parameter is normalized to the minimum and maximum of the corresponding observations. At the snowtography stakes, only snow depth time series data are used for model calibration. Calibration excludes days when snowfall occurs (as well as the following 2 day) because we observe inconsistency between snowtography and SNOTEL station snow depths during the events (see also Figure S2 in Supporting information).

3.5 | Estimation of the amount, timing and duration of NWI to soil

The NWI to soil is computed daily at each stake as the sum of rainfall not contributing to snowpack (R_o passed through the interception

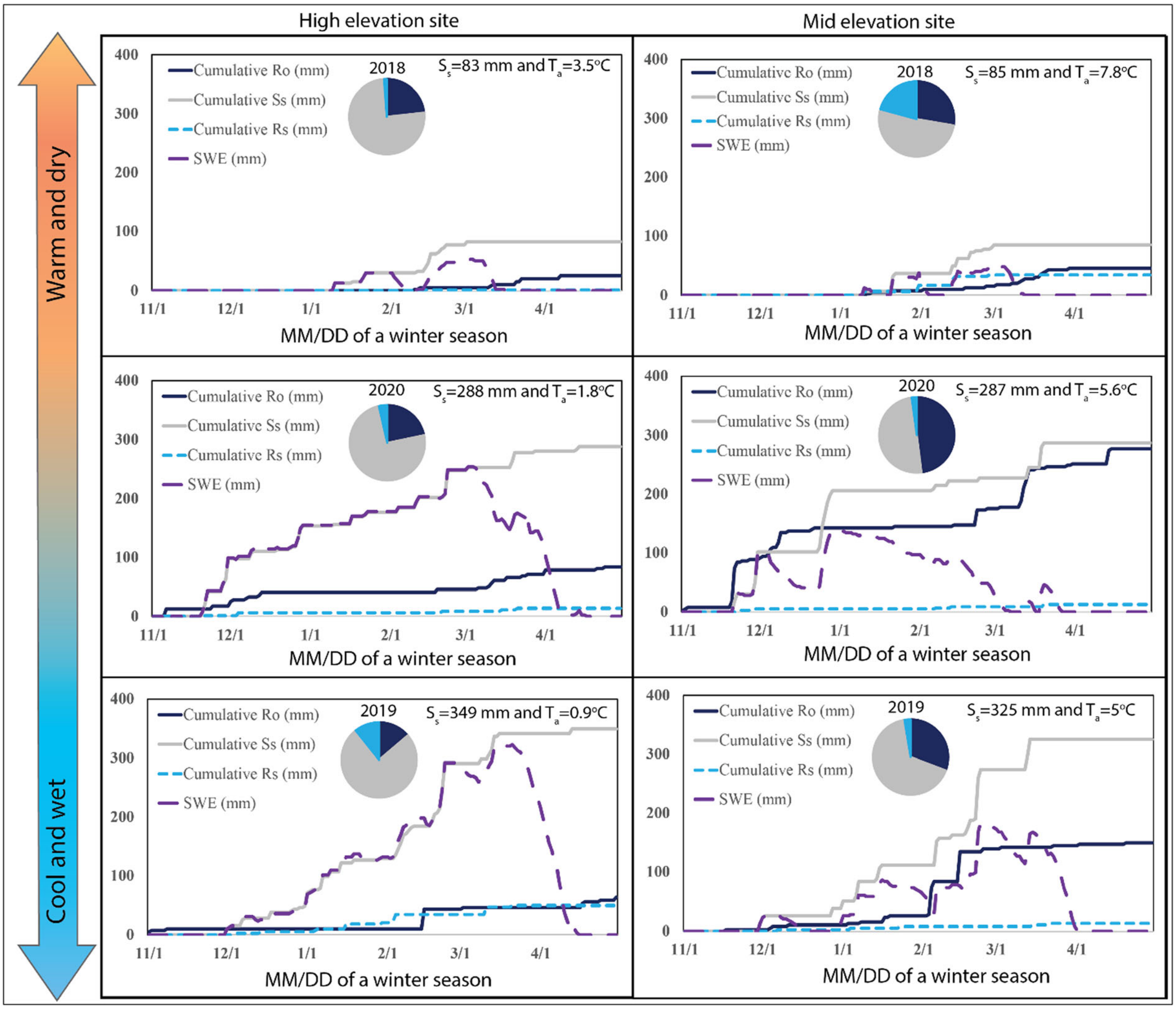

FIGURE 3 Cumulative winter time series of R_o, R_s and S_s at the high- (left column) and mid-elevation (right column) sites. Inset pie charts show cumulative values for the given winter. Mean daily air temperatures (T_a) and total snowfall amounts (S_s) are given for each winter.

model) and snowmelt (Figure 2). At each snowtography stake, the average amount of time precipitation is stored above ground; the NWI time lag is determined as the time interval between the 50th percentiles of cumulative winter precipitation (P_{50}) and cumulative winter NWI (NWI_{50}). NWI duration is computed as the number of days between the 10th and 90th percentiles of cumulative NWI for a given winter. Note that at ephemeral snowpack sites, evaluating NWI duration in terms of snow-covered duration or duration of ablation phase is problematic due to multiple mid-winter melt events and the component of precipitation, Ro, that contributes to NWI but not to an existing snowpack.

4 | RESULTS

Most analyses in the following sections focus on the winter season (November–April) as this the period when appreciable snowpack can occur at the research sites.

4.1 | Study period weather and success rate of the proposed PPM

4.1.1 | Study period weather

The three study winters span a wide range of weather conditions (Figure 3). At both the high- and mid-elevation sites, Winter 2018 was the warmest and driest (i.e., had the highest mean daily air temperature and lowest snowfall amount), while Winter 2019 was the coolest and wettest, with Winter 2020 intermediate. Therefore, the three study winters are referred to as: Winter 2018—warm and dry; Winter 2019—cool and wet; and Winter 2020—intermediate conditions. This variety of winter weather provides an opportunity to explore the performance of the PPM and the impacts of CC on NWI over a range of meteorological conditions at an ephemeral snowpack/mid-elevation versus stable seasonal snowpack/high-elevation site.

During the three winters, there was more precipitation at the mid-elevation than at the high-elevation site, but the fraction of

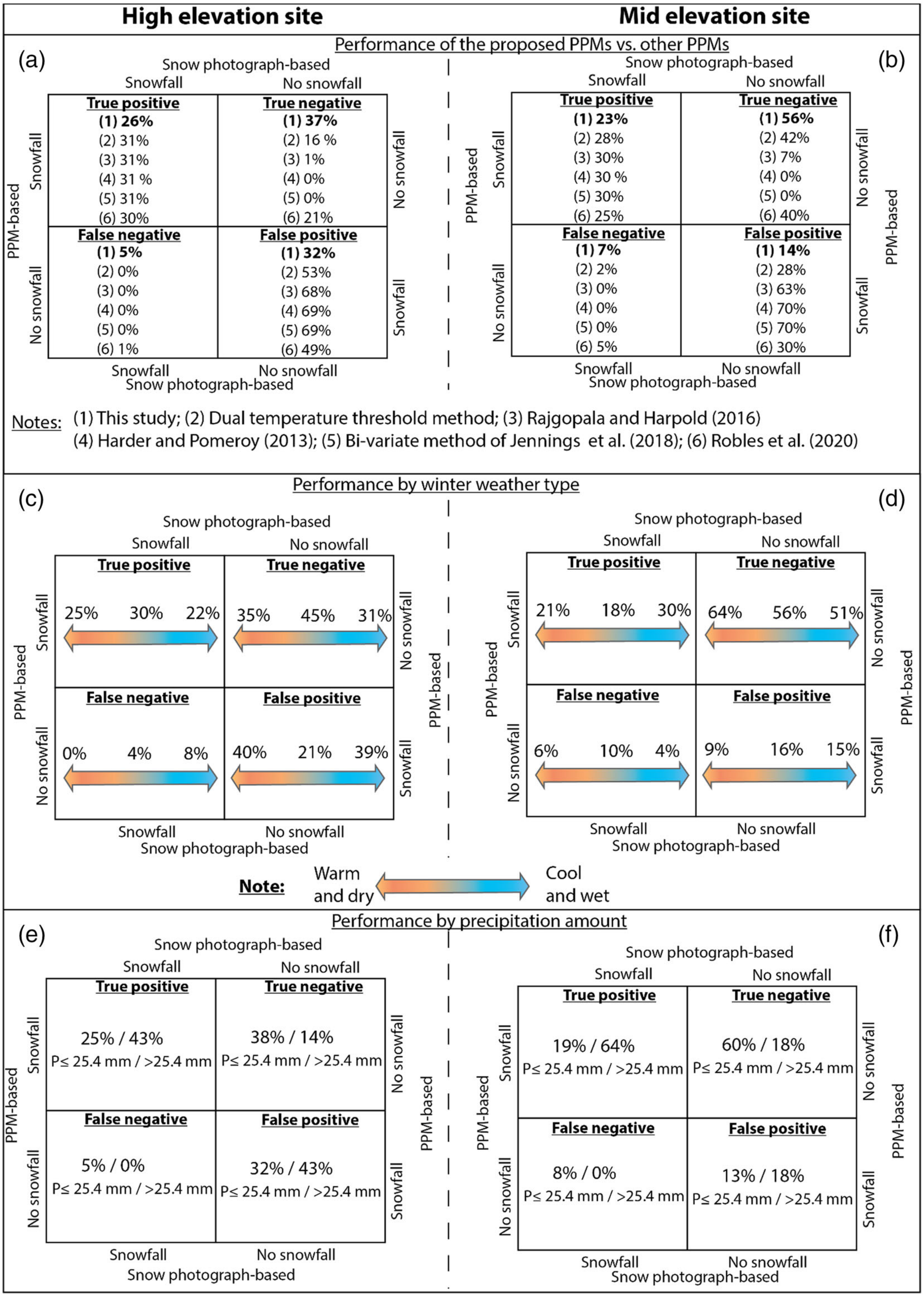

FIGURE 4 Performance of the proposed precipitation partitioning method (PPM) in comparison to other PPMs for classifying days into snow/non-snow days during the winter season for the high- (a) and mid-elevation (b) site. Performance of the proposed PPM by winter weather type (c and d) and precipitation amount (e and f) for high- and mid-elevation sites

precipitation as snowfall was greater at the higher elevation site. At the mid-elevation site, total precipitation and fraction of precipitation as snowfall during three winters were 165 mm/52% (Winter 2018), 577 mm/50% (Winter 2020) and 488 mm/67% (Winter 2019). In contrast, at the high-elevation site, total precipitation and fraction of precipitation as snowfall during three winters were 109 mm/76% (Winter 2018), 386 mm/75% (Winter 2020) and 462 mm/76% (Winter 2019). At the high-elevation site, the proportion of R_s is larger during Winter 2019 than its proportion for any other winters due to a few warm rain events.

4.1.2 | Precipitation partitioning mass balance and snowfall day identification

The PPM developed here for SNOTEL station records was successful in terms of total precipitation mass balance and identification of snowfall days, which was validated using snow photographs. For the combined three winters, mass balance errors for precipitation were 6% and 8% at the mid- and high-elevation sites, respectively. For individual winter seasons, the maximum total error for precipitation was 7% (Winter 2020) for the mid-elevation site, and it was 11% (Winter 2019) for the high-elevation site (TableS1 in Supporting information). The overall success rate for correctly identifying snowfall and non-snowfall days for the combined three winters—defined as the sum of true positive and true negative percentages—was 63% and 79% at the high- and mid-elevation sites, respectively (Figure 4a,b). For individual winter seasons, this success rate varies between 53% (Winter 2019) and 75% (Winter 2020) at the high-elevation site. In contrast, at the mid-elevation site, the success rate varies between 74% (Winter 2020) and 85% (Winter 2018). The new PPM has overall mass balance errors less than 10% of the total winter precipitation and a success rate of at least 63% across both high- and mid-elevation sites.

The proposed PPM shows a greater success rate for correctly identifying snowfall/non-snowfall days and less overprediction of snowfall days for the mid- than the high-elevation site, especially for large precipitation events (Figure 4). The overall success is 79% at mid-elevation site, which is 16% higher than the success rate at the high-elevation site. The overall model response also showed 14% overprediction of snowfall days at the mid-elevation site, which is slightly better than the overpredictions of 32% for snowfall days at the high-elevation site. Across three winters with contrasting weather types, the PPM success rate was in general higher at the mid-elevation site (range of success rate: 74%–85%) than at the high-elevation site (range of success rate: 53%–75%) (Figure 4c,d). Based on daily precipitation amounts, the success rate is 3% greater for the daily precipitation amounts >25.4 mm than for lesser amounts at the mid-elevation site, but it is 6% lower at the high-elevation site when using the same daily precipitation amount thresholds (Figure 4e,f).

Our PPM showed a better performance and a higher success rate in identifying snowfall/non-snowfall days for both high- and mid-elevation sites than existing PPMs (Figure 4a,b). The existing PPMs considered here were (i) dual temperature threshold (0.6 and 3.6°C) method that used linear interpolation for air temperature between the threshold temperatures (Pipes and Quick (1977) reviewed in Harder and Pomeroy (2013)); (ii) Rajagopal and Harpold (2016) method that is based on Dai (2008) mathematical model with Rajagopal and Harpold's (2016) calibrated parameters for the Arizona and New Mexico sites; (iii) Harder and Pomeroy (2013) method when using their fitted model coefficients for daily time steps; (iv) temperature and relative humidity or bivariate model from Jennings et al. (2018); and (v) Robles et al. (2020) method with parameters for moderate snow conditions. For example, at the high-elevation site, the proposed PPM is 12% more effective than the second-most effective method, that is, Robles et al. (2020) method. At the mid-elevation site, the proposed PPM is 9% more effective than the second-most effective method based on dual temperature threshold.

4.2 | Pattern of subcanopy total snowfall and effective radius of canopy influence at high- versus mid-elevation site

In general, increased CC reduced subcanopy snowfall, and this reduction with CC was steeper for the high- than for the mid-elevation site (Figure 5a). With a unit increase in canopy cover fraction, the total amount of subcanopy snowfall for three water years was reduced by 20% versus 30% at the mid- and high-elevation sites, respectively, in comparison to total snowfall amount at the corresponding reference open locations (see also Figure S2 in Supporting information). Also, at both sites, the total snowfall amount showed significant variability with location when considering stakes with very low canopy cover fractions. Objective optimization of modelled canopy interception to match snowtography depth changes showed the effective radius of canopy influence was 7 m at the high-elevation site and 3 m at the mid-elevation site (Figure 5b). This difference in effective radius could be the result of a number of site differences (physical characteristics of canopy, snow density, wind patterns, etc.), which are discussed in Section 5.2.

4.3 | Patterns of snow and rain interception loss

4.3.1 | Canopy snow fluxes

Interception and sublimation vary most strongly with CC at the high-elevation site (Figure 6). While throughfall, sublimation and unload represent the dominant canopy fluxes at the high-elevation site, throughfall, unload and drip fluxes dominate at the mid-elevation site. For example, for Winter (2020) under dense canopy at the high-elevation site, canopy snow mass balance shows throughfall, sublimation and unload account for 38.6%, 26.2% and 28.4% of total mass balance, respectively (the remaining 6.8% is attributed to drip). In contrast, for the same winter season and under similarly dense canopy at the mid-elevation site, throughfall accounts for 56.1%, unload accounts for 28.2%, drip accounts for 10.2% and sublimation accounts for 5.5% of the total mass balance. Interestingly, the rates at which increasing canopy influences interception and sublimation are greatest at the high-elevation site. For an intermediate warm and wet winter at the high-elevation site, a unit increase in canopy cover fraction, that is, going from an open to a highly canopy-covered condition, increases interception and sublimation fractions by 58%/25%. In contrast, for the same increase in CC, interception and sublimation fractions increase by 24%/4% at the mid-elevation site. Overall, simulated canopy snow storage was able to mimic observed conditions (Figure 5c,d), with better matching at the high-elevation site.

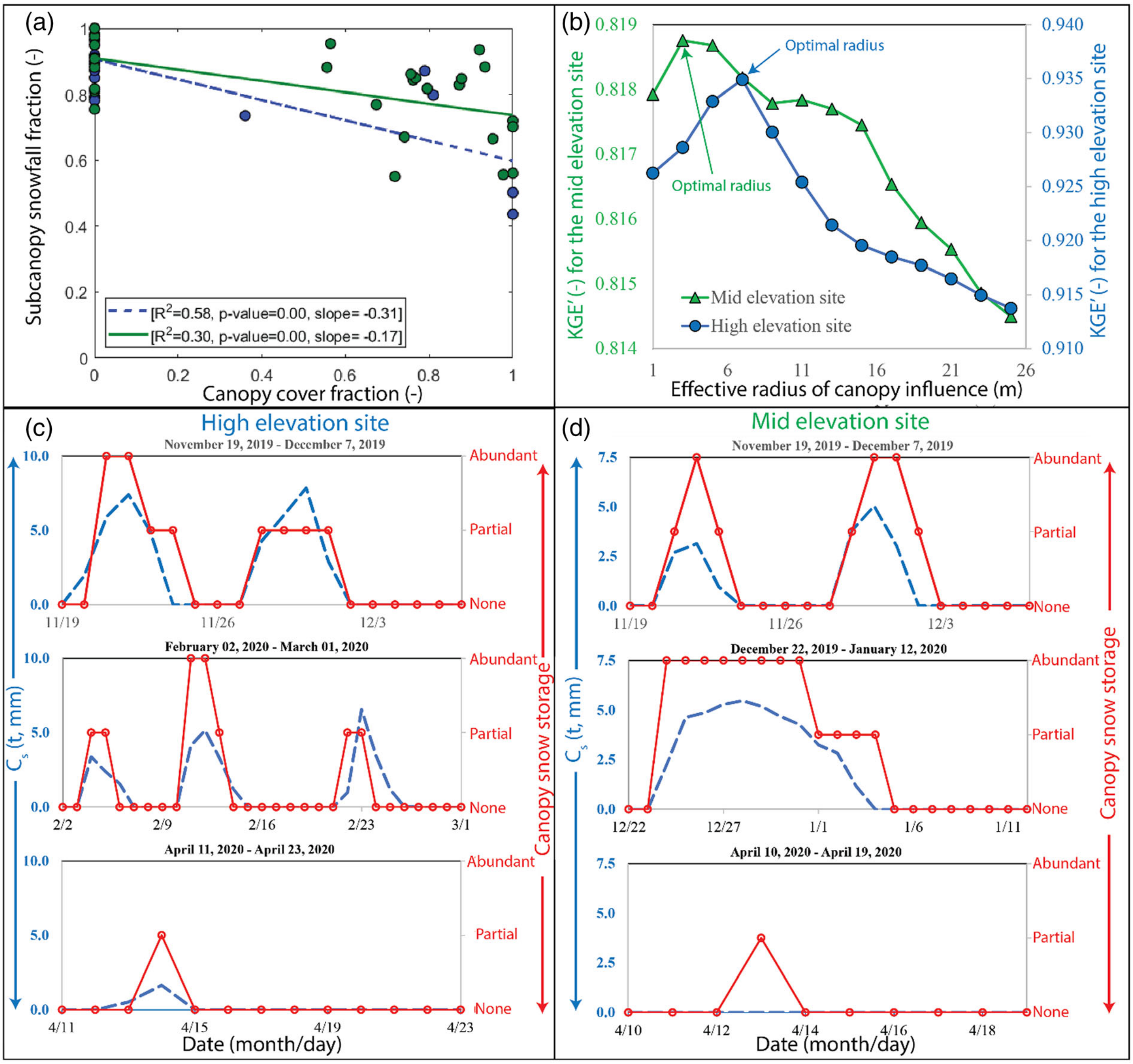

FIGURE 5 (a) Pattern of the ratio of total 3-year snowfall at any stake to total snowfall at SNOTEL station over the whole study period. (b) Effective radius of canopy influence for snowfall interception. (c) Pattern of modelled canopy snow storage (dashed blue curve; left axis) and photograph-based canopy snow storage (solid red curve with markers; right axis) for selected dynamic periods at the high-elevation (c) and mid-elevation (d) sites

4.3.2 | Canopy rain fluxes

The pattern of rain throughfall fraction with CC is similar between the high- and mid-elevation sites, but there is a greater fraction of the rainfall that is evaporated and a lower fraction of rainfall that is dripped from the high-elevation site (Figure S6). At the high-elevation site, from a highly covered stake 32% (75 mm from 237 mm total rainfall) of total rainfall was evaporated during three winters, which is 17% higher than total evaporation fraction (15% or 81 mm from 532 mm total rainfall) from the highly covered stake at the mid-elevation site. When considering rain and snow interception processes together, a higher fraction of rainfall than snowfall is lost to the atmosphere at both sites (Figure S7 in Supporting information). Note that modelled rainfall interception processes are entirely dependent on CC, so there is very little scatter in the relationships in Figure S6.

4.4 | Simulated snowpack dynamics

The snowpack model was able to mimic snowtography depth observations that differed strongly with forest cover at both high- and mid-elevation sites (Figure 7a,b). There was greater variability in observed snow depth for the intermediate Winter 2020 than the warm/dry and cool/wet winters (Figure S8 in Supporting information), and we focus here on 2020 results. In comparison to using a single set of calibrated model parameters from the SNOTEL station, models whose parameters were calibrated independently at each snowtography stake were

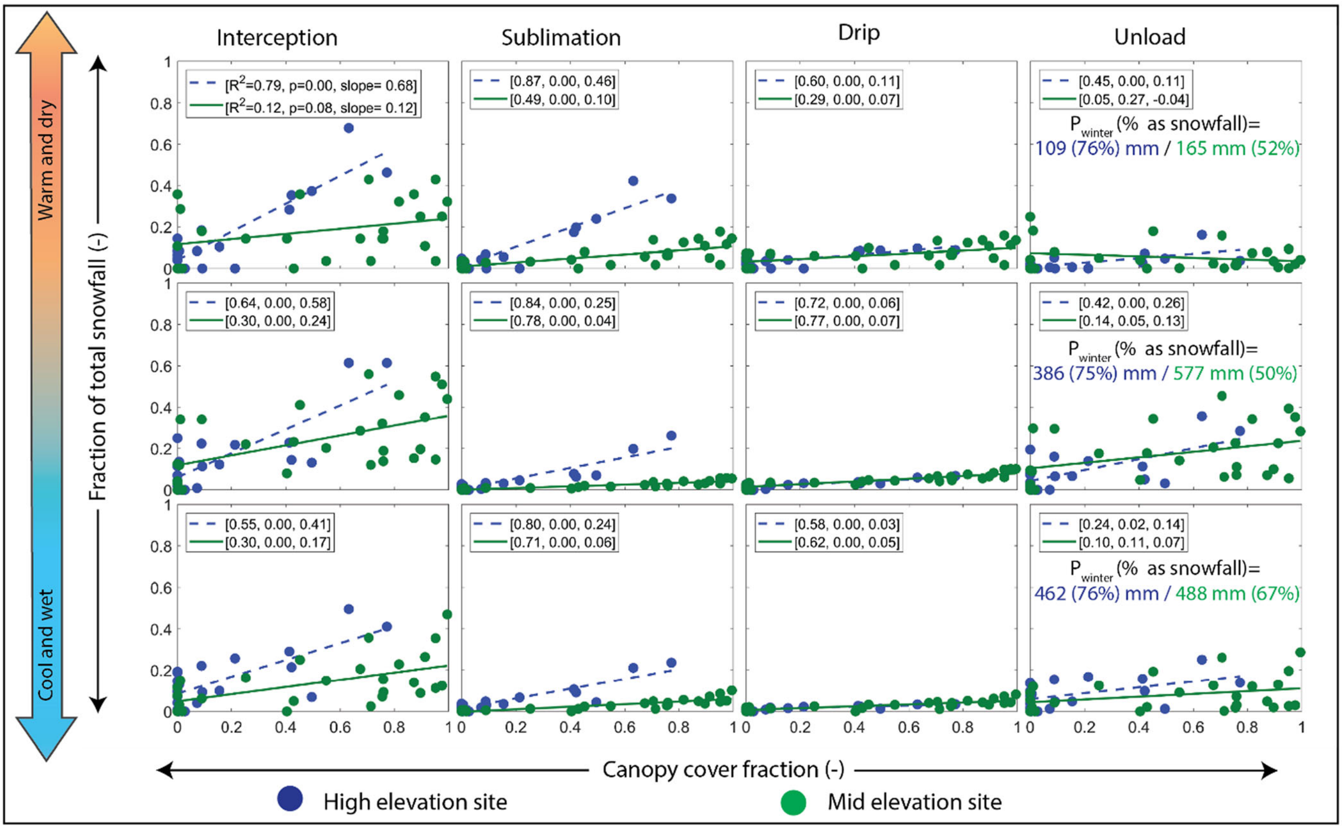

FIGURE 6 Canopy snow fluxes versus canopy cover using the optimal radius of canopy influence determined for each site (Figure 5). The total winter precipitation and percentage of precipitation as snowfall for each winter are listed in the right panel for both sites.

better able to simulate snowpack ablation patterns (Tables S2–S5) and the timing of NWI. Finally, this stake-specific snowpack snowmelt model calibration makes sense here because the 1-D SNOW17 model cannot account for 3-D effects on radiation, snow accumulation and wind patterns.

4.5 | NWI amount, timing and duration

Consistent with interception results (Figure 6), NWI amount per winter decreased with greater CC for both sites, and the reduction in NWI was steeper for the high- than for the mid-elevation site (Figure 8a1–a3). NWI relationships with CC varied with winter meteorological conditions. Interestingly, CC had the strongest influence on NWI during the intermediate winter and less influence in both the warm/dry and cool/wet winters.

Consistent with colder winter temperatures, the NWI time lag for a given CC for any season was larger for the high-elevation than for the mid-elevation site. Interestingly, increasing CC reduced the NWI time lag between precipitation and NWI at both high- and mid-elevation sites, and the rate of this canopy influence was steeper for the high- than the mid-elevation site (Figure 8b1–b3). The time lags were lowest for any CC during the warm and dry winter in comparison to other winters. Finally, across the gradient of CC, the time lags at both sites were most variable during 2020, the winter with intermediate weather conditions that may suggest a greater role of CC on NWI timing during average winter conditions.

NWI duration versus CC showed a contrasting relationship between the high- and mid-elevation sites; increasing CC caused NWI duration to increase at the high-elevation site but decrease for the mid-elevation site (Figure 8c1–c3). Interestingly, there was a cross-over point between the NWI duration and CC relationships between the sites. At very low canopy covers, NWI duration was larger for the mid-elevation site, but at very large CC values, NWI duration was larger at the high-elevation site. Finally, similar to NWI amount and timing, NWI duration had a somewhat different relationship with CC for different winters.

5 | DISCUSSION

This study quantifies how forest cover regulates forest-snow-water interactions in terms of the amount, timing and duration of NWI to soil at an ephemeral versus a stable seasonal snowpack site over three winters with contrasting winter conditions. We find that forest cover plays a major role in determining not only the amount but also the timing and duration of NWI to soil, and that canopy effects are stronger at the colder site with stable snowpack (Figure 8). Specifically, increasing CC reduces NWI amount and NWI time lag at both ephemeral and stable seasonal snowpack sites and it prolongs the duration of

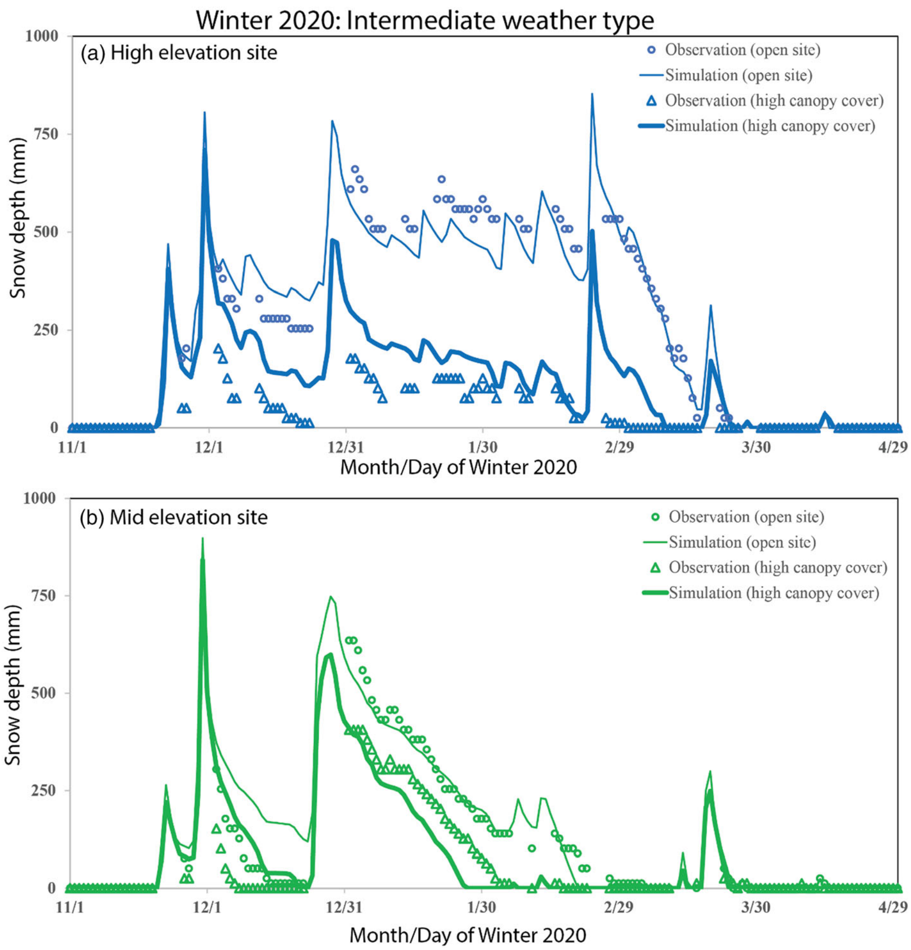

FIGURE 7 Pattern of the observed and simulated snow depth for open and high canopy cover locations at the high- (a) and mid-elevation (b) sites

NWI at a stable seasonal but shortens it at an ephemeral snowpack site. Furthermore, the radius of canopy influence on snow interception is at least twofold larger at a stable seasonal than an ephemeral snowpack site (Figure 5). As a critical step in modelling canopy snow and rain interception processes, a new method to partition precipitation is proposed that distinguishes rain, which adds mass to snowpack from rain contributing moisture directly to the soil surface, which is particularly important at an ephemeral snowpack site (Table 1, Figure 4). In the following discussion, we synthesize forest cover impacts on canopy snow processes, snowpack dynamics and NWI for ephemeral versus stable seasonal snowpack sites under a range of winter meteorological conditions. We also highlight the new understanding made possible by expanding snow observations through the snowtography technique within forests, discuss limitations of the current approach and existing instrumentation setup and outline future directions.

5.1 | Proposed conceptual model, study limitations and future directions

A conceptual summary illustrating forest cover-snow-water interactions for the high- elevation/stable seasonal and mid-elevation/ ephemeral snowpack sites is presented in Figure 9. The orders of importance of canopy snow processes found in this study at the two sites are interception > sublimation > unload > drip at the high-elevation site and interception > unload > drip > sublimation at the mid-elevation site (Figure 9a1 and 9a2). While the order of canopy snow processes at the mid-elevation sites is consistent, the order of canopy process for the high-elevation site is different from the order reported for sites located in maritime climates. Maritime climate observations suggest throughfall, drip and unloading as the dominant canopy snow fluxes, with sublimation being the least important (Storck et al., 2002). This difference in canopy snow processes can be attributed to a relatively warmer and drier winter conditions at the mid-elevation site and for maritime climate sites that can lead to a denser new snowfall than relatively lighter new snowfall at cooler continental climate sites (Dingman, 2002). In the present study, due to a larger intercepted snow mass by canopy at the high-elevation site, subcanopy snowpack depth (relative to open areas) is lower at the high-elevation than at the mid-elevation site. Between rain and snow canopy processes, a higher fraction of rainfall than snowfall is lost to the atmosphere per unit increase in CC at both sites.

Going from an open to a highly covered location, that is, as CC increases, there is steeper reduction in NWI to soil, and consequently, there is a steeper increase in the sublimation and net interception water loss at the high- than at the mid-elevation site (Figure 9b1). These findings are consistent with other studies where a greater sublimation loss from a higher than from a lower elevation site is reported

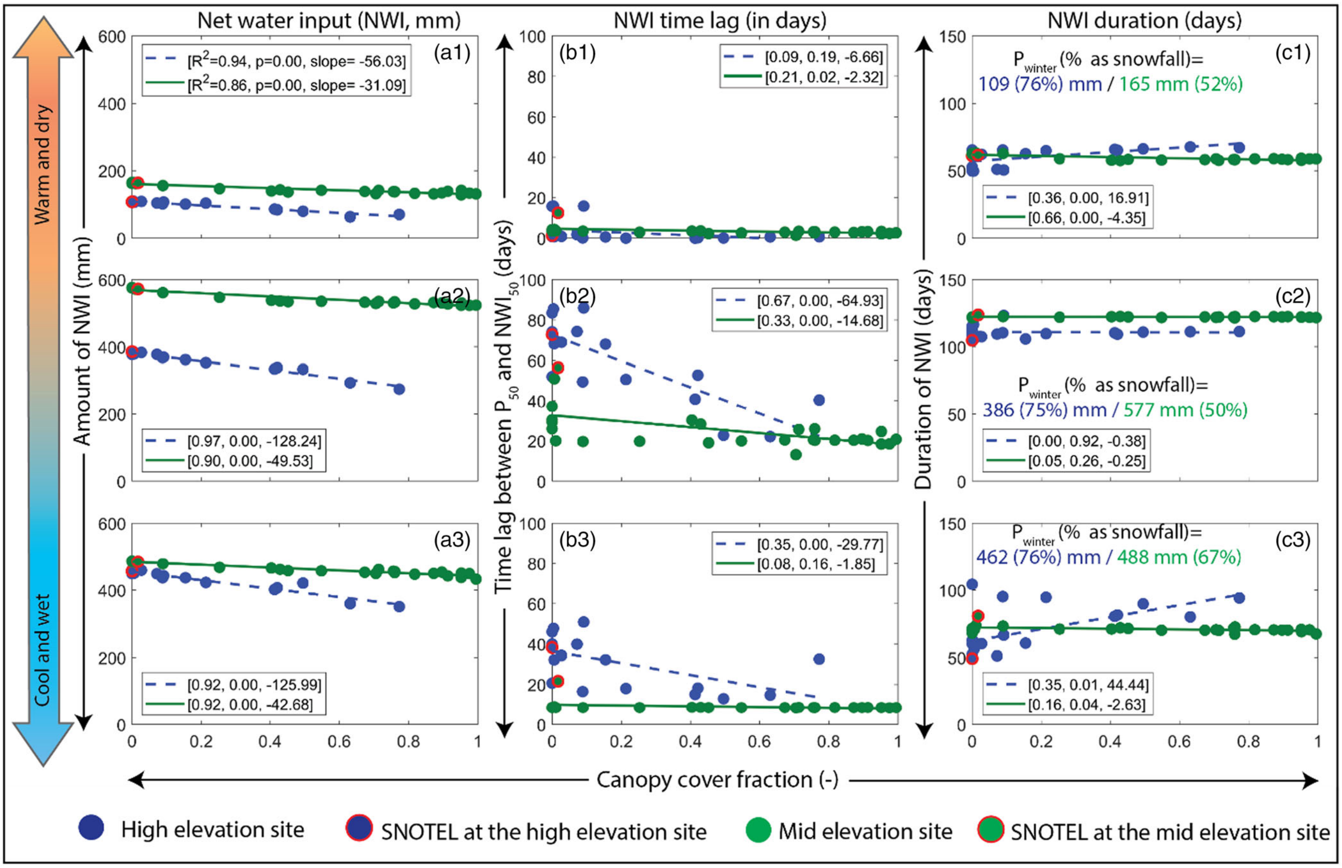

FIGURE 8 Relationship of canopy cover with net water input (NWI) amount, timing and duration. Net interception water loss is total precipitation minus net water input. The total winter precipitation and percentage of precipitation as snowfall for each winter are listed in the right panel for both sites.

(Montesi et al., 2004). With an increase in CC, the NWI time lag also decreases at both sites, but this decrease is again steeper at the high-elevation site, despite the fact that the time lag is, in general, greater at the high-elevation site for all levels of CC (Figure 9b2). While the duration of NWI decreases with CC at the mid-elevation site, it increases with CC at the high-elevation site (Figure 9b3). This increase in NWI duration with CC is due to an earlier but slower snowmelt at the highly covered locations at the high-elevation site. In contrast, the decrease in NWI duration with increase in CC at the mid-elevation site can be attributed to: (i) a relative synchronization of snowmelt process at both open and highly covered locations (the melt rate is still higher at the highly covered than open locations) and (ii) forest becoming a heat source (a radiative paradox, see also Lundquist et al. (2013) and references therein) under warm meteorological conditions. This finding is consistent with the framework recently proposed by Safa et al. (2021) for snowpack dynamics between open and under canopy locations for warm sites and with those reported by Broxton et al. (2020), which find an increase in snowpack ablation rate due to forest cover in Arizona field sites.

Prevailing winter weather can impact the amount, timing and duration of NWI to soil at a site in various ways (Figure 9c1–c3). These changes, though smaller than the impact of forest canopy on the amount and timing of NWI to soil, are still important. During a winter with intermediate weather (precipitation and temperature), forest canopy has the greatest impact on the amount and timing of NWI to soil, in comparison to the two winter weather end members (Figure 9c1 and 9c2). The sign of the gradient of NWI duration with CC remains the same for all three winter weather types, that is, positive for the stable seasonal and negative for the ephemeral snowpack site, but the strength of the relationship between duration and CC becomes insignificant during the intermediate weather winter for both sites (Figure 9c3). By magnitude, this gradient is also the lowest for an intermediate winter weather compared with the two end member winters for both sites. Thus, weather-forest cover-snow-water interactions are intricate and site-specific, highlighting the value of combining SNOTEL station data with measurements spatially distributed across gradients of forest canopy.

There are several limitations of the present work related to the simple parameterizations utilized for canopy and snowpack processes. For example, the selected snow interception model does not explicitly address impacts of wind-distributed snowfall. However, this is partially accounted for by the fact that SNOW-17 is calibrated at each stake individually, which implicitly considers any wind and/or vegetation structure influence on snowpack dynamics. The requirement to

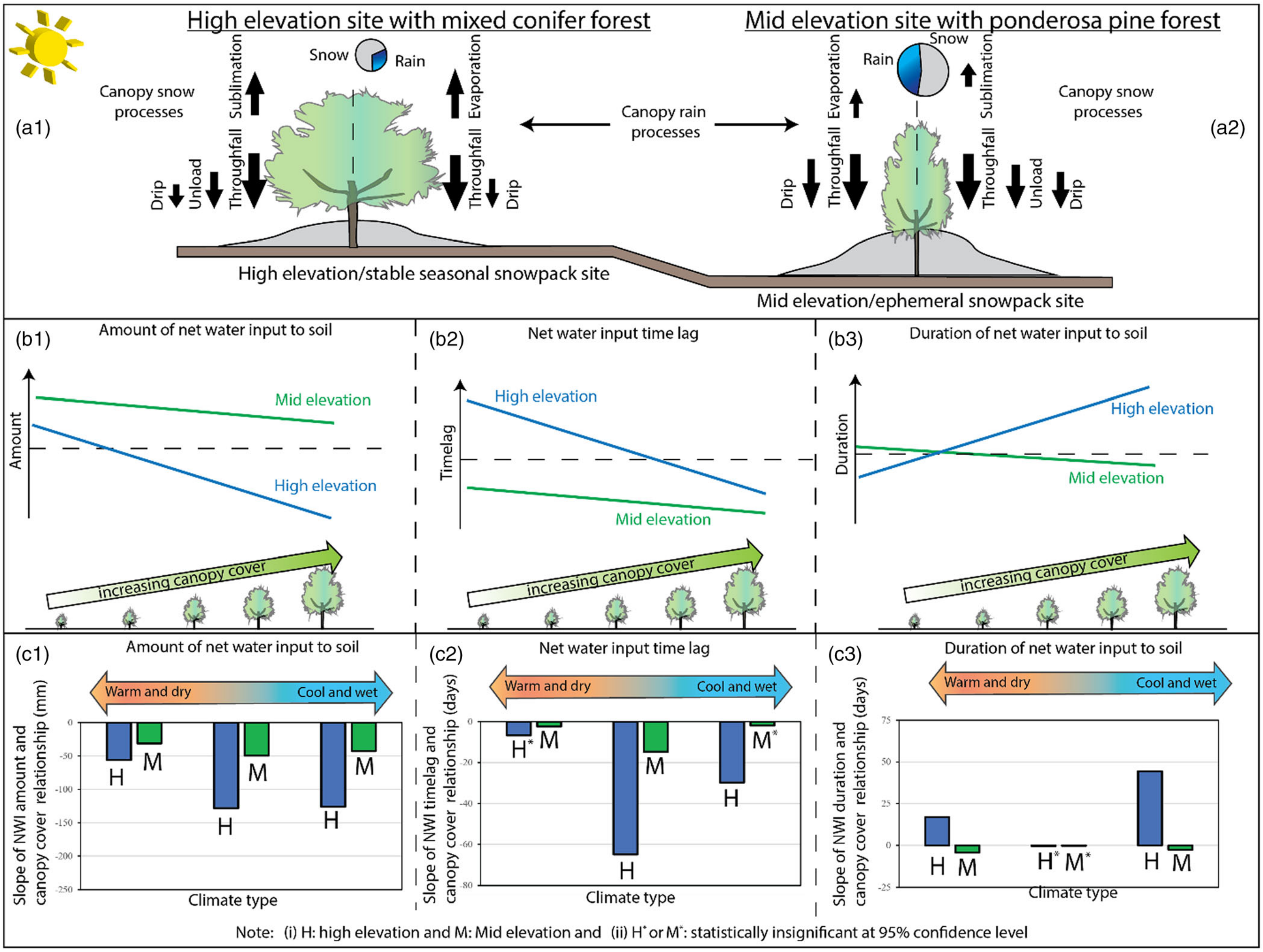

FIGURE 9 Conceptual models of canopy snow and rain processes (**a1/a2**), impact of canopy cover/meteorological conditions on amount **b1/c1**, time lag **b2/c2** and duration **b3/c3** of net water input to soil for the high-elevation/stable seasonal and mid-elevation/ephemeral snowpack sites

individually calibrate the model at each snowtography stake presents a challenge to widespread implementation of the snowpack modelling approach. It is likely that the need for individual calibration arises in part because CC, used here, is an incomplete predictor of forest geometric structure and its influence on processes of snow accumulation and ablation (Broxton et al., 2021; Moeser et al., 2020). Note that the interception modelling and precipitation partitioning methods do not have individual calibrations. In addition to limitations with the modelling approaches, the field measurements do not sample all environments equally. Most notably, there are relatively few canopy-covered stakes at the high-elevation site (two fully canopy-covered stakes and two partially covered stakes). This is due in part to the snowtography site designs (which employed linear transects to capture gradients of solar and wind exposure across clearings). Furthermore, the high-elevation site had relatively little CC in general (due to the occurrence of pre-existing montane in meadows, rather than small forest gaps, as well as substantial fire effects from the 2011 wildfire). Finally, due to the relatively short data record, this study only considers one season to represent warm/dry, average and wet meteorology at each site. Although it would be better to have a longer climatology, we believe that many of the differences shown here would also apply to other years, especially since there are pronounced meteorological differences between the different years (especially for the warm/dry year).

5.2 | Radius of canopy influence and controls on snowfall interception

We found that the optimal radius of canopy influence at which snow interception processes are better represented/simulated for a forested site is at least two times higher for the high- than the mid-elevation site. This difference in radius of canopy influence at the two sites can be attributed to: (i) either an internally denser canopy structure of mixed conifer trees at the high-elevation site in comparison to sparse internal canopy structure of mature ponderosa pine trees at the mid-elevation site (Schmidt & Gluns, 1991); (ii) drier snow due to cooler temperatures that may promote more canopy snow interception at the high-elevation site (Hoover & Leaf, 1967; Schmidt & Gluns, 1991); or

(iii) differences in snowfall event characteristics at the two sites, that is, a larger number of (on average) smaller snowstorm events at the seasonal site than the ephemeral snowpack site (Figure S2c versus Figure S3c in Supporting information), which is consistent with the observations and simulation results reported elsewhere (Broxton et al., 2014; Schmidt & Gluns, 1991; Xiao et al., 2019).

A comparison of snowfall interception fraction and the strength of the relationship between interception and CC for both stable seasonal and ephemeral sites suggests that in addition to CC, forest canopy structure, that is, spatial arrangement of canopy gaps and gap sizes in relation to surrounding tree heights, should also be considered in any future work for understanding forest cover-snow interactions. Safa et al. (2021) have shown that under low snow cover conditions, factors other than CC also impact snowpack dynamics. The high-elevation mixed conifer forested site (mean CC = 18%, based on snowtography stakes) intercepts 15% of total snowfall (with dense canopy stands intercepting as much as 50% of snowfall), which is at the lower end of values reported in the literature, likely due to sparse CC at this site. For a mixed conifer stand in the central Sierra Nevada, an interception rate of ~15% (up to 34% for a dense canopy stand) is reported (Kittredge, 1953). For an unburned mixed conifer stand in New Mexico with overall canopy density of 57%, an interception of 25% to 45% of snowfall is reported (Harpold et al., 2014). At the mid-elevation site (mean CC = 52% of mature ponderosa pine, based on snowtography locations), the average interception rate is 19% (with dense stands intercepting up to 44%), slightly higher on average than the 15% at the high-elevation site and comparable with prior reports for ponderosa forest in several western US states (Connaughton, 1935; Kittredge, 1953; Rowe & Hendrix, 1951). Overall, the rates of interception from ponderosa pine canopies with given amounts of CC are lower than for other conifer species due to less closed canopy structure (USDA Forest Service, 1997).

5.3 | Strengths and weaknesses of the proposed PPM

The new PPM developed here advances our ability to represent snowpack and snowmelt dynamics through differentiation of whether rain does/does not contribute mass to snowpack. If such contributions, that is, contribution of rain to an existing snowpack, are ignored (as with the existing methods evaluated in this study), errors in total winter precipitation may range up to 5% (but up to 21% during the warm and dry winter) and 7% (up to 11% during the cool and wet winter) for the mid- and high-elevation sites, respectively (Figure 3).

The proposed PPM provides more accurate results in terms of identifying snowfall days with a success rate that is at least 9% higher than the existing methods evaluated in this study, especially for sites with an ephemeral snowpack (Section 4.1). However, a slightly degraded PPM performance under cooler winter temperatures of the high-elevation site is notable when comparing daily precipitation amount thresholds (Section 4.1). The maximum mass balance error for precipitation for any winter season evaluated in this study is also relatively higher for the high-elevation site than the mid-elevation site (11% versus 7% mass balance error for precipitation; Section 4.1.2). Note, however, that the success rate of the proposed PPM in terms of correctly identifying true snowfall events is higher for larger than smaller snowfall events for both sites (true positive fractions in Figure 4e,f). For snowfall events under warmer air temperature conditions, the proposed PPM would predict a higher rate of rainfall than snowfall, depending on existing snowpack condition and change in observed SWE and snow depth conditions, which could impact canopy snow storage and fluxes. Nonetheless, as the overall success rates, mass balance errors and underprediction of non-snowfall days are relatively better for the mid-elevation ephemeral snowpack site than for the high-elevation stable seasonal snowpack site, the proposed PPM appears promising for understanding hydrologic partitioning and snow interception processes in a growing number of ephemeral snowpack sites resulting from a warming climate (Petersky et al., 2019; Petersky & Harpold, 2018).

5.4 | Implications for forested headwaters management

This study suggests that understanding of NWI to soil from forested ecosystems using SNOTEL stations can be significantly improved by addition of spatially distributed time series, such as those provided by snowtography, because of differences in the amount, timing and duration of NWI across gradients of forest cover (Figures 8 and 9). The results of this work clearly illustrate that the relative differences of NWI amount, timing and duration vary for different sites and climatically different winters, and it is critical to include forest cover-snow interactions. Here, NWI amounts differed between highly covered locations and forest clearings (where most SNOTEL stations are installed) by up to ~128 mm (Figure 8a2), consistent with known biases in location of SNOTEL stations (Broxton et al., 2019; Harpold et al., 2012; Molotch & Bales, 2005; Roth & Nolin, 2017). Furthermore, SNOTEL station-based information can overestimate the average NWI lag by 0.5 to 2 months (Figure 8b2), potentially leading to large inaccuracies in prediction of snowmelt runoff, soil moisture availability and groundwater recharge patterns. The results from this work also show that some improvements in the regression models (Figure 8) are possible through long-term monitoring of snowpack conditions by using spatially distributed snowtography stakes that cover a variety of CC and snowpack conditions and thus providing a larger and more robust dataset to regression models. Future work to improve assessment of CC impacts on NWI should be distributed across a wide climatic range of sites, extend across multiple years to capture interannual variability and aim to capture a wide range of forest structure. Additionally, future work should address interactions of climate and forest structure with topography, which is a primary control on snowpack and NWI not addressed here. In future work within a 3-D framework (SnowPALM model of Broxton et al., 2014), the Snowtography site designs selected will more comprehensively sample the dominant snow and energy balance regimes (e.g., warm edges and cool edges). Finally, our follow-up work will leverage the time series of NWI to soil from this study as inputs to soil moisture modelling to further understand impacts of spatial and temporal NWI dynamics on soil moisture availability for forests, runoff generation and groundwater recharge.

6 | CONCLUSIONS

This study shows that with an increase in forest cover, there is a steeper reduction in amount and time lag for the NWI to soil at a stable seasonal snowpack than an ephemeral snowpack site. The duration of NWI, however, decreases with CC at an ephemeral site, but it increases with CC at a stable seasonal snowpack site. Forest cover has the greatest impact on the amount and timing of NWI to soil at both stable seasonal and ephemeral snowpack sites during a winter with intermediate winter conditions. Distributed snowtography revealed that the optimal canopy radius, that is, the radius at which observed canopy snow interception is best represented by interception models, is ~two times greater at a cold stable seasonal snowpack site as compared with a warmer ephemeral snowpack site. We developed a new precipitation partitioning algorithm that explicitly partitions between rainfall that adds to SWE and rainfall that does not, and this PPM provides more accurate results for snowfall days than the other methods evaluated in this study that partitioning between rain and snow at these sites. Overall, this study provides an improved understanding of how forest cover impacts NWI to soil at an ephemerally versus stable seasonally snow-covered site, which is essential to making well-informed forest management decisions in changing forested ecosystems due to warming climate. In addition, the low-cost snowtography method, which allowed us to characterize how snowpack dynamics and NWI to soil differed across canopy gradients, can provide spatiotemporally distributed information about snowpack dynamics to complement existing monitoring networks.

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CONFLICT OF INTEREST

We do not have any conflicts of interests. USDA is an equal opportunity provider and employer.

SIGNIFICANCE OF THIS RESEARCH

High-elevation forested watersheds provide a range of ecosystem services including water supply, carbon sequestration, habitat and recreation. While hydrologic partitioning has been well-studied in high-elevation cold watersheds with stable seasonal snowpack, less is known about hydrologic partitioning in the growing number of warm watersheds with ephemeral winter snowpacks. A better understanding of forest-water relationships in ephemeral snowpack sites is essential for making informed forest management decisions under warming climate. Therefore, this study is aimed at providing an improved understanding of climate-forest-snow-water relationships at contrasting sites with ephemeral and stable seasonal snowpack.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. The snowtography and lidar data used in this work were acquired by the Arizona Remote Sensing Center at the University of Arizona through funding from the Salt River Project. The 2013 lidar data from Four Forest Restoration Initiative (4FRI) are available from the USDA Forest Serviceafter agreeing with its non-disclosure agreement. The 2019 lidar data can be made available by the Arizona Remote Sensing Center upon request.

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SUPPORTING INFORMATION

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