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Quantifying the Influence of Vegetation on Net Snow Accumulation Across Elevations, Aspects and During Years With High and Low Snowfall

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ABSTRACT

Seasonal snowmelt from forested mountain catchments is the primary water source for both people and ecosystems in the western United States. As changes in climate and vegetation alter relationships between snow accumulation and water availability, quantifying the influence of ecosystem structure on snow water resources is a critical challenge. To address this knowledge gap, we performed 2 years of distributed snow surveys to quantify how vegetation structure, topography and winter conditions interact to control net snow accumulation. The ratio of net snow water equivalence (SWE) at peak accumulation to winter snowfall (SWE:P) was 0.85 (range 0.67–1.03). This variability in SWE:P was associated with seven distinct vegetation environments that differentially influenced snow accumulation across all sites and years. Greatest snow accumulation was found in open areas immediately north of forests (SWE:P = 1.03 ± 0.05), followed by small gaps in conifer forests (SWE:P = 0.95 ± 0.07), small gaps in aspen forests (SWE:P = 0.88 ± 0.08), nonshaded open areas (SWE:P = 0.88 ± 0.05), under aspen canopies (SWE:P = 0.81 ± 0.04), under coniferous canopies (SWE:P = 0.76 ± 0.04) and lowest in open areas in south-facing forest edges (SWE:P = 0.67 ± 0.07). These spatial patterns in net SWE input were more pronounced in nontopographically shaded environments, suggesting that the influence of vegetation on local hydroclimate and net snow accumulation was greater in areas with higher solar radiation input. The consistency of these patterns across high and low elevations and during low- and high-snow years suggests that forest structure can be used to distribute spatial patterns in snow water input in both undisturbed forests and in response to forest management.

1 | Introduction

Mountain snowpacks act as natural freshwater reservoirs by accumulating months of winter precipitation until spring snowmelt when ecological and human demand increase (Mote et al. 2005; Viviroli et al. 2007; Bales et al. 2006; Li et al. 2017). Resource managers typically use snow accumulation from the National Resource Conservation Service snow telemetry (SNOTEL) network (meteorological stations and snow courses) on April 1st to estimate spring runoff for water supply allocation, reservoir management and drought risk (Serreze et al. 1999). This statistical approach, using only a few measurement points, works well if spatial patterns of snow accumulation and ablation remain unchanged. However, climate change is altering the relationships between snow accumulation and streamflow generation by decreasing the average snowpack snow water equivalence (SWE) (Mote et al. 2005, 2018; Harpold et al. 2012; Zeng et al. 2018), decreasing the fraction of precipitation falling as snow (Knowles et al. 2006; Klos et al. 2014), initiating earlier and slower snowmelt (Clow 2010; Barnett et al. 2005; Musselman et al. 2017, 2021) and increasing water vapour exchanges between the snowpack and atmosphere (Hood et al. 1999; Sexstone et al. 2018). Shifts in the amount and timing of snow water input are particularly critical for mountain forests, as they influence soil moisture availability for plant growth under changing climate conditions (Tague et al. 2009; Tague and Peng 2013; Harpold et al. 2015) and vegetation recovery after disturbances (Tague and Moritz 2019; Webb et al. 2023).

Climate change also is causing significant shifts in forest ecosystem structure due to drought, insect infestation and wildfires. Forest cover and its structure play a major role in snow accumulation (Golding and Swanson 1978, 1986; Faria et al. 2000; Varhola et al. 2010; Broxton et al. 2020), altering the amount and timing of net water input in nonintuitive ways. The spatial variability in snow accumulation is a function of snowfall (Trujillo and Molotch 2014), which is influenced by latitude, elevation and orography (Pomeroy et al. 2002); wind redistribution (Golding and Swanson 1978; Troendle 1983; Elder et al. 1991; Winstral et al. 2002); and winter ablation, including melt and vapour loss. Vegetation affects the snowpack by modifying the energy balance at the snow surface through interception (Hedstrom and Pomeroy 1998; Storck et al. 2002), shading and sheltering of solar radiation (Gustafson et al. 2010; Musselman et al. 2008, 2015; Rinehart et al. 2008; Veatch et al. 2009), modification of wind speeds and turbulent fluxes (Essery and Pomeroy 2004; Winstral and Marks 2002; Link and Marks 1999) and emission of longwave radiation (Essery et al. 2008; Sicart et al. 2004, 2006; Pomeroy et al. 2009). Recent work has emphasized the need to account for these complexities in forest structure and their influence on snow accumulation by classifying watersheds into distinct snow environments based on position relative to vegetation (Dwivedi et al. 2024; Currier and Lundquist 2018; Biederman et al. 2025). However, these relationships between snow and vegetation structure are further complicated by changes in elevation and aspect (Tennant et al. 2017). Vegetation differentially interacts with elevation, slope and aspect, influencing mass (amount of precipitation and wind loading) and energy exchanges (Varhola et al. 2010; Çitgez et al. 2024). Given the complex interactions between snow, forest structure and climate, improved net snow water input predictions are necessary to understand climate change and forest disturbance impacts on ecosystem and water resource resiliency.

These complex interactions between vegetation and local hydroclimate contribute to the ongoing challenge of accurately predicting net snow water input for water supply forecasts (Elder et al. 1991; Winstral et al. 2002; Dozier et al. 2016; Gordon et al. 2022). Numerous approaches have been developed for estimating spatially distributed SWE including the interpolation of ground observations constrained by remotely sensed snow cover area (Fassnacht et al. 2003), remotely sensed snow cover area combined with spatially distributed snowmelt models (Molotch et al. 2005; Molotch 2009; Molotch and Margulis 2008), use of passive (Vander Jagt et al. 2013; Vuyovich et al. 2014) and active microwave sensors (synthetic aperture radar) (Tsang et al. 2022; Marshall and Bühler 2023), combination of ground observations with a physical model assimilating airborne and satellite observations with a numerical weather model (e.g., snow data assimilation system) (Clow et al. 2012; Lv et al. 2019), integration of airborne snow observatory data (Painter et al. 2016; Bair et al. 2016; Yang et al. 2023) and methods in machine learning using input data from satellite sensors, land surface models and ground observations (Broxton et al. 2019, 2024; Cui et al. 2023; Liljestrand et al. 2024). Ground observations, on which these methods rely, are often derived from the SNOTEL network. However, SNOTEL sites are generally located within a limited elevation band in sheltered north-facing environments (nontopographically complex terrain), which are often not representative of the entire catchment (Molotch and Bales 2005) and becoming less representative of total snowpack in drier snow years (Nolin 2010; Hammond et al. 2023). Current methods of estimating the spatial distribution of net SWE using remote sensing techniques work well in wide open areas yet struggle with complex topography, vegetation cover and small-scale variability (Dozier et al. 2016; Barnhart et al. 2024). Broxton et al. (2015 and 2021) demonstrated how fine-scale models, which resolve tree-scale processes using LiDAR-parameterized snowpack energy and mass budgets, significantly improve snow water input estimates in forested environments. However, applying such high-resolution models over large areas remains computationally limited.

Regional differences in snowpack dynamics within the Western United States arise from distinct climatic and energy controls, including solar radiation, wind and humidity. Currier and Lundquist (2018) demonstrated how the dominant process controlling snowpack variability (solar radiation shading or wind) differs between various climate regions. Harpold and Brooks (2018) emphasized how humidity, directly and indirectly, acts as a strong regional control on seasonal snow responses to warming temperatures. Tennant et al. (2017) observed how snowpack sensitivity varies systematically with elevation across hydroclimatic regions, reflecting how topographically driven gradients (temperature and precipitation) shape spatial patterns in snow accumulation. Together, these studies highlight how snowpack sensitivity to climate drivers is not uniform and depends on local hydroclimatic settings. However, less is known about how fine-scale forest characteristics interact with these regional drivers to influence snow accumulation. The accelerating rate of climate change and forest disturbances, combined with the importance of forest microstructure on net snow accumulation, highlights the need for new insights in integrating fine-scale spatial patterns of forest demography into high-resolution models used for distributing net SWE. Therefore, we ask, are there consistent relationships between forest structure and net snow accumulation across elevation, aspect and during years with high and low snowfall? To address this question, we performed distributed snow surveys across a range of elevations, aspects and vegetation structures at maximum accumulation during two winters. We use the results from these surveys to develop transferrable metrics describing net SWE distribution at multiple scales and under varying climatic and ecological conditions.

2 | Materials and Methods

2.1 | Study Area

The Big Cottonwood Canyon (BCC) catchment (40.641° N, 111.689° W), located within the Wasatch Range of Northern Utah (Figure 1), has a dry and semiarid climate, with strong elevational gradients in temperature and precipitation from the

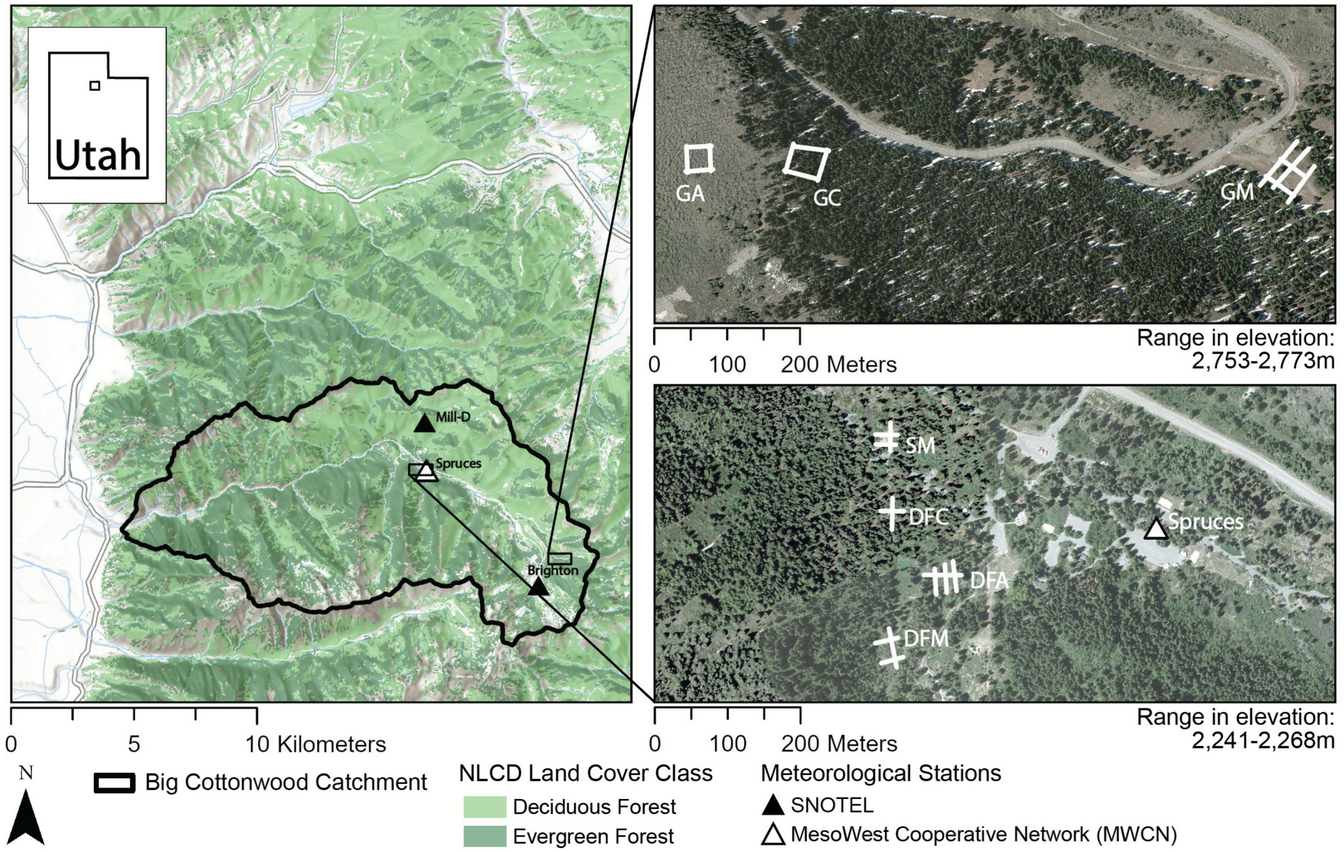

FIGURE 1 | Site and transect locations near Salt Lake City, UT, in Big Cottonwood Catchment: Guardsman Meadow (GM), Guardsman Conifer (GC), Guardsman Aspen (GA), Days Fork Meadow (DFM), Days Fork Aspen (DFA), Days Fork Conifer (DFC) and Spruces Meadow (SM). Higher elevation sites are proximal to Brighton SNOTEL and lower elevation sites are proximal to MWCN Spruces, both measurement stations where precipitation data is collected. Additional long-term meteorological stations, two SNOTELs, were used for calculations of catchment average meteorological characteristics.

valley floor to mountain watersheds. BBC is a forested, cold-temperate environment characteristic of regions that support seasonal, continental snowpacks. As such, our findings are most representative of mid-elevation, colder, drier, forested mountain catchments, where larger temperature gradients between the air and the snow surface drive vapour fluxes. BCC receives roughly 800–1200 mm/year of precipitation, the majority as snow, with April 1st SWE typically between 400 and 800 mm at higher elevation SNOTEL stations. Mean winter air temperatures range from −4°C to −2°C, and relative humidity frequently exceeds 50% during the accumulation period. These conditions are comparable to those reported for other cold, continental mountain catchments in the western United States, which exhibit similar precipitation totals, April 1st SWE, and humidity–temperature regimes that strongly influence forest–snow interactions (Tennant et al. 2017; Currier and Lundquist 2018). Precipitation falls as snow between October and April (winter months), resulting in snowmelt driving 80%–100% of Utah's streamflow (Barnett et al. 2005; Julander and Clayton 2018) and regional groundwater recharge (Manning and Solomon 2004). As a major source of drinking water for Salt Lake City, BCC is a protected watershed area, with the highest water yield of any Wasatch Front canyon stream in Salt Lake County (Schwager and Cowley 2000). BCC has a mean elevation of 2607 m, exhibits varying slope aspects (32% northerly, 19% easterly, 25% southerly, 25% westerly aspects) and is predominantly characterized by conifer spruce fir (46%) and aspen (35%) forests across an area of approximately 129 km^2. Forest height ranges from 4 to 30 m, with interspersed meadows or gaps.

2.2 | Experimental Design

We address what topographic and vegetative factors control spatial patterns in net snow accumulation, total accumulation minus midwinter ablation prior to April 1st, using 2 years of snowpack data across seven sites ranging in elevation, aspect, vegetation type and forest gap sizes. Survey sites were located near a higher elevation Brighton SNOTEL station (2672 m in elevation, 1.6 km away) and a lower elevation MWCN-Spruces station (2256 m in elevation, 400 m away). We performed snow depth transects and density observations at each site near April 1st in 2022 and 2023 to quantify spatial patterns between two snow years. Transect start and end points were roughly aligned along north–south and east–west orientations (parallel or perpendicular to energy gradients), which followed straight paths across accessible terrain and were designed to study the transitions within and between energy gradients (Figure 2). In larger forest gaps, north–south transects were designed to traverse from under the canopy, across the open meadow, and back under the canopy to capture transitions across varying vegetation structure. East–west transects in these gaps were positioned entirely within open meadow environments, at various distances from adjacent forest edges. In smaller gaps, transects were positioned to sample both continuous canopy cover and small openings, ensuring that the full range of forest structure within each site was represented. Snow depths were recorded to the nearest centimetre using a probe inserted vertically into the snowpack to the ground surface; 5-point, 1-m spacing depth measurements were taken along each transect at 3-m spacings along the north–south and east–west orientations. Snow densities were taken in varying vegetation environments at each site during snow depth surveys using a federal sampler, a small diameter sampler designed for deep, alpine snowpacks (Clyde 1932; Dixon and Boon 2012; López-Moreno et al. 2020). A federal sampler was used instead of digging snow pits to maximize the number of sites visited in a single day, allowing for the collection of 11 densities in both 2022 and 2023.

2.3 | Meteorological and Climate Data

Mean air temperature (between the first day of continuous snow cover and April 1st), day of peak SWE, April 1st observed SWE, April 1st accumulated snowfall (sum of incremented precipitation between the first day of continuous snow cover and April 1st) and number of days without precipitation were calculated from the two SNOTEL stations (Brighton: 2672 m and Mill-D: 2732 m) within BCC (Table 2). These long-term SNOTEL stations were used to place the two winter seasons into longer term climatological context. Using both stations demonstrates that lapse rates for temperature and precipitation are similar across the catchment. We calculated snowfall input at each site using proximal (located within 101-m elevation of study sites) meteorological station precipitation adjusted based on annual precipitation-elevation lapse rates. Higher elevation sites are proximal to the higher elevation Brighton SNOTEL station (1.6 km in lateral distance away) and lower elevation sites to the MWCN-Spruces station (400 m away). Annual lapse rates were calculated using April 1st accumulated snowfall and meteorological station elevation (2022: 21.7 mm/100 m; 2023: 73.9 mm/100 m).

2.4 | Topographic and Vegetation Characteristics

Mean site elevation, slope and aspect (Table 1) were calculated from 0.5 m digital elevation models (DEM) (UGRC 2020a). Mean site elevations ranged from 2241 to 2773 m; slopes ranged from 5° to 20°; aspects ranged from 266° (WSW) to 41° (NE) (Table 1). National Land Cover (MRLC 2021) and High-Resolution Orthophotography (UGRC 2012) were used to identify forest types, varying from spruce fir to aspen to mixed forests. Bare Earth 0.5-m LiDAR DEM subtracted from First Return 0.5-m LiDAR digital surface model (DSM) (UGRC 2020b) was used for canopy cover, mean and maximum canopy height and gap size to mean tree height ratio calculations. Topographic solar forcing was calculated between Nov. 1 (1989–2021 mean start of accumulation) and April 1st on a 0.5 m LiDAR DEM using ArcGIS Solar Analyst (Fu and Rich 1999) and normalized to a flat, open control 0.5-m LiDAR DEM. Topographic solar forcing (the ratio of terrain-modified solar radiation to that on a flat surface) ranged from 0.75 at a more north-facing site to 1.02 at a more south-facing site.

2.5 | Vegetation Environment Classifications

To examine the spatial structure in snow depths, transects traversed through three different energy environments: gaps, under conifer canopies, and under aspen canopies. Under canopy was defined strictly on in situ determination of the presence or absence of canopy above measurement. The ratio of gap length to mean tree height was divided into two classes of gap sizes: large gaps (> 1 mean tree height) and small gaps (< 1 mean tree height), as snow interception of the adjacent forest maintains an important role below that threshold (Golding and Swanson 1986; Varhola et al. 2010; Dickerson-Lange et al. 2021).

TABLE 1 | Major topographic and vegetation characteristics of seven sites: Guardsman Meadow (GM), Guardsman Conifer (GC), Guardsman Aspen (GA), Days Fork Meadow (DFM), Days Fork Aspen (DFA), Days Fork Conifer (DFC) and Spruces Meadow (SM).

Site	Mean elevation (m)	Forest type	Canopy cover (%)	Mean canopy height (m)	Max canopy height (m)	Gap size:mean tree height	Mean slope (°)	Mean aspect (°)	Topographic solar forcing
Higher elevation									
GM	2773	Subalpine fir	22	21	27	2.8	9	251 (W)	1.02
GC	2758	Subalpine fir	61	20	24	0.85	18	41 (NE)	0.75
GA	2753	Aspen	51	9	15	0.67	20	266 (W)	1.00
Lower elevation									
DFM	2268	Douglas fir	40	21	26	2.1	12	17 (N)	0.87
DFA	2255	Mixed, Aspen	44	11	17	0.82	8	34 (NE)	0.91
DFC	2249	White fir	52	19	30	0.74	8	23 (NE)	0.92
SM	2241	Spruce	37	20	27	1.5	5	11 (N)	0.95

Note: Sites were selected to characterize snow accumulation in major forest types, gap sizes and aspects at high and low elevations. Study sites range in size from 0.4 to 0.1 ha.

2.6 | Statistical Classifications

Changepoint analysis was used within large gaps to identify distances at which the mean of snow depths and SWE changed most significantly, minimizing the total residual error (sum of squared deviations (SSE) from the mean, Equation (1)) (using MATLAB R2023a). Snow depths and SWE were classified into zones based on SSE, defined as follows:

$$SSE(m,n) = \sum_{i=m}^{n} \left(x_i - \overline{X}_{m:n}\right)^2 \tag{1}$$

where, $x_m \cdots x_n$ is a sequence of data points from index m to n, x_i is the i-th data point in the sequence, and $\overline{X}_{m:n}$ is the mean of the sequence.

$$SSE(m,n) = (n - m + 1)var\left(\left[x_m \cdots x_n\right]\right) \tag{2}$$

where *var* denotes the variance of the sequence.

Since SSE is equivalent to multiplying the variance of the segment by the number of points (Equation (2)), this metric can be used to identify changepoints that minimize total within-segment variability. The significance of mean snow depths and SWE between zones was tested using a one-way analysis of variance (ANOVA). Depth values were converted into SWE:P, the ratio between observed SWE and accumulated snowfall, and classified into identified vegetation environments. Determination of differences among vegetation environments and between years was performed using one-way ANOVA followed by two-sided Student t-tests.

3 | Results

We compared spatial patterns in snow accumulation during a year with below-average precipitation and near-average temperature and a year with above-average precipitation and below-average temperature. Mean catchment SNOTEL (from Mill-D and Brighton, Figure 1) April 1st accumulated SWE was 66% and 191% of the 1989–2021 mean for 2022 and 2023, respectively (Table 2). Mean catchment SNOTEL air temperature and April 1st accumulated snowfall were −2.8°C (±0.1°C) and 395 mm (±45 mm) in 2022 and −4.7°C (±0.5°C) and 1146 mm (±65 mm) in 2023 (Table 2). The snow accumulation season was shorter than the 1989–2021 mean (160 ± 18 days; November 1st to April 9th) in 2022 (120 days; November 23rd to March 22nd) and longer than the mean in 2023 (167 days; October 22nd to April 6th).

Accumulated snowfall on survey dates for high-elevation sites ranged from 445–449 mm in 2022 and 1198–1213 mm in 2023. For lower elevation sites, accumulated snowfall ranged from 287 to 293 mm in 2022 and 750 to 764 mm in 2023 (Table 3). Snow survey dates, centred around April 1, were within 1 to 13 days of the dates of the SNOTEL peak SWE.

Over 3000 snow depth and 22 snow density observations near peak accumulation were used to identify seven distinct vegetation environments, defined by vegetation structure, that influence net SWE accumulation across two winters. Density measurements collected across elevations, aspects and vegetation structures had no significant differences near peak accumulation (p-values 2022 = 0.11, 2023 = 0.94). As a result, we used a mean density value for each year (2022: 0.38 g/cm^3 ± 0.02, n = 11; 2023: 0.29 g/cm^3 ± 0.05, n = 11) to convert snow depths to SWE. The differences in p-values between years likely reflect contrasting snowpack and weather conditions around peak accumulation, with fewer storms and longer periods of clear, sunny skies enhancing solar inputs and temperature-gradient metamorphism while more frequent storms and overall colder, cloudier conditions in 2023 lead to more uniform densities across environments.

Observed SWE was typically lower than winter snowfall (i.e., SWE:P was less than 1.0) in almost all vegetation classifications across both years (Table 4). Net SWE in forest gaps was most similar to snowfall inputs, with statistically higher SWE:P (2022: 0.98; 2023: 0.88) than both under conifer (2022: 0.75; 2023: 0.77) and under aspen canopies (2022: 0.76; 2023: 0.85). SWE:P was 1%–8% higher under aspen canopies than under conifer canopies, yet only significantly higher in 2023 (2022 p-value = 0.12). These differences partially reflect canopy structure, where conifers retain needles year-round and continuously intercept snowfall while leafless aspen branches intercept less snowfall. Canopy interception played a proportionally larger role in the low-snow year, whereas in the higher snow year, greater snowfall reduced the fractional loss under aspen canopies, making the differences from conifers significant. SWE:P in forest gaps was significantly higher in 2022 (low-snow year) than in 2023 (high-snow year) (p-value < 0.01). In contrast, SWE:P under both aspen and conifer canopies was significantly greater in 2023 (higher snow year) than in 2022 (low-snow year) (p-values

TABLE 2 | Meteorological characteristics for long-term measurement stations within Big Cottonwood Catchment during 2022, 2023 and 1989–2021 mean.

Accumulation season	Mean air temperature (°C)	Day of peak SWE	April 1st SWE (mm)	April 1st accumulated snowfall (mm)	Number of days without precipitation
2022	−2.8 ± 0.1	March 22nd ± 0 days	359 ± 2	395 ± 45	98 ± 1
2023	−4.7 ± 0.5	April 6th ± 0 days	1191 ± 223	1146 ± 65	68 ± 1
Mean (1989–2021)	−2.9 ± 1.0*	April 10th ± 18 days	580 ± 181	601 ± 153	80 ± 14

Note: Stations include Brighton SNOTEL (2672 m) and Mill-D SNOTEL (2732 m). Mean temperature averaged from 2007* to 2021 (*start of Brighton temperature record) and accumulated snowfall calculated from start of continuous accumulation to April 1st. Storms were defined as days when precipitation was greater than 0 using daily precipitation increment data.

TABLE 3 | Topographic controls on accumulated snowfall inputs and observed SWE on survey dates closest to April 1st.

Site	2022			2023		
		Open			Open	
	Accumulated snowfall (mm)	Topographically shaded	Nontopographically shaded	Accumulated snowfall (mm)	Topographically shaded	Nontopographically shaded
Higher elevation	447 ± 2	466 ± 117	437* ± 90	1204 ± 8	964* ± 118	1036* ± 64
Lower elevation	290 ± 3	300* ± 70	235* ± 52	756 ± 6	740* ± 56	612* ± 41

Note: Higher elevation sites are similar in elevation, with a range of only 20 m, and are 101 m higher than the Brighton SNOTEL. Lower elevation sites are also similar in elevation, ranging by 27 m, with the MWCN-Spruces station being within the elevational range of the lower site elevations. Standard deviations are represented as plus or minus. *Indicates statistical significance between observed mean SWE and accumulated snowfall.

< 0.01). Spatial patterns in SWE:P across vegetation types (aspen versus conifer) and structures (small versus large gaps) were consistent across elevations, aspects and years (Figures 2 and 3). Mean SWE:P values in both small (2022: 0.98; 2023: 0.89) and large (2022: 0.98; 2023: 0.87) forest gaps were similar each year. In small gaps and under continuous vegetation (entire transects of GC T2, GA T2 and GA T3), there were no spatial gradients in SWE:P related to vegetation position (Figure 3).

Within large gaps, net SWE decreased with distance from shaded northeast edges (Figure 2). We identified two statistically significant transitions in snow depths and SWE in large gaps along transects moving away from northeast shaded gap edges, consistent across elevations and in both low and high years, using changepoint analysis (Figure 4). These transitions result in three statistically different accumulation patterns in open environments within large gaps. The first transition occurred between 23–25 m from the north forest edge in 2022 and 15–23 m in 2023. This zone of significantly higher SWE, approximately 1 to 1.2 mean conifer tree height from the north forest edge, is categorized as shaded open, having 22% or 76 mm (2022) and 5% (2023) or 46 mm more SWE than all other observations within large gaps. The second transition occurred 4–5 m south to southwest of the forest edge at each site in 2022 and 2–7 m in 2023. This zone, having 37% (2022) or 151 mm and 14% or 127 mm (2023) less SWE than all other observations within large gaps, is categorized as south forest edge (SFE). The remaining area between shaded open and SFE is categorized as nonshaded open.

One-way analysis of variance (ANOVA) revealed that SWE:P ratios were significantly different in all seven vegetation environments in both 2022 and 2023 (p-values = < 0.001) (Figure 5). However, additional two-tailed t-tests revealed no statistical difference between mean SWE:P under conifer and aspen canopies in 2022 (p-value = 0.12; Table S3). In 2023, no statistical difference in SWE:P was observed between small gaps shaded by aspen canopies and shaded open areas (p-value = 0.16), between under aspen canopies and nonshaded open areas (p-value = 0.83), or between SFE and under conifer canopies (p-value = 0.38; Table S3). For all vegetation classifications, SWE:P ratios between years are statistically different (Table S4).

Area-weighted averaged net SWE input across all vegetation environments was 14.5% ± 6.8% (SE) less than winter snowfall in 2022 and 16.3% ± 2.5% (SE) less in 2023. Vegetation had a larger influence on net accumulated SWE in nontopographically shaded sites, as SWE:P in topographically shaded open areas (GC, DFM, DFC and DFA) (2022: 1.02 ± 0.09; 2023: 0.92 ± 0.03) was up to 8% greater than in nontopographically shaded environments (GM, GA and SM) (2022: 0.95 ± 0.09; 2023: 0.85 ± 0.03) (Figure 6). Mean SWE:P values in all vegetation environments, except for SFE (p-value = 0.23), were significantly higher in topographically shaded environments than in nontopographically shaded sites (Table S5).

4 | Discussion

The consistency in these patterns of net SWE accumulation across elevation, aspect and wet versus dry years suggests that they arise from reproducible patterns of local hydroclimate

TABLE 4 | Accumulated snowfall inputs and observed SWE on survey dates closest to April 1st for the seven sites: Guardsman Meadow (GM), Guardsman Conifer (GC), Guardsman Aspen (GA), Days Fork Meadow (DFM), Days Fork Aspen (DFA), Days Fork Conifer (DFC) and Spruces Meadow (SM).

	2022					2023				
			Observed mean SWE (mm) Vegetation classification					Observed mean SWE (mm) Vegetation classification		
Site	Survey date	Accumulated snowfall (mm)	Gap	Conifer canopy	Aspen canopy	Survey date	Accumulated snowfall (mm)	Gap	Conifer canopy	Aspen canopy
Higher elevation										
GM	4/1	449	446 ± 44	322 ± 126*		4/7	1213	1031 ± 36*	843 ± 58*	
GC	4/4	446	466 ± 117	330 ± 90*		4/9	1202	964 ± 118*	891 ± 111*	
GA	4/4	445	343 ± 34*		300 ± 35*	4/7	1198	1074 ± 43*		985 ± 42*
Lower elevation										
DFM	4/3	293	305 ± 35	254 ± 85		3/26	764	743 ± 33	637 ± 118*	
DFA	4/3	290	267 ± 83	134 ± 58*	253 ± 46	3/26	754	698 ± 69	596 ± 65*	668 ± 42*
DFC	4/3	288	283 ± 47	250 ± 48		3/26	750	750 ± 42	712 ± 108*	
SM	4/3	287	232 ± 24*	188 ± 34*		3/28	755	610 ± 23*	505 ± 110*	

Note: Standard deviations are represented as plus or minus. *Indicates statistical significance between observed mean SWE at each vegetation classification and accumulated snowfall.

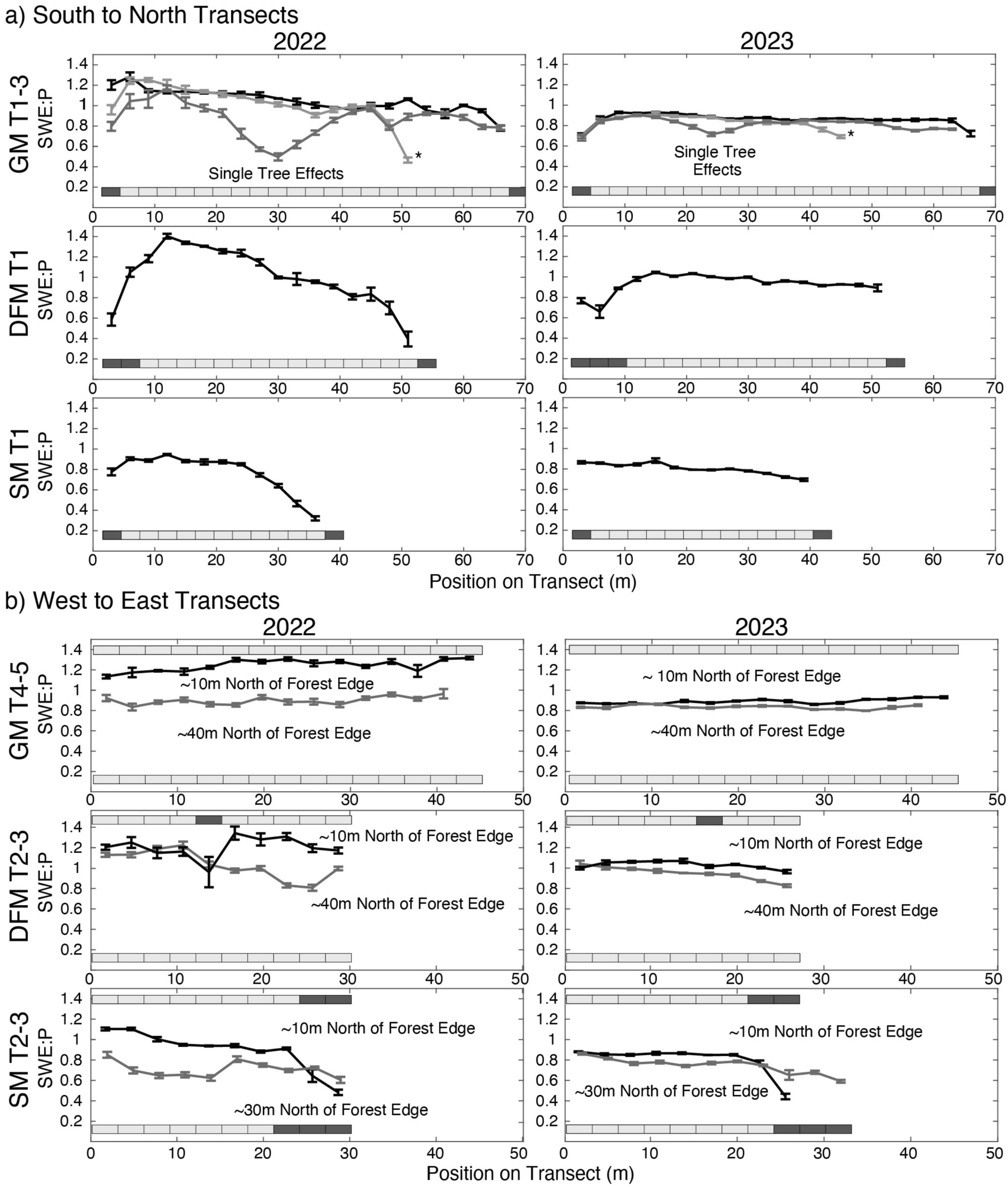

FIGURE 2 | Patterns in observed SWE to accumulated snowfall (SWE:P) for sites with large gaps in conifer forests (Guardsman Meadow (GM), Days Fork Meadow (DFM) and Spruces Meadow (SM)) along (a) south to north transects (perpendicular to energy gradients) and (b) west to east transects (parallel to energy gradients). Shaded boxes represent measurements taken under the canopy (darker shade) or in open areas (lighter shade), with standard error as error bars. *Transect reaches south of the canopy sooner than other transects.

resulting from vegetation structure. The static nature of topographical drivers of snow accumulation is well documented (Elder et al. 1991; Erickson et al. 2005), and our results demonstrate that forest structure similarly results in predictable patterns of snow accumulation. In contrast to topography, however, vegetation structure changes on human timescales due

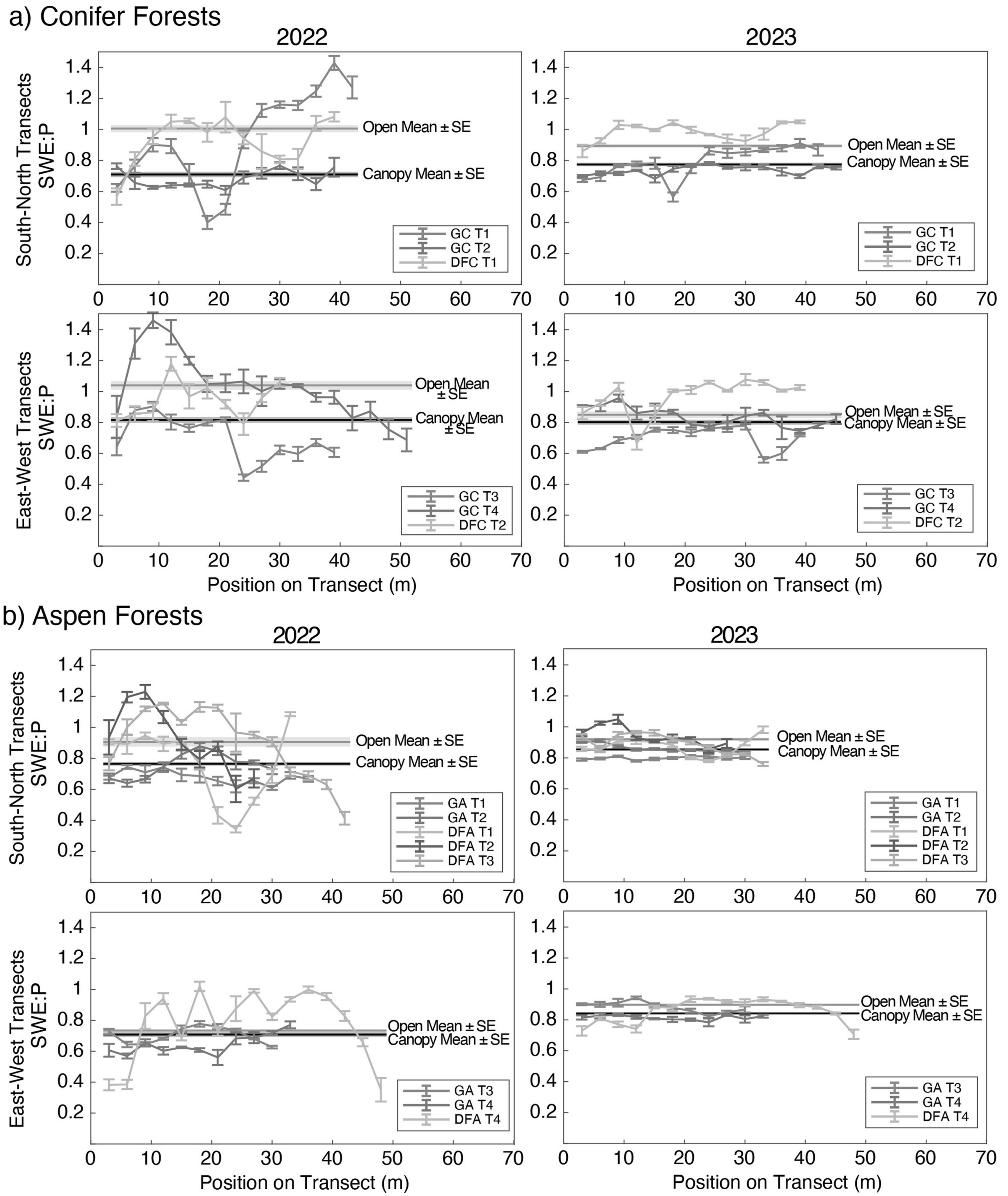

FIGURE 3 | Observed SWE to accumulated snowfall (SWE:P) transects for sites within (a) conifer forests (Guardsman Conifer (GC) and Days Fork Conifer (DFC)) and (b) aspen forests (Guardsman Aspen (GA) and Days Fork Aspen (DFA)). Standard error represented as error bars. Under canopy and open mean SWE:P (solid line) and standard errors (shaded area). GC, DFC and DFA sites are topographically shaded, while GA transects are nontopographically shaded.

to active management, including thinning and/or suppression of fire and insect, drought or fire-driven mortality. Vegetation both responds to and locally alters temperature and water availability during the growing season (Hu et al. 2010; Slatyer et al. 2022), and our data demonstrate similar impacts during the winter. Because growing season soil water availability is

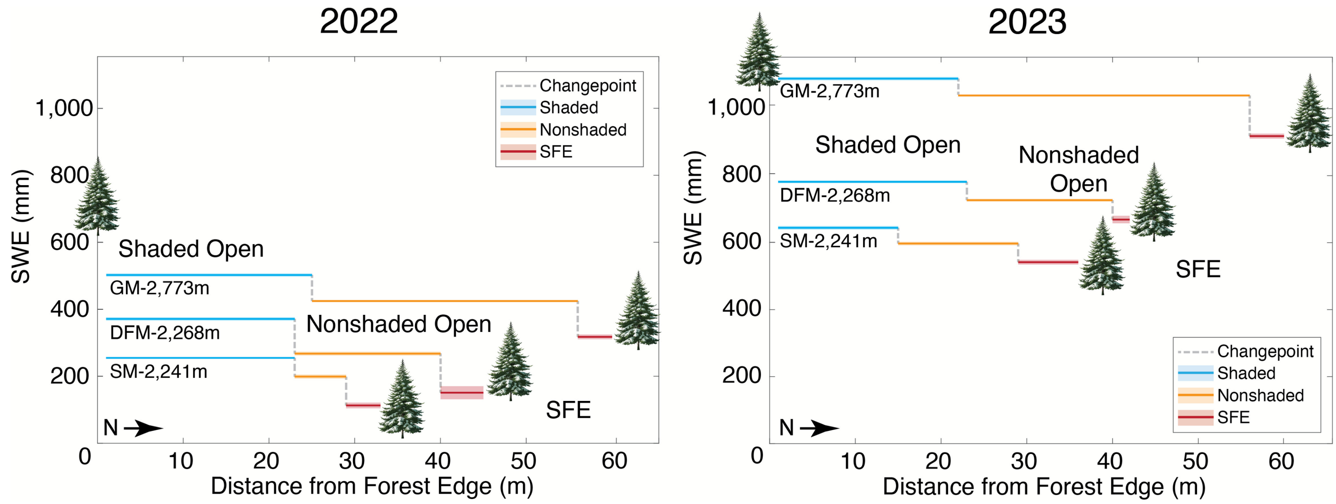

FIGURE 4 | SWE changepoint analysis of large gaps to distinguish boundaries of classifications (shaded open, nonshaded open, south forest edge (SFE)). GM shows an average of three transects. The grey dashed line indicates the point at which mean SWE changes significantly. Canopy and single tree effect values were excluded. Each classification's mean and standard error are represented by a solid line and shaded area, respectively.

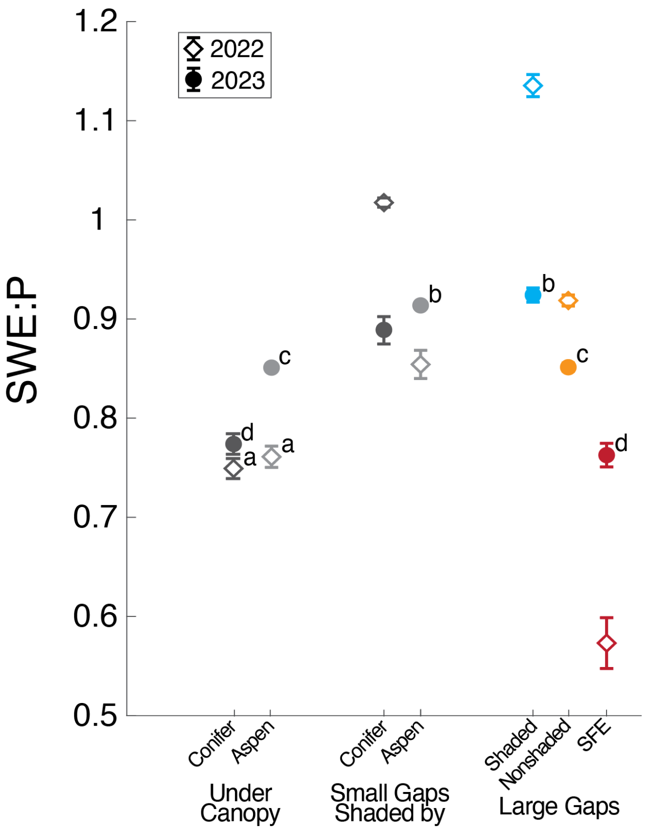

FIGURE 5 | Observed SWE to accumulated snowfall (SWE:P) variability under conifer and aspen canopies and in small (shaded by conifer and shaded by aspen forests) and large (shaded open, nonshaded open and south forest edges (SFE)) gaps. Mean and 95% confidence interval error bars. Letters indicate statistically significant differences resulting from *t*-tests.

closely related to the amount and timing of snow water input (Harpold et al. 2014), the spatial patterns in net SWE that result from the interactions between topographic and vegetation shading and sheltering in winter identified here and in similar studies (Tague et al. 2009; Rinehart et al. 2008) presumably impact plant growth during summer and susceptibility to drought or insects (Slatyer et al. 2022; Tai et al. 2018; Christensen et al. 2021). Consequently, the relationships developed here can be combined with high spatial resolution maps of forest structure to spatially distribute catchment-scale snow water input from only a few observations and to identify areas where vegetation may be most at risk from drought. The consistency in the relationships developed here indicates that local forest–snow interactions are reproducible under different meteorological conditions. Consistent wind redistribution patterns across our sites, combined with similar observations reported in other mountain catchments (Winstral and Marks 2002; Hiemstra et al. 2002; Winstral et al. 2013; Webb et al. 2020), demonstrate that wind and vegetation interactions can be parameterized and scaled. While wind can be a dominant driver of snow redistribution, our results demonstrate that the degree to which wind versus solar radiation governs snow accumulation shifts with annual hydroclimatic conditions, building on previous work from Currier and Lundquist (2018), Harpold and Brooks (2018), and Tennant et al. (2017). This highlights the need for models to integrate interception, wind and solar radiation, rather than attributing spatial variability in snow accumulation to a single driver. As such, this work fills a unique niche between large-scale statistical models of snow accumulation using remote sensing (Molotch et al. 2009; Schneider and Molotch 2016; Zheng et al. 2018; Yang et al. 2022) and small-scale plot studies of canopy versus gap (Storck et al. 2002; Musselman et al. 2008; Varhola et al. 2010).

When considering only under canopy and small gaps—historically the widespread focus of previous research—our results would suggest that forest disturbances, by reducing canopy cover, increase net SWE input by 15%, similar to what has been estimated or reported in some studies (Golding and Swanson 1986; Bewley et al. 2010; Pugh and Small 2011; Boon 2012; Pugh and Gordon 2013). In contrast, SWE:P in large, nonshaded open areas was not statistically different from that in under-canopy environments, highlighting the importance of gap size,

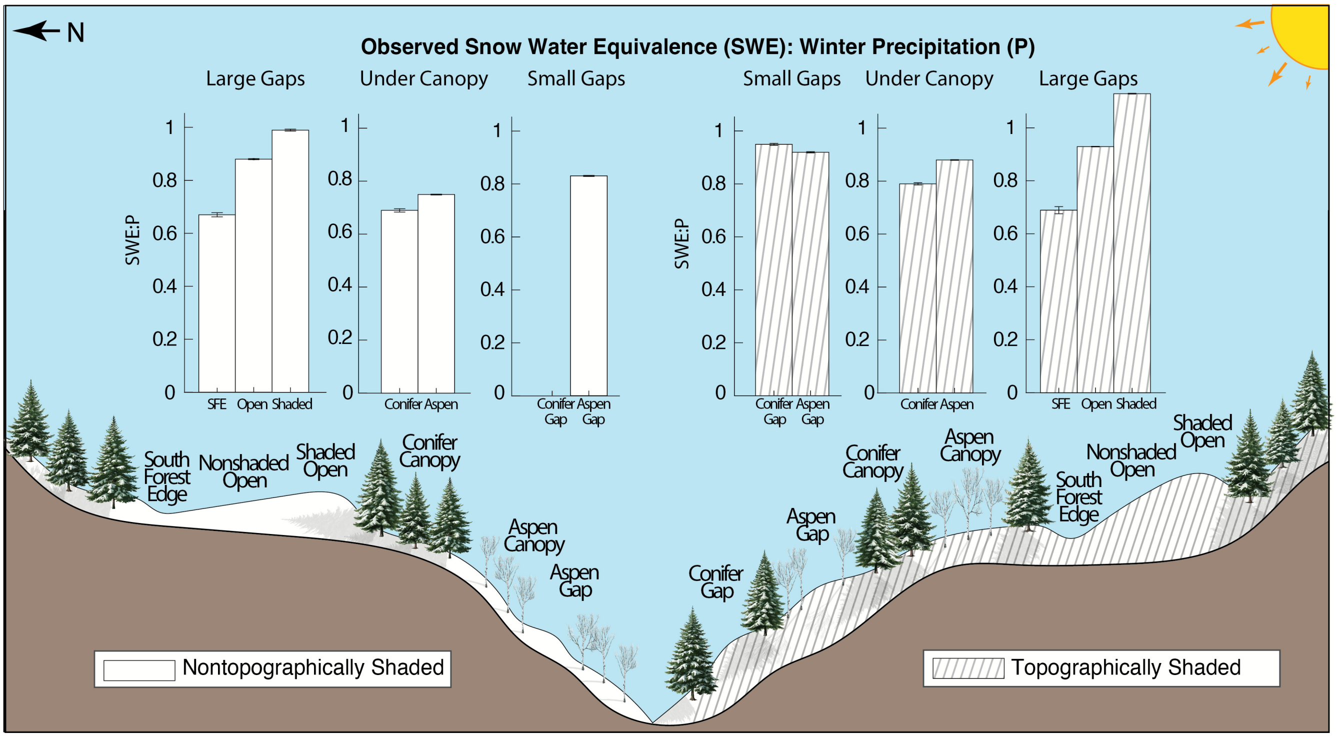

FIGURE 6 | SWE:P values are higher in topographically shaded areas (right) than in nontopographically shaded areas (left) across all seven vegetation environments: under conifer and aspen canopies, small gaps (shaded by conifer and shaded by aspen forests) and large gaps (shaded open, nonshaded open and south forest edges (SFE)). Error bars represent standard error.

orientation and canopy structure on interception, shading and sheltering of the snowpack. While canopy removal is often associated with increased net SWE, many of these studies focused on north-facing aspects (Troendle and King 1987; Stottlemyer and Troendle 2001; Winkler et al. 2010; Pugh and Small 2011); our results highlight that this effect is highly aspect-dependent. More recently, studies have found forest disturbances, such as the Cameron Peak Fire, disproportionately impact south-facing aspects by amplifying snow loss (McGrath et al. 2023; Kampf et al. 2022). While previous research focused on the role of aspect as a function of exposure to solar radiation and wind sheltering (Elder et al. 1991; Winstral et al. 2013; Varhola et al. 2010; Rinehart et al. 2008), fewer studies have examined the differential influence of vegetation by aspect (Ellis et al. 2011; Maxwell et al. 2019). Building on Rinehart et al. (2008) and others (Veatch et al. 2009; Gustafson et al. 2010; Biederman et al. 2012), we find vegetation modulates snow differently on shaded versus nonshaded aspects (Table 5). This is particularly evident in sparse to no vegetation, where solar radiation had a stronger influence on SWE than vegetation characteristics (Tennant et al. 2017). Our findings indicate that aspect-driven solar exposure amplifies snow loss in nontopographically shaded environments, explaining why canopy removal may decrease net SWE on south-facing aspects (Veatch et al. 2009; Gustafson et al. 2010; Biederman et al. 2012, 2014, 2015) by exposing the snowpack to higher energy inputs, yet increase net SWE on north-facing aspects by reducing midwinter losses (Troendle and King 1987). Our results, along with previous studies, suggest that a meta-analysis, such as the work by Goeking and Tarboton (2020), accounting for the differential influence of vegetation across aspects, could inform site-specific forest strategies aimed at enhancing net SWE.

Similarly, existing research on north-facing aspects suggests that converting conifers to aspens would increase net SWE (Dunford and Niederhof 1944; LaMalfa and Ryle 2008). Our results show that canopy type has a greater impact on net SWE under forest canopies than in small forest gaps, specifically in topographically shaded sites, supporting previous studies that found conifers are more effective interceptors than leafless aspen canopies (Dunford and Niederhof 1944; LaMalfa and Ryle 2008). However, at our sites canopy type has a smaller impact in forest gaps where both aspens and conifers seemingly provide sufficient shelter and shade to minimize sublimation and erosion by wind. This likely reflects the relatively weak winds observed at our sites during our study period. In locations or years with stronger winds, canopy type could play a larger role in modulating snow redistribution, with conifers providing greater shelter from wind than aspens. This distinction is important for transferring our results to windier settings within BCC or to other catchments where wind is a more dominant control on snow accumulation patterns. Since vegetation is not independent of aspect, aspen forests are more common on south-facing slopes within the BCC catchment, where we observed lower net SWE. Our findings indicate that while canopy type plays an important role within forests, vegetation structure—such as size of gaps and edge effects—exerts a greater influence in forest gaps.

Gap size alone does not fully dictate variability in net SWE, as both small and large gaps exhibited similar net accumulation. Instead, the position within gaps relative to surrounding vegetation plays a larger role. We observed SWE values most similar to winter snowfall at distances 0.5 to 1.2 times the mean

TABLE 5 | SWE:P values for areas influenced and uninfluenced by vegetation, under topographically shaded and nontopographically shaded conditions.

	Uninfluenced by vegetation	Influenced by vegetation				
		Under canopy		Shaded open		SFE
		Aspen	Conifer	Aspen	Conifer	Conifer
Topographically shaded	0.93 ± 0.12	0.88 ± 0.07*	0.79 ± 0.04*	0.92 ± 0.12	1.00 ± 0.05*	0.69 ± 0.26*
Nontopographically shaded	0.88 ± 0.05	0.75 ± 0.06*	0.69 ± 0.07*	0.83 ± 0.12*	0.99 ± 0.06*	0.67 ± 0.07*

Note: Vegetation influences include under canopy, shaded open and south forest edge (SFE) environments, leading to higher SWE:P in open areas shaded by conifers and lower SWE:P under canopies and in SFE, compared to uninfluenced, open areas. Plus/minus standard deviation. *Indicates statistical significance between environments influenced by vegetation from uninfluenced by vegetation.

tree height from the southern forest edge, similarly to Golding and Swanson (1978 and 1986), with net SWE decreasing from the forest edge. Observed net SWE exceeded snowfall inputs in shaded environments in 2022 (Figure 5), likely due to wind redistribution. Losses from under canopies can be offset by gains in shaded environments, where redistributed snow accumulated. Redistribution was particularly pronounced in small gaps and shaded sites in the drier year, with leeward deposition enhanced. This suggests that redistribution may be similar in both years, but relative SWE in deposited areas is higher during lower snowfall years. This is consistent with Webb et al. (2020), who found within-stand boundary effects on SWE extend several canopy heights into forests, reinforcing that forest edges exert a measurable influence well beyond the immediate clearing boundary. These spatial patterns align with the distance at which vegetation influences snow accumulation, found to extend 1 to 1.5 mean tree heights for north-of-forest edge effects (Lundquist et al. 2013; Biederman et al. 2012; Broxton et al. 2015, 2020; Currier et al. 2022) and roughly 4 m for south-of-forest edge effects (Currier et al. 2022). However, Dwivedi et al. (2024) suggest that reduced snow accumulation at warm forest edges may reflect a shift in earlier infiltration rather than a decrease in net snow water input due to vapour loss. Consistent with this, our 2022 field observations indicated signs of melt primarily at SFE in lower elevation sites. Yet, snow density values were not significantly higher at SFE relative to other environments, and the presence of melt-freeze crusts closer to forest edges transitioning laterally to faceted snow grains suggests that reduced SWE at these locations was not solely attributable to melt-driven densification. This aligns with the findings of Musselman et al. (2008), whose snow structural analysis reported extensive faceting adjacent to south-facing tree holes, suggesting that mass was lost as vapour rather than melt which would result in equilibrium metamorphism and densification. Our work quantifies the gradient in SWE, as shaded open areas had the highest net SWE, with 51% (2022) to 14% (2023) more snow than under canopies, 24% (2022) to 8% (2023) more than nonshaded open areas and 98% (2022) to 21% more than SFE. These patterns are consistent across elevations and years, with vegetation having a greater influence in nontopographically shaded sites.

Vegetation shading is likely to become increasingly important for enhancing net SWE as climate change intensifies forest disturbances—such as drought, pine beetle mortality and wildfires—and increases the frequency of warmer, drier years. The differences in net SWE were more statistically significant across environments in the drier year compared to the wetter year, suggesting spatial patterns due to microclimate differences are more pronounced in years when there is less snow overall. This finding is similar to Boon (2012) and Storck et al. (2002), where interstand differences were reduced in high-snowfall years due to heavy snowfalls exceeding the interception capacity of the canopy. Higher SWE:P under canopies in 2023 compared to 2022 suggests that in higher snow years, more snow reaches the ground, likely due to reduced sublimation and/or increased offloading. As canopies approach maximum storage capacity, their interception ratio decreases (Roth and Nolin 2017). At the same time, the fate of intercepted snow shifts—either the canopy remains at maximum capacity for longer because vapour loss creates little new storage space or excess snow is offloaded, allowing more snow to reach the ground beneath. This pattern is consistent with the colder temperatures and more frequent storms in 2023, yet similar wind conditions between years (Table 2). Despite the expectation that low-snow years result in a greater percent loss of snowfall (Sexstone et al. 2018), we observed higher mean percent and mass losses in 2023. Colder temperatures, more frequent snowfall and a longer accumulation season in 2023 likely led to a less dense snowpack with greater surface area exposed to vapour loss (Pomeroy and Brun 2001), while a prolonged dry period in 2022 likely led to snowpack compaction and reduced surface area. Consistent wind and solar energy across different climatic conditions contribute to stable spatial patterns in fractional net SWE, with snow surface area playing a key role in vapour loss, thus providing a baseline for assessing the impacts of forest disturbances on net SWE.

The response of local water availability to forest management and disturbances is likely to vary based on aspect. Alternating clusters of trees with east–west oriented gaps, approximately 1 to 1.2 tree heights wide may optimize net snow water input by maximizing shaded environments northeast of forest edges and minimizing nonshaded environments southwest of forest edges on nonshaded aspects, whereas thinning with small gaps may optimize net snow water input on shaded aspects. This approach provides elevation, aspect and vegetation type guidance on how and why active management might vary between locations. Catchments at higher latitudes and/or with greater tree heights may benefit from maintaining or promoting larger gaps, as the sun angle is lower with increasing effects from shading. Whereas catchments at lower latitudes and/or with shorter tree heights might expect higher net SWE with small gaps, as the sun angle is higher and shading decreases. Because our sites represent the more common forest types in the western United States (conifer and deciduous) with a range in canopy cover (from 22% to 61%) and species type (aspen, spruce, white fir, Douglas fir and subalpine fir), results allow researchers and managers of other continental snowpacks to assess how net accumulated SWE may respond to changes in canopy cover. Based on our results, we recommend future management efforts aimed at enhancing net SWE also integrate ecological considerations such as forest regrowth (Krogh et al. 2024) and meltwater contributions to downslope ecosystems in maintaining habitat connectivity. For example, greater net SWE in shaded areas may enhance soil moisture availability into the growing season, while areas with lower net SWE may expose soils to earlier drying.

Just as the importance of vegetation structure varies based on topographic shading, vegetation has a larger influence on net SWE input in drier years and drier sites. Lower SWE:P values were observed in most environments during the drier year, despite a greater mean percent loss and double the mass loss in the wetter year (amplified impact of vegetation under low-snow conditions). Our findings are consistent with Farwell (2025) and Lundquist et al. (2013), whose work highlights how local forest structure more strongly influences snow accumulation in drier years, while broader climate processes dominate in wetter years. This suggests that snow-vegetation interactions will become more important for ecology and water resources as the climate warms and snow decreases.

5 | Conclusion

Observed net SWE values were consistently lower than accumulated winter snowfall, suggesting midwinter vapour loss as the primary driver of spatial variability in net snow accumulation. Midwinter ablation was predictably related to a hierarchy of controls (topography, vegetation cover, type of vegetation, size of gap and position relative to vegetation) that influence net SWE at different spatial scales. Across all sites, we observed consistently higher net SWE in low radiation, wind-sheltered environments and consistently lower net SWE in higher energy, windier environments. These patterns in net accumulated SWE varied predictably within seven distinct vegetation environments across wet and dry years, as well as varying elevations and aspects suggesting that spatial vegetation maps can be used to distribute SWE accumulation. Topography either amplified or muted the influence of vegetation, as nontopographically shaded areas had lower net SWE than in topographically shaded areas, which may explain the varying responses to snowpack following forest disturbances. Implementing these categorical classifications provides a transferrable statistical method that is slightly more complex than canopy versus open but does not require higher resolution spatial data and process modelling. Forest disturbances, particularly in response to climate change, exacerbate snow loss on south-facing terrain, making it imperative to consider how vegetation modulates net snow water input across varying elevations, aspects and winter seasons when modelling net SWE for water resources and sustainable forest management.

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Data Availability Statement

Terrain basemap (Esri, TomTom, Garmin, FAO, NOAA, USGS, OpenStreetMap contributors and the GIS Community, ESRI, USGS), high-resolution orthophotography (UGRC 2012), stream locations (UGRC 2016), watershed boundary (UGRC 2023), topography (DEM and DSM) (UGRC 2020a, 2020b), vegetation (MRLC 2021; UGRC 2012; Riley et al. 2021; USDA 2023), climate data (NRCS 2025; Mesowest 2025) and snow depths and densities (doi.org/10.4211/hs.d6cfaee5c5994ae2875fd957453dbfcf) are publicly available online.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Mean forest characteristics at each site, calculated using ArcGIS. DEM and DSM from UGS, TreeMap (Riley et al. 2021) and TCC (NLCD) datasets from the US Forest Service (USDA, 2023). Visual inspection confirmed accurate spatial alignment between transect locations and forest characteristic datasets. **Table S2:** Results from two-tailed *t*-tests between higher and lower elevation observed SWE, then nontopographically shaded and topographically shaded observed SWE. **Table S3:** 2022 and 2023 SWE:P *p*-values resulting from two-tailed *t*-tests. **Table S4:** SWE:P *p*-values resulting from two-tailed *t*-tests between years. **Table S5:** Topographically and nontopographically shaded SWE:P *p*-values resulting from two-tailed *t*-tests between years. **Table S6:** Number of observations in each environment. Over 3000 observations over 2 years. **Figure S1:** SWE:P in each vegetation environment. Lower SWE:P on south-facing slopes and higher SWE:P on north-facing slopes.