Ranking Forest Effects on Snow Storage: A Decision Tool for Forest Management

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Abstract Forests modify snow accumulation and ablation rates as well as overall snow storage amounts and durations, with multiple processes acting simultaneously and often in different directions. To synthesize complex forest–snow relations and help guide near-term management decisions, we present a decision tree. The framework is based on a hypothesized hierarchy of processes and associated variables that predict forest effects on snow storage. In locations with high wind speeds, forests enhance snow storage magnitude and duration relative to open areas. Where wind speeds are low, and winter and spring air temperatures are colder, forests diminish snow storage magnitude but enhance duration. Where air temperatures are warmer, forests diminish both snow magnitude and duration. Forest structure and aspect are secondary influences. We apply the decision tree framework to map the influence of forests on snow storage under historic climate conditions across the western United States, but this decision tree is applicable in any region with forests and snow. This framework provides practitioners a first-step evaluation to guide management decisions that consider where and how forests can be managed to optimize in situ water storage alongside other objectives, such as reducing wildfire hazard. This framework also articulates geospatial hypotheses, in order of anticipated importance, to be tested in future investigations of forest–snow–climate relations.

Plain Language Summary Forests affect the amount of snow that accumulates on the landscape and how long it lasts before melting. Thus, the removal of forest canopy via timber harvest, thinning, or fire influences how long water is stored on the landscape as snowpack and summer water availability for soils, instream, and water consumption. However, predicting whether forest cover accelerates or delays snowmelt relative to a nearby open area has proven difficult due to complex forest–snow processes that vary with location. In addition, under-forest observations of snow are sparse. We present a binary decision tree framework to predict how the forest cover affects the amount and duration of snowpack relative to an adjacent open location. The intent is both to articulate a testable hypothesis for future research and to support forest management decisions that strive to balance both water resource considerations and other natural resource objectives, such as reducing wildfire hazard. We utilize publicly available climate and topographic data to present an example application for the western United States. The resulting map illustrates how the effect of forest canopy cover on snow storage varies by region and elevation and has implications for the forest management under current and warming climate conditions.

1. Introduction

Forest–snow interactions have been studied for over a century due to the importance of forest management to snow and water resources (Bosch & Hewlett, 1982; Church, 1933; Rothacher, 1970; Stednick, 1996; The Ouray Herald, 1906). Even though the key influences of forest cover on snow processes are widely observed, advances in practical scientific prediction have been slow because whether forest cover delays or accelerates snowpack disappearance varies with climate (Lundquist et al., 2013), topographic position (Ellis et al., 2013; Strasser et al., 2011), latitude (Musselman et al., 2008; Seyednasrollah & Kumar, 2019), and forest characteristics such as canopy density (Kittredge, 1953). The absolute amount and duration of snow storage across the landscape largely depends on climate and elevation, but the relative difference in snow storage between the adjacent forested and open areas with no overstory canopy also varies substantially. Snow storage duration has been observed to range from snow lasting more than three weeks longer in the forest relative to an adjacent open area (Koivusalo & Kokkonen, 2002; Lundquist et al., 2013) to snow disappearing more than 12 weeks earlier in a forest relative to an open area (Dickerson-Lange et al., 2017). Meanwhile, snow...
is operationally monitored only in openings (Farnes, 1967), optical remote sensing cannot detect snow beneath the trees (Rittger et al., 2020), and an accurate modeling of under-canopy snow is an ongoing research challenge (Clark et al., 2015; Essery et al., 2009; Lundquist et al., 2021; Rutter et al., 2009). Therefore, predictions for the net effects of a change in forest cover, such as from timber harvest, silvicultural thinning, or fire, on snow storage are typically site specific (Gleason et al., 2013; Harpold et al., 2020; Krogh et al., 2020; Schneider et al., 2019). No guidance exists for unstudied areas.

As researchers, we are asked to provide our “best guess” for guiding near-term forest management actions in locations we have not directly investigated. Thinning and prescribed fire are being implemented across the western United States (U.S.) to reduce wildfire hazard, increase forest resilience, and improve forest health. For example, in Washington State, U.S., a state-wide forest health plan calls for thinning more than 1 million acres of public lands that have been identified as needing forest restoration to decrease wildfire hazard and restore ecological health (Haugo et al., 2015; Washington State Department of Natural Resources, 2018). However, the focal area of the forest health plan is east of the crest of the Cascade Range and constitutes a regional data gap in forest–snow observations, despite strong stakeholder interest in integrating hydrologic effects into the forest management strategies (Wigmosta et al., 2015). This example is just one of many throughout the U.S. that illustrates how understanding the potential hydrologic impacts of forest management actions is critical for developing multibenefit strategies and for avoiding unintended reductions in snow storage.

Accurately accounting for forest effects on snow storage will become even more important under warming climate conditions, with increases in forest disturbances (Westerling, 2006) and changes to hydrology that include earlier snowmelt with consequent decreases in summer low flows (Adam et al., 2009; Dickerson-Lange & Mitchell, 2014; Elsner et al., 2010; Hamlet & Lettenmaier, 2007; Mote et al., 2005; Stewart et al., 2005). Differences in snow storage duration between the adjacent forested and open areas are similar in length (i.e., 0–12 weeks; Dickerson-Lange et al., 2017; Lundquist et al., 2013) to projected shifts toward earlier snowmelt timing due to climate change (e.g., Elsner et al., 2010; Stewart et al., 2005). Thus, an improved understanding of forest–climate–snow interactions has applications for both improving fidelity of climate change impacts modeling as well as supporting local adaptation goals that range from forest resilience to water supply (Churchill et al., 2013; Hessburg et al., 2015; Wigmosta et al., 2015).

In this study, we propose a hierarchy of forest–snow processes that combine to determine overall forest effects on the amount and duration of snow storage (Section 2). Using the hypothesized binary decision tree framework, we map the predictions of how forests affect snow storage relative to adjacent open areas across the western U.S. (Section 3). This framework synthesizes our current understanding of forest–snow–climate interactions (Sections 2 and 4) to support forestland and water management decisions (Section 5) and articulates testable hypotheses to guide additional research (Section 6) to better understand and represent these processes.

2. Decision Tree Framework: Hierarchy of Primary Forest–Snow Processes

2.1. Review of Forest–Snow Processes

Forests influence snowpacks by modifying water and energy fluxes at a range of spatial and temporal scales. Forests modify snow accumulation processes via attenuation of wind and associated influences on snow deposition patterns as well as via canopy snow interception and subsequent sublimation, melting, or unloading (e.g., Currier & Lundquist, 2018; Storck et al., 2002). Forests also modify snow ablation processes, which include snowmelt and sublimation. Shading from sunlight reduces net solar radiation, and sheltering from wind reduces turbulent heat exchange (Marks et al., 1998; Musselman et al., 2013). Forests emit thermal radiation, which increases net radiation, and deposit needles and branches, which decrease snow albedo and increase net radiation (Hardy et al., 2000; Lawler & Link, 2011; Musselman & Pomeroy, 2017).

As a result of the processes described above, changes in the forest cover affect the amount and duration of snow storage. These changes impact water availability to the terrestrial and aquatic ecosystems as well as water resources for out-of-stream uses (Dore et al., 2012; Goeking & Tarboton, 2020; Grant et al., 2013; Harpold et al., 2020; Hubbart et al., 2007; Perrot et al., 2014; Pugh & Small, 2012).
2.2. Conceptual Basis and Hypotheses

Whereas the majority of current literature examines one process in isolation or net effects at one location, the decision tree framework presented herein reflects a new, proposed hierarchy of processes to enable landscape-scale prediction of forest effects on snow storage. Previous work demonstrates that the combined effects of forest–snow processes can flip from the forests retaining snow to the forests accelerating the disappearance of snow, and this framework provides a method for classifying locations to identify the direction of this overall effect of forest on snow storage. The framework ranks the importance of different forest–snow processes in determining how the amount and duration of snow storage in the forest compares to the open (Figure 1). A forest site is defined as stand-scale (1–10s of hectares, or $10^2–10^3 m^2$) forest with similar stem density and canopy cover. A reference open site is defined as an adjacent site of similar scale with no trees (or canopy cover) and no forest edges to influence snow accumulation or ablation processes. This decision tree considers the local-scale (1–10s of hectares) difference in snow storage between a forest site and reference open site and then maps that local difference across larger, landscape-scale (100s to >10,000s of hectares) spatial variations in elevation and climate. At a larger scale, the total magnitude of snow storage changes as well as the direction (longer or shorter) of the local forest's influence on snow storage.

The fundamental hypotheses, which are the basis for the decision tree framework, are: (a) the forest effects on accumulation are more important than the forest effects on ablation for determining net snow storage, including both magnitude and duration (Dickerson-Lange et al., 2017; Lundquist et al., 2013); and (b) climate variables override local complexities in forest structure, topographic position, and weather (Lundquist et al., 2004, 2013). The classes are defined by the open versus forest difference in snow storage duration, which is largely driven by the difference in snow storage magnitude (Dickerson-Lange et al., 2017). The resulting forest–snow classes can be mapped to provide a visual representation of the hypothesized effect of forests on snow storage across the landscape. This classification and mapping approach is analogous to previous snow classification efforts (e.g., Sturm et al., 1995; Trujillo & Molotch, 2014), but is the first framework we know for classifying and mapping the overall effect of forest on snow storage.

2.3. Decision Tree Framework

The difference in snow storage magnitude and duration between a closed forest canopy and an open reference site with similar topographic position and climate is hereafter referred to as relative snow storage. Three numbered nodes (Figures 1a and 1b) in the decision tree terminate at five classes (Figure 1c) to predict the relative snow storage between an adjacent forest and open site. Each node represents a primary influence on relative snow storage and incorporates local data to decide between two paths, with threshold values for binary splits based on literature values. The order of nodes reflects the hypothesis that the forest effects on accumulation processes, versus ablation processes, dominate the overall influence of forest cover on the magnitude and duration of snow storage. Therefore, the accumulation effects are considered in Nodes 1 and 2 and the ablation effects in Node 3.

The five terminal classes are assigned a letter and named for the dominant condition(s) that affect relative snow storage. The classes are ordered to range from greater snow accumulation magnitude and longer snow cover duration in the open on the left, to similar snow magnitude and longer duration in the forest on the right (Figure 1c). The differences in snow storage relative to an open reference site are illustrated with a conceptual time series of snow water equivalent (Figure 1e). To help guide forest management actions, these classes align with a continuum of increasing snow retention under the forest cover (left to right; Figure 1d). Whereas there are five named cases in the decision tree, the cases more realistically represent a spectrum of effects. Further details on how secondary influences can shift an individual site's position on the spectrum are included in Section 4. Each node is described below, including physical processes on which the node is based, the decision variable, and threshold values.

2.3.1. Node 1: Occurrence of Preferential Deposition and Redistribution

In windy locations, the presence of trees exerts a strong control on the spatial distribution of snow, with maximum snow accumulation in the lee of individual trees or ribbon forests at most sites studied (Currier & Lundquist, 2018; Fortin et al., 2015; Gary, 1974; Geddes et al., 2005; Hiemstra et al., 2002, 2006; Liptzin & Seastedt, 2009). Such patterns can result from preferential deposition during a storm (Qiu et al., 2011) and...
Figure 1.

**NODE 1:** OCCURRENCE OF PREFERENTIAL DEPOSITION AND REDISTRIBUTION (Wind Speed)

- Low Wind Speeds: $< 5 \text{ m s}^{-1}$
- High Wind Speeds: $\geq 5 \text{ m s}^{-1}$

**NODE 2:** MAGNITUDE OF INTERCEPTION EFFECT (Winter Temperature)

- Warmer Winter: DJF Mean Temp $\geq -1 \text{ °C}$
- Colder Winter: DJF Mean Temp $< -1 \text{ °C}$

**NODE 3:** MAGNITUDE OF FOREST SHADING EFFECT (Timing of Majority of Snowmelt Before or After Spring Equinox (20 March))

- Earlier Melt: MA Max Temp $\geq 6 \text{ °C}$
- Later Melt: MA Max Temp $< 6 \text{ °C}$

**Forest Effects on Accumulation**

**Class:**
- A1. WARM & Early
- A2. WARM & Late
- B1. COLD & Early
- B2. COLD & Late
- C. WINDY

**Magnitude:**
- Peak$_{open}$ $>>$ Peak$_{forest}$
- Peak$_{open}$ > Peak$_{forest}$
- Peak$_{open}$ = Peak$_{forest}$

**Duration:**
- Much Longer Open $\leftrightarrow$ Longer Open
- Longer Open $\leftrightarrow$ Longer Forest
- Longer Forest (Edges)

**Secondary influences may shift classification (see Table 1)**

**Forest Actions:**
- Large Canopy Gaps and Heavy Thinning
- Small Gaps and Light Thinning (Less Clear/Climate Change Zone)
- Retain Forest Cover (Edges)

Increasing snow retention under forest cover

**Snow Water Equivalent**

- Open - Reference
- A1 - Warm and Early
- A2 - Warm and Late
- B1 - Cold and Early
- B2 - Cold and Late
- C - Windy

**Date**

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**Figure 1.**
from snow redistribution in between storms (Li & Pomeroy, 1997), with forest edges acting like snow fences (Tabler, 1994, 2003).

Observations in Oregon and Idaho, U.S., suggest that wind-driven preferential accumulation within and at the edges of forests can switch snow storage duration from snow lasting longer in the open to longer in the forest, despite warm winter climate and high canopy snow interception rates (Dickerson-Lange et al., 2017). The importance of high winds in determining the relative snow storage is further supported by the observations in a windy location within the Spanish Pyrenees, where the snow disappearance timing in the open and the forest was observed to be synchronous, despite warm winter air temperatures that would suggest that snow would persist longer in the open (López-Moreno & Latron, 2008; Revuelto et al., 2015).

We hypothesize that at locations with high wind speeds, wind is the dominant factor in determining relative snow storage, as winds preferentially deposit snow within or adjacent to the forest and scour snow from the open areas and deposit it near the forests. Note that we lump snow storage at the forests edges, which are a key influence on wind-influenced snow deposition (Currier & Lundquist, 2018), with forest snow storage rather than with open snow storage. Within-stand spatial variability in the density and arrangement of trees and canopy cover are hypothesized to be the secondary influences on snow and are discussed in Section 4.

Thus, the first decision node passes locations without high winds into Node 2 for further classification and partitions the locations with high winds into Class C. Within this class, we hypothesize that the wind-driven effects on snow accumulation control the difference in magnitude of peak snow storage, which is similar between forest and open, or potentially greater within the forest or along the forest edges. With similar peak magnitude, snow storage duration is subsequently longer within the forest or along the forest edges where ablation rates are reduced due to sheltering and shading.

As the decision variable and threshold value for Node 1, we select a December, January, and February (DJF) average wind speed of $\geq 5$ m s$^{-1}$, measured at 10 m above ground surface. Snow redistribution between storms requires a critical wind speed of at least 5 m s$^{-1}$ for dry snow (Hiemstra et al., 2006; Li & Pomeroy, 1997; Pomeroy & Gray, 1990) and potentially higher than 8 m s$^{-1}$ (Clifton et al., 2006). Wet and denser snow, generally associated with warmer winter air temperatures, has higher cohesion and is generally not redistributed by wind. While preferential snow deposition processes, in contrast to redistribution processes, has been found to occur at wind speeds lower than 5 m s$^{-1}$ on exposed leeward slopes (Dadic et al., 2010; Mott et al., 2014, 2018), the wind-related forest–snow patterns have been noted only at sites with a high frequency of winds greater than 5 m s$^{-1}$ (Currier & Lundquist, 2018; Dickerson-Lange et al., 2017; Lundquist et al., 2013). The observation and prediction of wind in complex terrain remains both an active area of research (Hiemstra et al., 2006; Liston et al., 2007; Mott & Lehning, 2010; Reynolds et al., 2020; Winstral et al., 2013) and operational challenge (Malek, 2008). For the purpose of Node 1 classification, local evidence for the presence of high winds during or immediately after snow storms is more important than the period and threshold value for quantifying high wind speeds.

2.3.2. Node 2: Magnitude of Interception Effect

Snow interception rates are higher in warmer climates due to a higher snow cohesion at warmer air temperatures. Specifically, the fraction of total precipitation intercepted by a tree branch (or study board) more than doubles when storm air temperatures increase from below −3°C to about −1°C (Kobayashi, 1987; Pfister & Schneebeli, 1999; Shidei et al., 1952). Such warm storms have led to the greatest canopy interception amounts ever recorded (Martin et al., 2013; Shidei et al., 1952). These same environments frequently have interstorm air temperatures above freezing, which lead to intercepted snow sublimating or melting rather
than unloading to contribute to under-canopy snow storage (Satterlund & Haupt, 1967; Shidei et al., 1952; Storck et al., 2002). As a result, in the warmer maritime and transitional climates of the U.S. Pacific Northwest (PNW), ratios of peak snow depth in the open as compared to the forest have been observed to range from 1.2 to 3.8, with a median of 2.4 (Dickerson-Lange et al., 2017). In contrast, in colder continental climates like the U.S. Intermountain West, ratios at two sites range from 0.9 to 1.6, with a median of 1.3 (Harpold et al., 2015). Higher amounts of winter precipitation are generally linked to warmer winter climates, which also influence the difference in snow storage (e.g., see Figure 2 of Lundquist et al., 2013).

Given that warmer temperatures drive the physical processes that enhance both canopy snow interception and higher winter precipitation, we propose winter temperature as the decision variable for Node 2. At Node 2, the magnitude of the canopy interception effect divides the remaining locations into Classes A and B (Figure 1). Class A includes locations with a warmer winter climate where increased snow cohesion leads to larger differences between peak snow storage in forests and open sites. Class B includes locations with a colder winter climate where decreased snow cohesion leads to smaller difference between peak snow storage in forests and open sites. For a threshold value, we select a mean DJF air temperature of −1°C, proposed by Lundquist et al. (2013), to distinguish a higher canopy interception effect (>−1°C) from a lower canopy interception effect (<−1°C).

### 2.3.3. Node 3: Magnitude of Forest Shading Effect

Forest cover can reduce or enhance the net radiative inputs to the under-canopy snowpack, which contribute to the ablation rates (e.g., Ellis et al., 2011; Lawler & Link, 2011; Seyednasrollah et al., 2013; Sicart et al., 2004). Trees block sunlight through canopy shading, reducing incoming solar radiation (Mahat & Tarboton, 2012; Sicart et al., 2004), but the forest contributes more longwave (i.e., thermal) radiation to the under-canopy snowpack than the atmosphere, which can result in higher net longwave radiation under forest canopy than in the open (Lawler & Link, 2011; Lundquist et al., 2013; Pomeroy et al., 2009; Sicart et al., 2004). The relative importance of the effects of decreased shortwave versus increased longwave radiation on snow storage within a forest depends on air temperature, the timing of snowmelt relative to the solar elevation angle, latitude, topographic shading, slope, aspect, atmospheric humidity and cloudiness, and forest structure (Brotxton et al., 2015; Ellis et al., 2013; Lundquist et al., 2013; Lundquist & Flint, 2006; Seyednasrollah & Kumar, 2014; Seyednasrollah et al., 2013; Strasser et al., 2011).

The role of canopy shading is diminished where and when the timing of the ablation season, which occurs from peak snow accumulation to snow disappearance, occurs earlier in the year, due to the lower solar elevation and thus lower total incoming shortwave radiation. Distinguishing between early and late snowmelt subdivides each of Classes A and B into two subclasses, which account for the relative importance of canopy shading in determining melt rates and snow duration (Figure 1). Where snowmelt occurs later in the year and canopy shading substantially slows ablation rates in the forest relative to the open, the snow storage duration in the forest may be longer than in the open, despite starting with more snow in the open. Thus, the influence of canopy shading has the potential to set up a situation that is considered typical in colder, continental interior locations (e.g., Colorado, U.S. and Alberta, Canada): more snow accumulation in the open, but longer lasting snow in the forest.

Topographic position, including both aspect and slope, also influences the amount of canopy shading, but several studies have demonstrated that time of year when melt occurs is the dominant influence on the net radiation balance differences between forest and open (Seyednasrollah & Kumar, 2014; Strasser et al., 2011). Thus, we include the topographic position in the framework as a secondary effect.

In colder winter climates (i.e., Class B), which have a smaller difference in peak snow storage magnitude when the ablation season begins, the timing of snowmelt predicts whether snow storage duration will flip between longer in the open or longer in the forest. The magnitude of the canopy shading effect is diminished by early snowmelt timing in Class B1 (cold and early), resulting in snow storage duration that ranges from longer in the open to approximately the same. In Class B2 (cold and late), the importance of canopy shading is amplified, setting up the conditions for snow storage duration to be longer in the forest, despite starting the ablation season with less snow in the forest. In contrast, in warmer winter climates, the large difference in peak snow storage magnitude between forest and open dominates relative snow storage.
duration, which ranges from much longer to longer in the open in classes A1 (warm and early) and A2 (warm and late), respectively (Figure 1).

We subdivide Classes A and B based on the timing of peak snow, which marks the onset of the ablation season, relative to the spring equinox (about 20 March for the northern hemisphere), since that is the time of most rapid change in solar elevation. Sites with peak snow before the spring equinox are early melt sites, whereas sites with peak snow after the spring equinox are late melt sites. Snowmelt timing can be directly determined from nearby snow observations (e.g., U.S. SNOW TELEmetry network) or from gridded model results, or indirectly based on a temperature-based proxy for snowmelt timing.

3. Application of Framework to Map Forest-Snow Classes

3.1. Data Sources
To illustrate how to apply the decision tree framework, we use publicly available data in the western U.S. at an 800-m resolution (Figure 2), although the framework could alternatively be applied to a single location or a different resolution grid. We focus on locations that are classified as forested, based on deciduous, coniferous, and mixed forest classes in the National Land Cover Database (NLCD; Homer et al., 2015), resampled to 800 m from 30-m native resolution using a majority resampling approach. We further focus on forests that experience mean DJF air temperatures less than 3°C (PRISM Climate Group, 2012), which exclude areas that are unlikely to have snow (Figure 2a). The input data and the results are available as gridded files and the processing code is available as an R script in a HydroShare data repository (https://doi.org/10.4211/hs.76e60d8b9ead4c33898c14dd677c6e06).

Given the large spatial extent of the western U.S. application, we use gridded datasets as inputs and proxies for the Node 1 and 3 decision variables. For Node 1, we use topographic curvature as a proxy for exposure to high winds. We compute the topographic curvature across the 800-m digital elevation model (DEM) from PRISM (PRISM Climate Group, 2012) using a 9 by 9 pixel moving window, as implemented by the Jenness DEM Surface Tools toolbox (Jenness, 2013). We then identify pixels for which curvature was greater than three standard deviations higher than the mean (i.e., convex) as ridgetops (Figure 2b). For Node 2, we use the gridded 30-year average (1981–2010) of DJF mean daily air temperature normals from PRISM. The data illustrate a strong east–west and north–south gradient in DJF air temperatures (Figure 2c). For Node 3, in this representation, we select a mean March and April (MA) maximum daily air temperature of 6°C to distinguish early from late melt locations. This proxy is based on the previous work by Kapnick and Hall (2010), which utilized more than 70 years of observations from the Sierra Nevada, U.S., to quantify spring air temperature associated with the timing of peak snow (see their Figure 6). Where mean MA maximum daily air temperatures are warmer than 6°C, we infer that the onset of the ablation season is before the spring equinox, and vice versa. We use the gridded 30-year average (1981–2010) of MA maximum daily air temperature normals from PRISM, which reflect an elevational gradient, with colder spring temperatures at higher elevations (Figure 2d).

3.2. Forest-Snow Classes
The result from incorporating the geospatial inputs described above into the decision tree framework is an 800-m resolution map of forest–snow classes (Figure 3), which we vet against paired forest–open observations below. Whereas the scale of the prediction is aligned with the 800-m input data, the result is a first-order estimate of relative snow storage for a paired, stand-scale forest and open reference site within an 800-m pixel. The framework is flexible to incorporate higher resolution gridded data or point data, which could provide an improved prediction where there is high spatial variability in wind, winter temperature, or the timing of snowmelt. However, a higher resolution application does not imply prediction at a smaller spatial scale, such as snow storage within a 1–10 m canopy gap.

The observations from the western slopes of the Cascade Range in Washington and Oregon and the Sierra Nevada Range in California are congruent with the dominant classification as Class A1, which is associated with much higher snow accumulation and much longer snow duration in the open. Previous work reported snow persisting 1–13 weeks (i.e., 5–93 days) longer in the open in this region, shown in Figure 3 as points...
Figure 2. Input spatial data for the western United States application the model, all displayed on hillshade maps. Input data include (a) extent of forest, (b) convex areas as a proxy for wind exposure, (c) average December, January, and February daily mean air temperature, and (d) average MA maximum air temperature.
Figure 3. Predicted climate–forest–snow classes across the western United States, displayed on a hillshade map. Locations of observational studies that are referenced in the text are marked with numbers.
1 (Dickerson-Lange, Lutz, Gersonde, et al., 2015), 2–4 (Dickerson-Lange et al., 2017; Roth & Nolin, 2017), 5 (Storck et al., 2002), 6 (Bales et al., 2011), and 7 (Harpold et al., 2015). The one exception is along the Cascade Crest, at Hogg Pass, OR (point 3 in Figure 3), where snow storage duration was 15–29 days longer in the forest, which was attributed to high winds and verified by local observations (Dickerson-Lange et al., 2017). The observations from central and northern Idaho and western Montana, which are all located in Class B1 (cold and early), report the relative snow storage duration that ranges from 1 day longer in the forest to an average of 10 days longer in the open, shown in Figure 3 as points 8–11 (Carson, 2010; Dickerson-Lange et al., 2017; Hubbart et al., 2007; Schneider et al., 2019). Additional observations from the locations classified as Class B1 (cold and early) in Utah and New Mexico demonstrate the relative snow storage duration ranging from the same, points 12 (LaMalfa & Ryle, 2008) and 16 (Musselman et al., 2008) in Figure 3, to an average of 4 days longer in the forest, point 15 (Harpold et al., 2015). One of two Colorado sites classified as Class B2 (cold and late) recorded snow lasting an average of 13 days longer in the forest, point 13 (Rutter et al., 2009). In contrast, the observations from Niwot Ridge, near Boulder, Colorado do not align with the relative snow storage duration associated with Class B2; the difference in snow disappearance timing during 5 years of observations averaged 11 days longer in open positions as compared to under forest canopy positions, point 14 (Harpold et al., 2015). However, these observations are from single sensors located under small canopy openings and may reflect smaller scale variation in canopy cover rather than a stand-scale comparison between forest and an open area outside the influence of forest edges. This difference illustrates the variability in forest effects on snow storage across spatial scales and highlights the need for this type of framework to synthesize effects at a scale that is relevant to management decisions.

5. Secondary Influences Shift Relative Snow Storage

The primary nodes of the decision tree framework reflect our hypotheses about which forest effects on snow storage are most important and how each forest effect scales with climate to determine relative snow storage at a particular location. Local complexities, which we incorporate into this framework as secondary influences (Table 1), do not lead to new classes, but rather suggest the directionality of smaller adjustments in position on the spectrum of relative snow storage (Figure 1 and Table 1). Secondary influences are represented conceptually by the envelope around the line plots in Figure 1e and are discussed below.

Forest structure, which is the result of species composition and site conditions, as well as the history of management and disturbance, is a secondary influence on all three nodes. The magnitude and directionality of influence largely depends on the spatial scale at which the forest structure is considered. Numerous previous studies have compared snow storage between forests and open areas. However, there is a broad range of characteristics represented within both categories, such as forests that range from overstocked second-growth Douglas-fir to unevenly thinned lodgepole pine, and open areas that range from 0.1 ha gaps to 50 ha clear-cuts. Despite the local variation in the forest and open characteristics, climate variables emerge as first-order predictors of differential snow storage (Dickerson-Lange et al., 2017; Lundquist et al., 2013).

At windy sites (Node 1), forest edges contribute to preferential deposition of snow immediately downwind of the forest barrier, and longer lengths of forest edges result in more snow adjacent to and within the forest (Broxton et al., 2015; Currier & Lundquist, 2018). This process is illustrated by the establishment and presence of ribbon forests particularly in windy locations, which retain snow on the landscape and provide a source of soil moisture to these forests (Bekker et al., 2009). More forest edges will shift a site classified as C (Wind) toward larger snow storage magnitude and longer snow storage duration in and at the edge of the forest (i.e., further toward the right in Figure 1c).

Forest structure is also a secondary influence in determining both the amount of interception (Node 2) and the amount of shading provided by the forest (Node 3). Although the differences between evergreen species appear to have little effect on interception (Hedstrom & Pomeroy, 1998; Storck et al., 2002), forests with lower stem density, less canopy cover, or more clumped canopy cover (i.e., as opposed to evenly distributed canopy cover) intercept less snow (Gary & Troendle, 1982; Schneider et al., 2019), which shifts the net effect of forest on snow duration toward the snow lasting longer in the forest. Conversely, the same forest structural characteristics provide less shading, which shifts the net effect of forest on snow duration toward snow lasting longer in the open. Although neither canopy snow interception nor canopy shading are linear
functions of canopy cover, the opposite influences of canopy structural characteristics on snow accumulation and ablation at least partially cancel each other out. This canceling effect supports the hypothesis that the forest structural characteristics are a second-order variable for predicting relative snow storage across landscape scales.

Winter air temperature is not only the decision variable for Node 2 but also contributes as a secondary influence to the processes represented in both Nodes 1 and 2. Warmer winter air temperatures contribute to higher snow cohesion and therefore less wind redistribution from open areas to forests (Node 1). Mean winter air temperature is the overriding control on the amount of canopy snow interception (Node 2), but winter air temperature variations also contribute to Node 2 as a secondary influence. A higher frequency of winter air temperatures above the melting point contributes to more melting of canopy snow (Andreadis et al., 2009; Storck et al., 2002) and to higher rates of under-canopy melt driven by the longwave radiation emission from the trees (Essery et al., 2008; Lawler & Link, 2011; Lundquist et al., 2013), both of which further reduce under-canopy snowpack.

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### Table 1

| Secondary influence | Net effect shifts toward longer in open | ↔ | Net effect shifts toward longer in forest |
|---------------------|----------------------------------------|---|----------------------------------------|
| **Node 1: Occurrence of preferential deposition and redistribution** |
| More snow accumulation in open | ↔ | Equal snow accumulation in forest and open to more snow accumulation in forest |
| Length of forest edges | Less forest edge = Less preferential deposition adjacent to forest edges | More forest edges = more preferential deposition at edges |
| Winter temperature | Warmer winter temperatures = Less wind redistribution from open areas to forest areas | Colder winter temperatures = More wind redistribution from open areas to forest areas |
| **Node 2: Magnitude of interception effect** |
| Much more snow accumulation in open | ↔ | Equal snow accumulation in forest and open |
| Stem density | Higher stem density = more interception | Lower stem density = less interception |
| Canopy cover/sky view factor | Higher canopy cover = more interception | Lower canopy cover = less interception |
| Canopy clumping (assuming same stem density) | Low canopy clumping = more interception | High canopy clumping = less interception (more accumulation within small gaps) |
| Frequency of DJF temp >0°C | More canopy snow melt and drip (warmer) = less sluffing of canopy snow to under-canopy snow | Less canopy snow melt and drip (colder) = more sluffing of canopy snow to under-canopy snow |
| Frequency of DJF temp >0°C | More under-canopy mid-winter melt driven by longwave radiation (warmer) = less under-canopy snow | Less under-canopy mid-winter melt driven by longwave radiation (colder) = more under-canopy snow |
| **Node 3: Magnitude of forest shading effect** |
| Less shading effect and slightly slower ablation rates in forest | ↔ | More shading effect and much slower ablation rates in forest |
| Stem density | Lower stem density = less shading | Higher stem density = more shading |
| Canopy cover/sky view factor | Lower canopy cover = less shading | Higher canopy cover = more shading |
| Canopy clumping (assuming same stem density) | High canopy clumping = less shading | Low canopy clumping = more shading |
| Aspect | Northeast-facing = less shading | Southwest-facing = more shading |
| Cloudiness during ablation season | Cloudy conditions = less shading | Sunny conditions = more shading |
| Fire | Recent fire = less shading and lower albedo within recently burned forest | No fire = more shading and higher albedo within unburned forest |

*Reduction in canopy cover, or increase in sky view factor, can be the result of forest management, insect outbreak, or fire. DJF, December, January, and February.*
Topographic position, atmospheric conditions, and recent fire are additional secondary influences on the amount of shading provided by the forest (Node 3). The topographic position modifies the amount of incoming solar radiation, setting a limit on how much the forest shading effect can reduce snow ablation rates (Ellis et al., 2013; Seyednasrollah & Kumar, 2014; Sicart et al., 2004; Strasser et al., 2011). Thus, the relative impact of forest shading is enhanced on steep, southwest-facing slopes (McCune & Keon, 2002), and relative snow storage is shifted toward snow lasting longer in the forest. Similarly, the impact of forest shading also depends on cloudiness, with shading being more important where clear skies dominate the ablation season (Seyednasrollah & Kumar, 2014). Where a forest has been recently burned, black carbon deposition and standing charred stems have been shown to increase net solar radiation by 200% (Gleason et al., 2013). A recently burned forest with lower canopy cover and lower under-canopy snow albedo will provide a greatly diminished shading effect.

Lastly, an additional complicating factor is that the forest characteristics that are secondary influences on snow storage classification are also closely tied to climate (primary nodes) as well as topographic position (another secondary influence). Forests in drier, colder locations that are composed of Ponderosa or lodgepole pine are naturally sparser in terms of canopy cover than warmer, wetter forests dominated by western hemlock or Pacific silver fir (Bruns & Honkala, 1965). Similarly, variations in evaporative demand and access to water also influence forest density on north- versus south-facing slopes.

5. Applications to Forest Management

5.1. Linking Hypothesized Classes and Management Actions

The framework presented here offers forest managers a tool for considering the effects of forest cutting and retention on patterns of relative snow storage. The duration of snow storage on the landscape influences the timing and magnitude of the spring freshet and onset of baseflow (Bosch & Hewlett, 1982; Jones & Post, 2004; Lyon et al., 2008; Wilm & Dunford, 1948), stream temperature (Gravelle & Link, 2007; Leach & Moore, 2014), and soil moisture availability (Harpold et al., 2015; Veatch et al., 2009), and therefore fire patterns (Kane et al., 2015). Thus, in locations where fire resilience, ecological health, or summer low flows are of particular concern, the decision tree can be applied to include snow storage effects as one of multiple considerations for where and how to manage forests. Recommendations for optimal forest structures to retain snow have a long history, and many previous recommendations of creating gaps, cutting strips, and thinning still hold (Anderson, 1956; Church, 1912; Kittredge, 1953; Maule, 1934; Troendle & King, 1985). Here, we refine these site-specific recommendations to reflect the climatic context of each forest–snow class. Maps developed from the decision tree framework can identify key locations at which to test actions via local data collection or aerial imagery analysis.

5.2. Class A: Large Canopy Gaps and Heavy Thinning

In terms of management decisions, some of the secondary effects related to forest structure are worth careful consideration. For Classes A1 and A2, both snow storage magnitude and duration will be maximized by reducing canopy cover through the introduction of large canopy gaps (diameter larger than 2x average canopy height) or heavy thinning (retaining ≤50% of canopy cover) via mechanical cutting or prescribed fire (Dickerson-Lange, Lutz, Martin, et al., 2015). Depending on the scale of implementation, these actions are likely to result in more water availability from snowmelt later in the year. However, we do not recommend even-aged regeneration harvest (clear cutting), where the increased wind exposure due to fetch may result in amplified ablation rates in the open and therefore may result in the opposite of the intended effect (Murray & Buttle, 2003; Varhola et al., 2013). Also, for Class A2 (warm and late), the forest shading effect is amplified by higher solar elevations during ablation, so gaps and patches less than 1x the average canopy height are advisable (Musselman et al., 2015; Seyednasrollah & Kumar, 2014).
5.3. Class B: Range of Canopy Gap Sizes and Thinning Intensity

In Class B, relative snow storage magnitude is larger in canopy openings, but duration can switch from longer in openings to longer under forest cover. Increased snow storage from reducing canopy cover will increase water availability from snowmelt, but the effect on snowmelt timing is variable between subclasses.

For Class B1, the same set of recommended actions as Class A1 applies, but the influence of these actions on snow storage is likely to be less, given the diminished differences between forest and open. In addition, regions with colder winter climates (Class B) are commonly associated with less cloudy winter and spring conditions. For these locations, the secondary influence of clear skies during the ablation season enhances the importance of canopy shading (Table 1) and therefore actions recommended for Class B2 (see below) may be more relevant.

For Class B2, actions to consider for maximizing snow accumulation while minimizing snow ablation include thinning to reduce stem density and canopy cover, introducing small gaps or closely spaced strip openings (Anderson, 1956), and deciduous tree patches, which reduce interception but provide some shading (Maule, 1934). Targeting thinning activities or larger openings in locations where the importance of forest shading is diminished, such as northeast-facing slopes or areas that are topographically shaded, could also be effective. Within Class B2, gap size has a strong influence on differential snow storage, which has been illustrated via modeling studies (Musselman et al., 2015; Seyednasrollah & Kumar, 2014). Lastly, an additional consideration for Class B2 is that prescribed fire as a method to reduce forest canopy cover may have the unintended effect of reducing snow storage duration. Residual black carbon deposition from the prescribed fire reduces snow albedo and increases ablation rates (Burles & Boon, 2011; Gleason et al., 2013, 2019).

5.4. Class C: Retain Forest Cover

For Class C, snow storage is maximized by retaining forest cover via suppressing fire, avoiding even-aged regeneration harvest, and reforestation. In these locations, the forest acts as a snow fence and retains snow. Forest spatial patterns that maximize the length of edges oriented perpendicular to the dominant wind direction, such as closely spaced strips or gaps of less than an adjacent tree height in diameter, or uneven-aged forests, are likely to maximize the snow storage magnitude and duration within and adjacent to the forest.

5.5. Climate Change and Forest Management

Strategies for locations classified as A and B under current climate conditions may shift with climate warming. Therefore, the most appropriate management actions today may not be the best management actions in the future, the specifics of which warrants future work. Winter and spring snow processes may respond at different rates and in complex ways under climate change (e.g., Musselman et al., 2017). The use of the temperature thresholds proposed in this framework may not be appropriate for quantitatively differentiating future forest–snow classes, since they are based on current relations between temperature and forest–snow processes. However, the qualitative consideration of projected warming of winter and spring temperatures suggests that some locations currently classified as Class B are likely to shift toward Class A, with increases in canopy snow interception and relative snow storage duration increasingly extended in the open. Before implementing a gap creation to maximize the snow storage within locations that shift to Class A, however, the secondary effects of forest structure and composition along with other climate change effects should be considered. Given that forests that cover colder (and drier) locations (i.e., current Class B) tend to have lower stem density and lower canopy cover, the gap creation may be less effective in these areas even with warmer winter conditions. In addition, the rain–snow transition line will rise in elevation with climate warming, so forest management to enhance snow storage should be focused on higher elevations.

6. Future Work

The decision tree framework provides a first-order estimate of differences in snow storage between forests and open areas, based on hypotheses supported by the literature. This work provides an organizing structure that enables research to be placed in context, so it is easier to (a) share the state of the science with forest managers who need to make decisions now, (b) convey to the research community how the results...
from individual studies compare to each other provided differences in underlying climate variables, and (c) develop testable hypotheses related to the net effect of forest on snow storage that can guide research.

Our understanding of forest–snow processes will continue to evolve. We recommend the outlined hierarchy and subsequent decision tree and classification thresholds to be tested, and modifications be made as new information are acquired. Alternative formulations for the order of the nodes, as well as the decision variables and threshold values, could be tested. Additional, multiyear forest–snow observations across a gradient of climate, forest type, and landscape position are needed, particularly given that the direction of forest effects can flip from forest shortening to lengthening snow duration and that land surface model representations are developed from the same sparse observations that may not be readily transferable (Clark et al., 2015). The hypothesized hierarchy of decision variables also highlights the need to focus additional forest–snow research on accumulation processes, given their importance to determining the overall effect of forest on snow storage (Dickerson-Lange et al., 2017). In particular, wind–forest–snow interactions are neglected in many models, and the model representations that do exist are limited to a very few observational studies of canopy snow interception (Hedstrom & Pomeroy, 1998; Lundquist et al., 2021; Storck et al., 2002). Currently, lidar data revolutionize the ability to investigate small-scale forest–snow effects (e.g., Broxton et al., 2015; Mazzotti et al., 2019; Moeser et al., 2015). These high-resolution data provide a platform to study the forest effects on accumulation processes across climate gradients and to better integrate the secondary influences of forest structure into both conceptual and numerical models to predict relative snow storage.

Data Availability Statement

The input data, results, and processing code are publicly accessible via the HydroShare data repository (https://doi.org/10.4211/hs.7c660d8b9e94e33898c14dd677c6e06).

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