FOREST MANAGEMENT TO ENHANCE FOREST RESILIENCE TO CLIMATE CHANGE AND INCREASE WATER SUPPLY IN COLORADO

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The Colorado Rockies in the Indian Peaks Wilderness south of Rocky Mountain National Park.
Photo taken by Kristin Leger.

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ACKNOWLEDGEMENTS

The creation of this report would not have been possible without the guidance and expertise of my graduate committee members Dr. John Sanderson, Dr. Jonathan Salerno, Dr. Brett Bruyere, and Dr. Steven Fassnacht. I would like to give a special thanks to Rob Addington, the landscape ecologist at The Nature Conservancy Colorado, who helped me envision this project from the start of my graduate program. I would like to extend an additional thanks to Kerri Rollins and Mark Platten at CSU Extension, who provided valuable feedback to me throughout the process of writing this report. Finally, thank you to the Conservation Leadership Program Coordinator, Dawson Metcalf, for being a source of positive encouragement and support throughout the entire graduate program and Capstone process.

EXECUTIVE SUMMARY

In Colorado, climate change is causing warmer temperatures, drought, increased severity of wildfires and insect epidemics, and hydrological changes including a shift in winter precipitation from snow to rain and earlier timing of snowmelt (Lukas et al., 2014). These hydrological changes are creating a moisture deficit in forests, making them even more susceptible to severe wildfires (Rocca et al., 2014). Federal and state agencies, cities, universities, and conservation organizations such as The Nature Conservancy (TNC) are involved in current forest restoration efforts throughout the state to increase forest resilience to climate change. One such effort is the Front Range Collaborative Forest Landscape Restoration Program, which emphasizes the importance of managing forests for multiple benefits including wildfire mitigation, wildlife habitat, and watershed function (Addington et al., 2018). Increasing moisture retention in forests could further enhance forest resilience to climate change by alleviating drought stress, retaining fuel moisture, and reducing burn probability and wildfire risk. This report will explore management practices that have the ability to increase moisture retention by maximizing snow accumulation, retention, and runoff.

In addition to enhancing forest resilience to climate change, increased snow accumulation, retention, and runoff has the potential to increase water yield for downstream users. Water shortages are expected to occur in Colorado and throughout the western United States as a result of climate change and population growth. Management practices that can simultaneously increase water yield and improve forest resilience are desirable from an ecological and water resource management perspective.

To explore the potential for increasing water yield in Colorado, a literature review was conducted to examine the relationship between canopy removal and snow processes, and results were used to make management recommendations. Collectively, results indicate that snow and water retention, and consequently water yield, could be increased by managing forests to reduce forest density and create spatial heterogeneity across the landscape. Studies indicate this forest management should create many small gaps throughout the watershed rather than clearcutting vast areas to create large openings. Results emphasize the importance of retaining trees in high elevation forests to maximize the canopy edge effect. Management efforts should be concentrated in high elevation forests above 2,700 meters, and on north-facing slopes. The ability of these management activities to increase moisture retention in forests not only has the potential to increase water supply, but also to enhance forest resilience to wildfire and climate change, thus supporting current forest restoration efforts in Colorado.

The purpose of this report is to provide The Nature Conservancy Colorado with the most up-to-date management recommendations to enhance forest resilience to climate change while potentially increasing water supply for downstream users. TNC can then integrate these recommendations into existing and future forest management plans, or use this report to inform policy decisions. Hopefully this report will help TNC advance its work in forest restoration and water conservation in Colorado.

INTRODUCTION

Healthy forests provide a variety of ecosystem services including the provisioning of clean water, carbon sequestration, wildlife habitat, recreational opportunities, and cultural and spiritual value (Millennium Ecosystem Assessment, 2005). Climate change poses a direct threat to forest health and ability to provide these services (Jones et al., 2017). Warming temperatures lead to drought, increased frequency and severity of wildfires and insect epidemics, and hydrological changes including altered precipitation patterns and less snowpack (MacDonald and Stednick, 2003; Lukas et al., 2014). Management efforts that can increase forest resilience to climate change are desirable both from an ecological and human-use perspective. The ability of certain management activities to increase water retention and water yield would be beneficial for the forest ecosystem as well as downstream water users who depend on the health of forests for their water supply. Increased snow accumulation and retention enhance soil moisture storage, and may increase forest resilience to climate change, drought, and wildfire.

In Colorado, one third of the total land area is forested (MacDonald and Stednick, 2003), and 80% of the state's streamflow originates as snowmelt in the Rocky Mountains (Fassnacht et al., 2018). Colorado is often referred to as "the headwaters state" because 4 major rivers (the Colorado, Arkansas, Platte, and Rio Grande) that originate as snowmelt in Colorado's Rocky Mountains provide water to a total of 19 states in the US (Venable et al., 2017; Figure 1). Most of this snowmelt occurs in high elevation forests and alpine areas above 2,700 meters (MacDonald and Stednick, 2003). These forest ecosystems are therefore critically important for water resources. Without the snow that falls and accumulates there, these rivers would not be able to supply water to such a vast population.

Figure 1. The course of the Colorado, Platte, Arkansas, and Rio Grande Rivers (Venable et al., 2017).

Unfortunately, water is becoming an increasingly scarce resource in Colorado and throughout the entire western US. According to the Colorado Water Conservation Board (2019), the population of Colorado is projected to double to 9 million by 2050. This rapid population growth will have serious implications for water availability and will lead to an increasing gap in which there is not enough water supply to meet the demands of the population. Water scarcity is a contentious issue, and future shortages could lead to increased resource competition and conflict among the agricultural community, hydropower companies, local municipalities, private utilities companies, and Native American Tribes. To compound the water shortage that will result from population growth, climate change jeopardizes both water quality and quantity. Climate change is increasing the frequency and severity of wildfires, decreasing the amount of snow that falls in high elevation forests, and leading to earlier timing of snowmelt (MacDonald and Stednick, 2003). In the Colorado Rockies, increased temperatures, decreased snowpack, and earlier snowmelt have been detected (Fassnacht et al., 2018; Lukas et al., 2014).

The combination of population growth and climate change is putting substantial stress on a limited water supply, both within the forest and for downstream users. Many conservation organizations and government agencies have recognized the urgency of the situation and are working toward solutions. The Nature Conservancy (TNC) and The Colorado Water Conservation Board (CWCB) are two such groups. TNC is involved in forest restoration and water conservation projects throughout Colorado, in collaboration with private, state, and federal land owners (TNC, 2020). The CWCB is the primary water policy group in Colorado. In 2015 they published their Colorado Water Plan, which highlights the need for innovative and collaborative solutions to address the water supply and demand gap.

Current Forest Restoration Efforts:

TNC Colorado has been involved in several forest restoration project throughout the state. Some of these include the Collaborative Forest Landscape Restoration Program (CFLRP), the Upper South Platte Partnership, the Elkhorn Creek Forest Health Initiative, and the Rocky Mountain Restoration Initiative.

The CFLRP is a national program initiated by Congress in 2010 with project locations throughout the US, including the Front Range of Colorado (CFLRP, 2020; Figure 2). TNC was instrumental in developing the original proposal for the Front Range CFLRP alongside the US Forest Service and other partners through the Front Range Roundtable. Since then, their role has focused on project prioritization, treatment planning, monitoring and adaptive management. The Front Range CFLRP takes a multiple-use management approach, in which forests are managed for the multiple benefits of wildfire risk mitigation, watershed protection, and wildlife habitat (Addington et al., 2018). Effective management practices to achieve these goals include mechanical thinning and prescribed fire to enhance spatial heterogeneity (Addington et al., 2018). By incorporating more information on how high elevation forests in the Colorado Rockies can be managed to increase moisture retention, forest management plans can expand the scope of their goals to include increasing water supply. This report will explore specific forest management practices that have the potential to increase moisture retention and water yield by maximizing snow accumulation, retention, and runoff while also improving forests’ overall health and resilience to climate change.

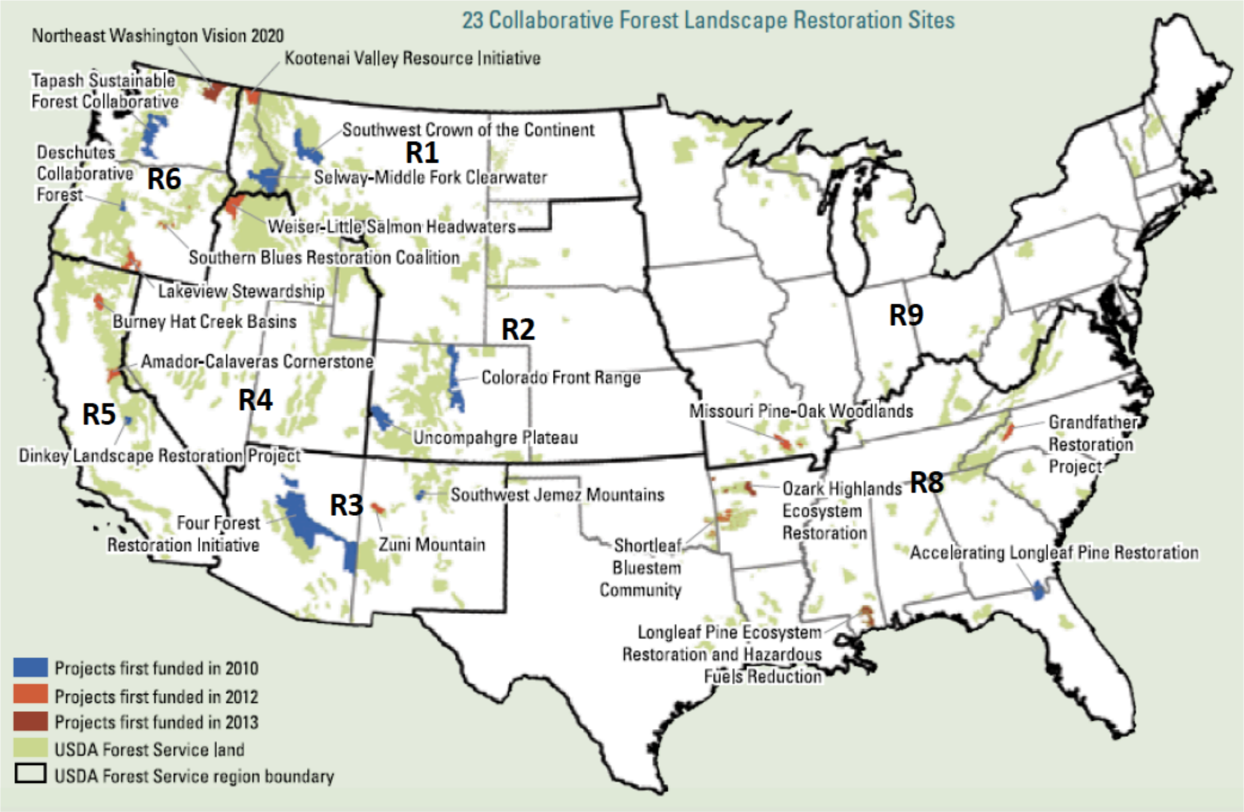


Figure 2. CFLRP project sites (CFLRP, 2020).

Funding for Forest Restoration:

Funding is one of the largest barriers to the implementation of large-scale forest restoration projects. By managing forests for multiple benefits (including water supply, wildfire mitigation, and wildlife habitat), there is greater opportunity for attracting funding and leveraging investments for greater collective impact. Climate change is increasing the risk of severe wildfire, and the federal government recognizes this risk. Federal funding is allocated to the US Forest Service annually to restore forests and increase their resiliency to wildfire (National Association of State Foresters, 2020). Pairing water resource goals with wildfire mitigation goals can be an effective strategy to secure funding.

A study conducted by Jones et al. (2017) looked at return on investment from fuel treatments in northern Colorado. They found that the cost of reacting to severe wildfires may be greater than the cost of proactively treating forests to mitigate the risk of such events. The authors refer specifically to the Buffalo Creek and Hayman fires in Colorado, which were followed by heavy precipitation events and flooding. Denver Water utilities company spent over $26 million in sediment removal from Strontia Springs reservoir and water quality treatment following these fires. Jones et al. (2017) suggest that fuel treatments in high priority areas that could have prevented this event would cost less than $26 million. In other words, there was a positive return on investment from fuel treatments that would enhance forest resilience to wildfire.

As demonstrated by the Strontia Springs reservoir example, it can be in the best interest of water utilities companies to invest in proactive forest management to increase the resilience of forests to climate change, rather than reacting to destructive events. In 2010 Denver Water started investing in forest restoration efforts in the Upper South Platte watershed with a program called *From Forests to Faucets* (Denver Water, 2020). This funding mechanism in which downstream water users pay for upstream forest restoration is called the water fund model (Figure 3). Another example in Colorado is the Peaks to People Water Fund, which aims to protect water resources in the Cache la Poudre and Big Thompson watersheds (Peaks to People, 2020).

Figure 3. Infographic created by Peaks to People Water Fund that describes how the water fund model works (Peaks to People, 2020).

Forest Hydrology Overview and Research Efforts:

Figure 4 depicts the complex interplay of processes involved in forest hydrology. Water enters the forest ecosystem in the form of precipitation as rain or snow. It can then either be “stored” in the system or “lost.” Precipitation is stored in the form of snowpack, depression storage, soil moisture, and groundwater. It is lost via evapotranspiration (i.e., the combination of evaporation and transpiration) and sublimation. Precipitation that is stored eventually leaves the system as streamflow, or runoff, and provides water to downstream users (Figure 4). The amount of runoff produced by a forest can be summarized by the following water balance equation presented by MacDonald and Stednick (2003):

$$\textbf{Runoff} = \textbf{Precipitation} - \textbf{Evapotranspiration} + \textbf{Change in storage}$$

Annual runoff is impacted by the amount of precipitation that a forest receives during any given year. High precipitation years will consistently produce more runoff than drought years (MacDonald and Stednick, 2003). For canopy removal to result in a subsequent increase in runoff, annual precipitation must exceed 450-500mm (Bosch and Hewlett, 1982). When annual precipitation exceeds this threshold, increases in water yield can result from canopy removal, dependent upon changes in evapotranspiration that may occur following canopy removal (MacDonald and Stednick, 2003). In Colorado, this threshold is exceeded in high elevation forests above 2,700 meters such as the Fraser Experimental Forest (Stottlemeyer and Troendle, 2001).

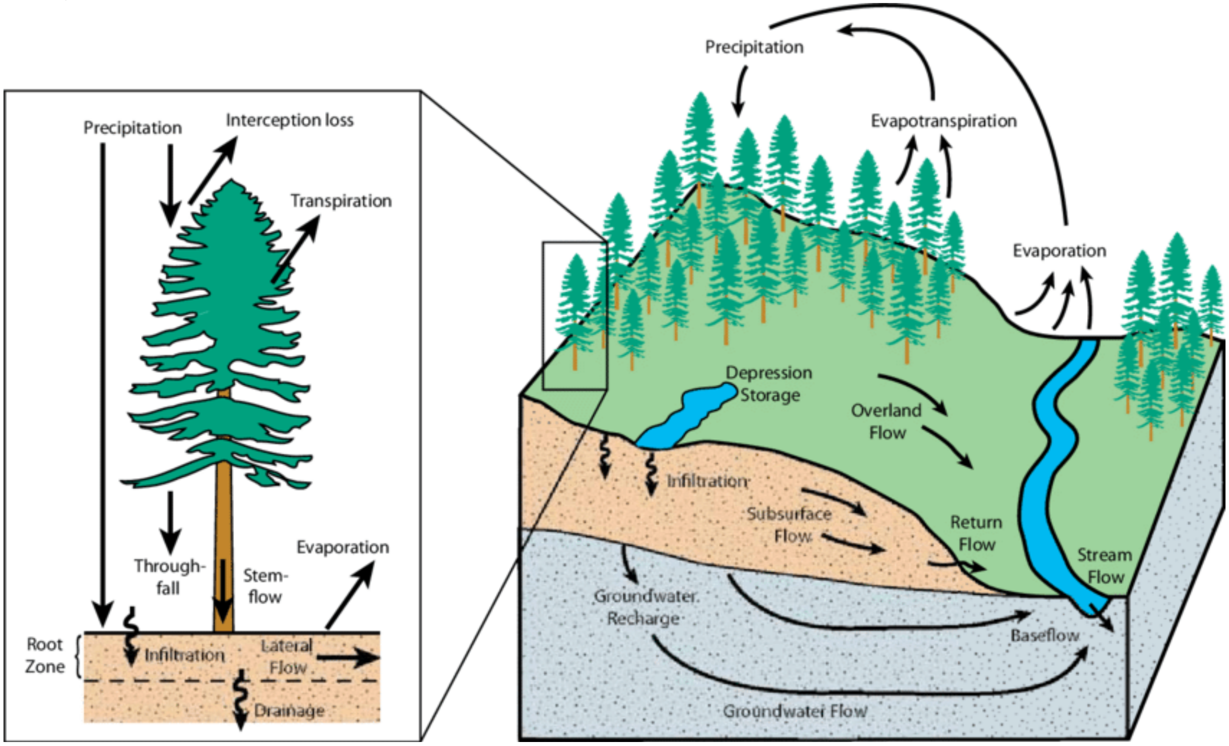


Figure 4. The forest hydrologic cycle as presented by Robin Pike (2010).

In snow-dominated regions like high elevation forests, interception is an important component of forest hydrology. In Colorado, as much as 30% of snowfall can be intercepted by the forest canopy and then sublimated back into the atmosphere, thus preventing it from accumulating on the ground as snowpack (MacDonald and Stednick, 2003). The removal of forest canopy decreases interception rates and increases the amount of snow that accumulates on the forest floor. This can lead to longer snow retention, higher soil moisture storage, and increases in runoff. The reduction of vegetation density also has ecological benefits including the mitigation of severe wildfire, improved wildlife habitat, increased understory plant diversity, and overall improvements in ecosystem health and resilience (Woods et al., 2006; Robles et al., 2014).

The relationship between canopy cover and snow accumulation sparked over a century of research to better understand the processes involved. The first studies were conducted in the early 1900's by Bates and colleagues at the Wagon Wheel Gap Experimental Forest in Colorado (Bates and Henry, 1928). Since then, forest hydrology research has continued around the globe.

In general, this research has pointed to a negative correlation between vegetation density and water yield, which has led to the general belief that canopy removal results in increased water yield (Hibbert, 1967; Stednick, 1996). However, recent studies have demonstrated that this is not always the case. A literature review conducted by Goeking and Tarboton (2020) found that forests at low latitudes and on south-facing slopes experience high net radiation. Canopy removal in these forests can actually result in a decrease in water yield because increases in ablation, or snow disappearance via sublimation and evaporation, outweigh increases in snow accumulation.

Recent forest hydrology research has recognized the importance of forest structure and the spatial arrangement of trees to maximize snow accumulation, retention, and streamflow (Goeking and Tarboton, 2020; Sun et al., 2018). Forest treatments that maximize snow accumulation and minimize ablation have the greatest potential to increase water yield and increase the forest's resilience to climate change (Musselman et al., 2008). Due to the anticipated water shortages that will result from both climate change and population growth in Colorado, the potential to increase water supply is of interest to water resource managers including utilities companies, municipalities, agriculture and industry. Over the past 20 years, several studies have been designed to compare different forest densities (e.g., large forest openings vs. small canopy gaps) to investigate which types of forest management activities have a greater potential to increase water yield. A synthesis of recent findings is needed to provide the most up-to-date management recommendations.

Objectives of this Report:

In order to address the need to synthesize recent forest hydrology research, a rapid systematic literature review was conducted for papers published between 2000-2020. The objectives of this literature review are to:

1) **Compile results from empirical and model-based studies that look at the impacts of canopy removal (via mechanical thinning and/or prescribed fire) on snow processes.**
2) **Use these results to provide practical management recommendations for how forests in Colorado can be managed to increase water yield and enhance forest resilience to climate change.**

Previous literature reviews have been conducted to examine the effects of canopy removal on snow processes and water yield on a global scale and throughout the western United States (Lundquist et al., 2013; Goeking and Tarboton, 2020). However, coastal climate patterns in California and the Pacific Northwest impact snow processes differently than those in the interior Rocky Mountains. A more region-specific assessment would provide management recommendations that are appropriate for the high elevation forests in Colorado. Therefore, the geographic scope for this report is limited to the Rocky Mountain Region of the US and Canada.

In addition to forest management practices such as mechanical thinning and prescribed fire, canopy removal can also result from natural disturbances such as insect outbreaks and wildfire. However, since forest managers do not have control over these natural phenomena, they will not be considered in this report.

METHODS

A rapid systematic literature review was conducted to examine the relationship between canopy removal and snow accumulation, retention, snowmelt, and streamflow—referred to collectively in this report as "snow processes." The review followed the steps outlined in the Systematic Review Protocol developed by the Collaboration for Environmental Evidence (2013). These steps include, 1) formulate research question using *PICOS* format *(P* = population/subject, *I* = intervention, *C* = control, *O* = outcome, *S* = study design and setting), 2) search databases for articles, 3) screen articles for relevance using inclusion criteria, 4) extract data from relevant articles, 5) synthesize data and make conclusions, and 6) write report.

Research Question:

This literature review aims to answer the following research question: *How can forests be managed to influence snow processes in the Rocky Mountain Region?* The question was formulated using the *PICOS* format:

P = snow processes (i.e., snow accumulation, retention, snowmelt, and streamflow)
I = forest management
C = no forest management
O = change in snow processes
S = empirical studies and model-based simulations; Rocky Mountain Region (RMR).

Here, the RMR includes the US states of Montana, Idaho, Wyoming, Colorado, Utah, New Mexico, Arizona, and the Canadian Rockies in British Colombia and Alberta (Figure 5). This geographic range was chosen because of similarities to Colorado in winter precipitation patterns.

Figure 5. Rocky Mountain Region (worldatlas.com).

Article Search:

Article searches were performed on June 22, 2020. A total of 366 articles were identified and screened for relevance: 120 articles from Web of Science, 46 from Academic Search Premier, and 200 from Google Scholar. Search criteria were limited to articles published between the years 2000–2020 in order to identify the most recent research on this topic. The *PICOS* was used to determine search terms.

The following Boolean search string was used to identify articles: *snow* AND ("forest management" OR "forest treatment*" OR "forest cover" OR "forest canopy" OR "canopy cover" OR "forest structure" OR "forest density" OR "vegetation density") AND ("water yield" OR "water quantity" OR hydrolog* OR hydrograph OR snowmelt OR runoff OR* *streamflow OR "snow water equivalent") AND ("United States" OR Rockies OR "Rocky Mountain*" OR "coniferous forest*" OR "mixed conifer" OR alpine OR subalpine).*

Screening:

Inclusion criteria were determined based on the *PICOS* to screen the 366 articles for relevance (Appendix B). After two rounds of screening, 38 articles met all the inclusion criteria. Two additional articles that were not captured in the database searches (MacDonald and Stednick, 2003; Stottlemeyer and Troendle, 2001) were recommended by experts in the field, yielding a total of 40 articles that would be included in the review (Appendix C).

Data Extraction & Synthesis:

Data were extracted manually from 40 articles. Several parameters were identified during this process including the study location, location features (e.g., elevation, forest type, annual temperature and precipitation, etc.), the study methods (e.g., empirical, model-based, mixed methods, or literature review), the *PICOS* of each study, and the outcomes (Table 1).

Table 1. Characteristics of included studies.
*Study type: 1= empirical; 2= model-based; 3= mixed methods; 4= literature review
**Snow processes measured: 1= snow accumulation; 2= snow retention; 3= snowmelt; 4= streamflow

Author	Year	Study type*	Location	Forest type	Elevation (m)	Snow processes measured**
Baker & Ffolliott	2003	1	AZ	Ponderosa pine & mixed conifer	N/A	1
Broxton et al.	2015	3	NM & CO	NM: ponderosa pine & mixed conifer; CO: lodgepole pine & Engelmann spruce	3040-3100	1
Broxton et al.	2020	1	AZ	Ponderosa pine & mixed conifer	2100-2950	1, 3
Dobre et al.	2012	1	ID	Ponderosa pine & mixed conifer	843-1236	1, 3, 4
Du et al.	2016	2	ID	Mixed conifer	945-1650	3, 4
Ellis et al.	2011	1	Alberta	Lodgepole pine & spruce-fir	1550-2750	1, 2, 3
Ellis et al.	2013	3	Alberta	Spruce-dominated conifer forest	2016-2028	1, 2, 3
Goeking & Tarboton	2020	4	Western US & Canada	Mixed conifer	N/A	1, 3, 4
Gottfried & Ffolliott	2009	1	AZ	Ponderosa pine	2388-2615	1, 2, 3
Greenacre	2019	1	Alberta	Lodgepole pine & spruce-fir	1475-2631	1, 2, 3
Harpold et al.	2015	1	CO	Ponderosa, lodgepole & spruce-fir	2250-3109	1, 2, 3
Hubbart et al.	2015	1	ID	Mixed conifer	1000-1600	1, 2, 3
Hubbart et al.	2007	1	ID	Mixed conifer	1000-1600	1, 4

Jost et al.	2007	1	British Colombia	Lodgepole pine & spruce-fir	1100-2100	1, 3
LaMalfa & Ryle	2008	1	UT	Spruce-fir forest vs. aspen stand	2000-2500	aspen vs. conifer
Lawler & Link	2011	2	ID	Mixed conifer dominated by western red cedar	N/A	3
Lundquist et al.	2013	4	Global (only RMR results extracted)	Mixed conifer	N/A	1, 2, 3
MacDonald & Stednick	2003	4	CO, WY, AZ	Ponderosa, lodgepole & spruce-fir	1707-3536	1, 2, 3, 4
Molotch et al.	2016	1	CO	Lodgepole pine & spruce-fir	3050	1
Molotch et al.	2009	1	NM	Ponderosa, lodgepole & spruce-fir	3020-3050	1, 2, 3
Musselman et al.	2008	3	NM	Spruce-fir	3012	1, 2, 3
Musselman et al.	2015	2	Alberta	Mixed conifer	1860	3
Pike & Scherer	2003	4	Western US & Canada	Lodgepole pine & spruce-fir	1521-3810	4
Pomeroy et al.	2008	1	CO	Lodgepole pine & spruce-fir	2780	3
Pomeroy et al.	2012	3	Alberta	Lodgepole pine & spruce-fir	1600-2825	1, 4
Stottlemyer & Troendle	2001	1	CO	Lodgepole pine & spruce-fir	2665-3880	1
Robles et al.	2014	2	AZ	Ponderosa pine	1800-2600	4
Sankey et al.	2015	1	AZ	Ponderosa pine & mixed conifer	3850	1, 2
Schneider et al.	2019	1	MT	Ponderosa pine & mixed conifer	1220	1, 2, 3
Schnorbus & Alila	2004	2	British Colombia	Mixed conifer & spruce-fir	700-2300	4
Seyednasrollah & Kumar	2014	2	ID	Mixed conifer & western red cedar	884	3
Seyednasrollah et al.	2013	2	Conceptual (model data from CO)	Tree simulation in model based on white spruce	N/A	2, 3
Sun et al.	2018	3	ID	Mixed conifer dominated by red cedar	N/A	1, 2, 3, 4
Tennant et al.	2017	1	CO	Mixed conifer	3043	1, 3
Troendle et al.	2010	1	CO	Lodgepole pine & spruce-fir	2665-3880	1, 4
Varhola et al.	2010	4	North American Rockies	Lodgepole pine & mixed conifer	N/A	1, 3
Veatch et al.	2009	3	NM	Ponderosa pine & spruce-fir	2768	1
Whitaker et al.	2002	3	British Colombia	Mixed conifer & spruce-fir	700-2300	1, 2, 3, 4
Woods et al.	2006	1	MT	Lodgepole pine & spruce-fir	1838-2421	1, 3
Zhang & Wei	2014	1	British Colombia	Spruce-fir	570-2350	4

RESULTS

All included studies examined the impacts of canopy removal via mechanical thinning and/or prescribed fire on snow processes. However, not all studies measured the same snow processes. For example, some studies measured changes in snow accumulation and retention but not snowmelt or streamflow, and vice versa. Similarly, studies compared a variety of different treatments. Some studies only compared clearcut areas with forested control plots, while others compared a variety of treatments (e.g., gap-thinning, strip-shelterwood, partial cutting, etc.). Treatments implemented in each study are listed in the Appendix (Appendix D).

This variation made it difficult to make direct comparisons across studies. However, general trends were able to be identified based on the results of each study. These trends are presented below.

Canopy Removal and Snow Accumulation:

The amount of water stored in snowpack is an important indicator of water yield (Schnorbus and Alila, 2004). This presents the opportunity to increase water yield by increasing snow accumulation throughout a watershed. Snow accumulation is most commonly measured by the maximum amount of water that is contained within the snowpack before spring snowmelt begins, called the peak snow water equivalent (SWE). For standardization purposes, this measurement is typically taken on April 1 in North America (Varhola et al., 2010).

In this review, 29 out of the 40 studies measured SWE response to canopy removal. Of these, 18 were empirical, 7 used mixed methods (i.e., a combination of empirical evidence and model-based simulations), and 4 were literature reviews. Twenty-six studies found an increase in SWE following canopy removal. The other 3 found mixed results, i.e., some of the study plots had greater SWE following treatment, some saw no change, and some experienced a decrease in SWE (Figure 6).

Much of the variation in the “mixed results” could be explained by treatment type. For example, Greenacre (2019) compared 3 different treatments in Alberta, Canada: clearcut with 85% canopy removal, partial cut with 59% canopy removal, and strip-shelterwood with 50% canopy removal in parallel “cut and leave” strips. Results showed that SWE increased in the strip-shelterwood and partial cut treatments, while the clearcut plots did not differ from the control (Figure 7). Furthermore, SWE in the strip-shelterwood plots increased by 227% compared to the control. This significant increase in SWE can be attributed to the canopy edge effect, in which shade provided by the “leave” strips protected snowpack in the open strips from incoming solar radiation and wind redistribution. Similarly, a study conducted by Broxton et al. (2015) in high elevation forests of Colorado and New Mexico found that the greatest SWE occurred at canopy edges throughout the treatment sites. **These studies highlight the importance of the spatial arrangement of trees and the canopy edge effect to maximize snow accumulation.**

Another study conducted by Dobre et al. (2012) compared changes in SWE across 4 different treatment types in the Priest River Experimental Forest in Idaho: mechanical thinning and mastication, prescribed fire, prescribed fire with salvage logging, and mechanical thinning with prescribed fire. They found a significant increase in SWE following both of the treatments that included mechanical thinning, but no change in the other two treatments. **These results indicate that prescribed fire, in combination with mechanical thinning, can have significant impacts on snow processes. However, prescribed fire alone may not alter forest structure enough to influence snow accumulation.** Similarly, Sankey et al. (2015) compared thinned plots to thin-and-burn plots and found the greatest increase in SWE following thin-and-burn treatments.

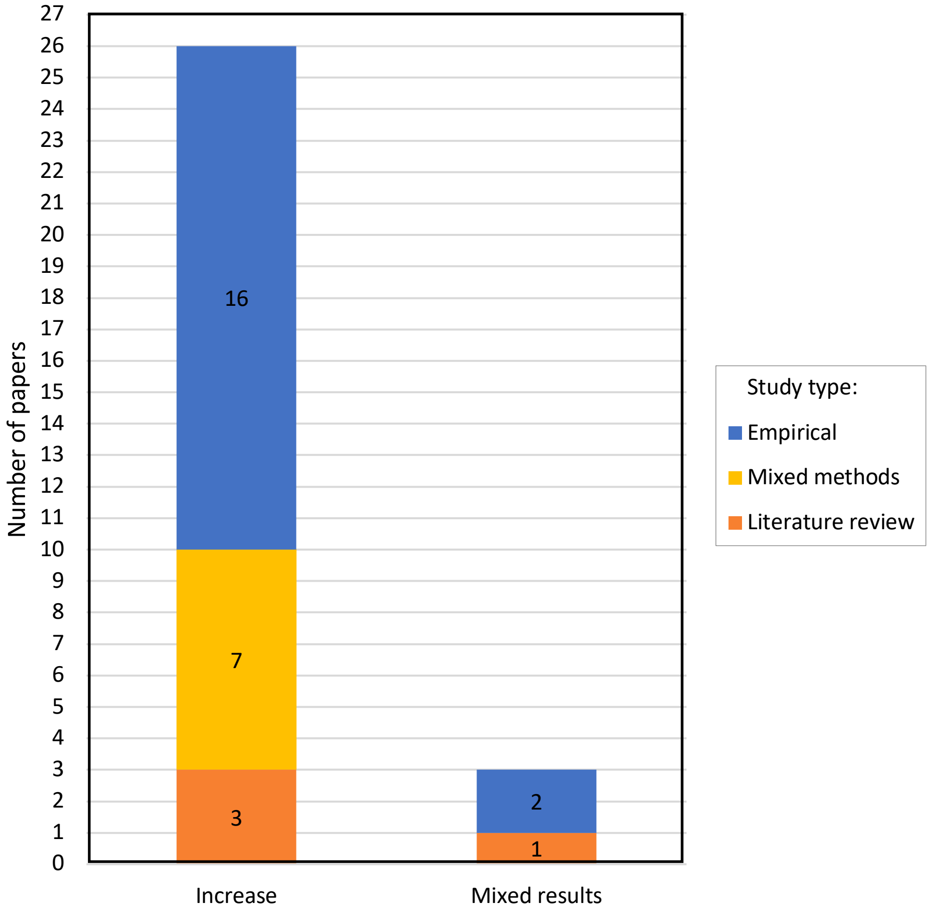


Figure 6. Number of papers associated with increase in SWE and mixed results following canopy removal.

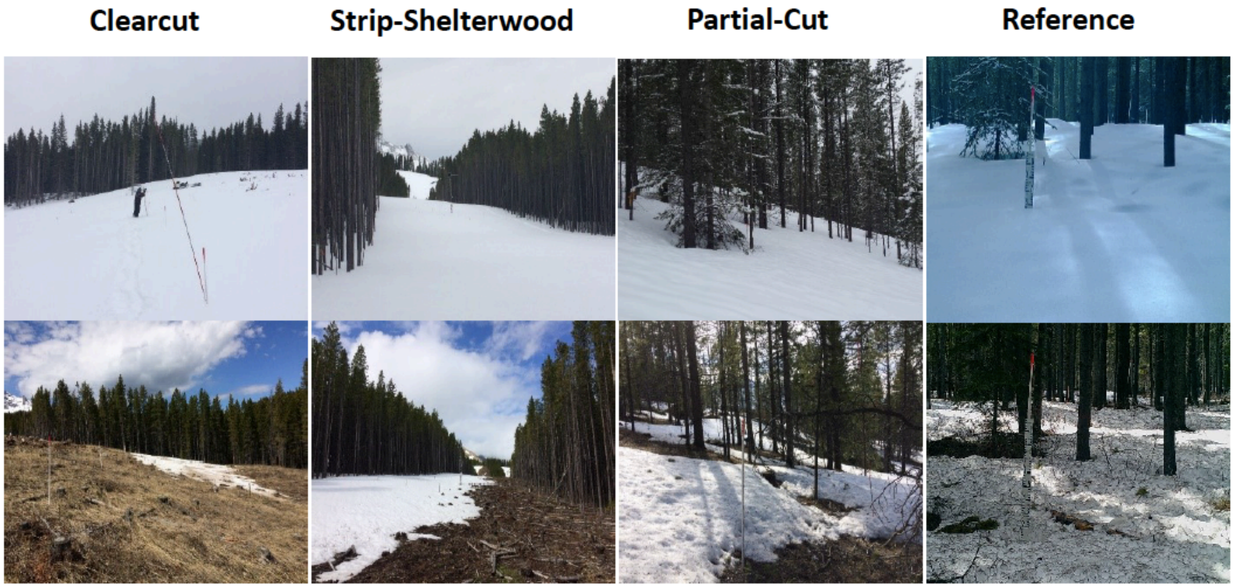


Figure 7. Comparison of snow accumulation among the three treatment types implemented in Alberta, Canada in a study conducted by Greenacre (2019). Photos on the top row were taken during winter (February and March 2017), and bottom row photos were taken during the spring snowmelt period (May 2017).

Canopy Removal and Snow Retention:

Snow retention can increase a forest's resiliency to drought and wildfire by allowing moisture to slowly seep into the soil and increase soil moisture storage. Climate change is resulting in earlier snowmelt by up to 4 weeks in Colorado (Lukas et al., 2014). Managing forests to prolong snow retention can offset this change by delaying the onset of spring snowmelt, which is beneficial from a water resources standpoint because it can increase water supply in the summer when conditions are hot and dry.

Snow retention is often measured by the snow disappearance date (SDD). In this review, 15 studies looked at snow retention. Eight were empirical, 1 was model-based, 4 used mixed methods, and 2 were literature reviews. Of these, 8 reported longer snow retention as a result of canopy removal, 1 reported no change, and 6 reported mixed results (i.e., results varied with treatment type and local conditions) (Figure 8).

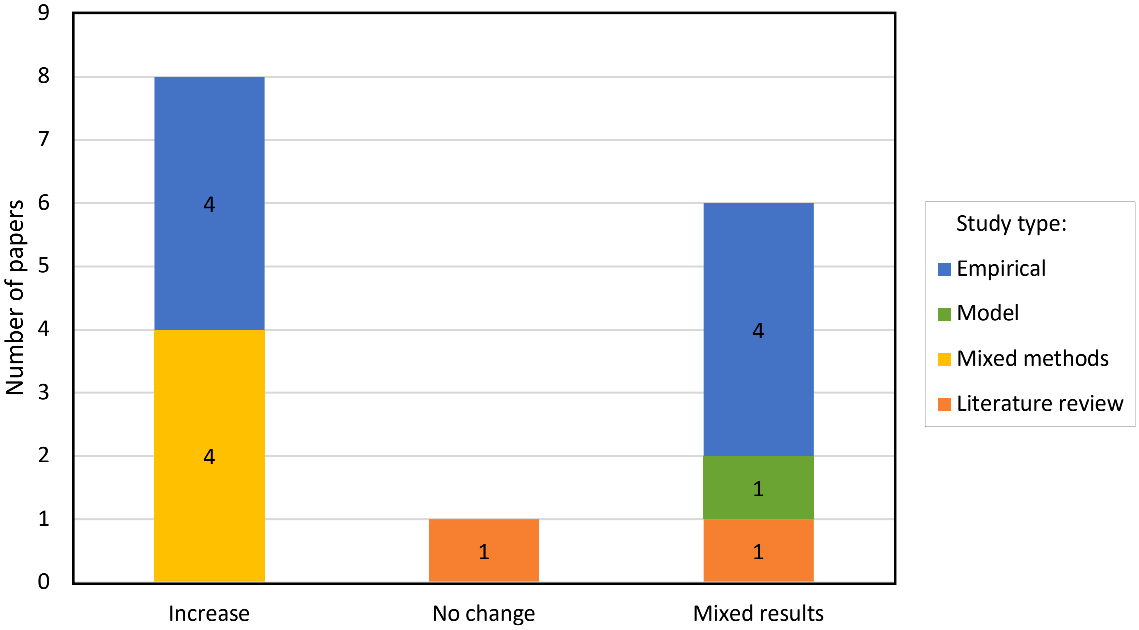


Figure 8. Number of papers associated with increase, no change, and mixed results for the response of snow retention to canopy removal.

Lundquist et al. (2013) performed an extensive literature review and meta-analysis and found that clearcutting trees to create large openings throughout the forest led to longer snow retention in lower latitudes and warmer climates, but shorter retention in cold, high elevation forests at higher latitudes where average winter temperatures are below -6°C. This phenomenon can be explained by regional differences in solar radiation. In warmer regions at lower latitudes and lower elevations, longwave radiation, which is indicated by air temperature, can get "trapped" under the forest canopy, causing the snow to melt quicker under the canopy compared to in the open. However, in higher latitudes and colder climates such as the Colorado Rockies, there is not as much longwave radiation under the canopy. Thus, the snow in the open areas that is exposed to more shortwave radiation melts quicker than that under canopy, ultimately resulting in longer snow retention under canopy compared to open areas in these cold climates (Lundquist et al., 2013). **These findings emphasize the importance of retaining trees in the high elevation forests of the Colorado Rockies to enhance spatial heterogeneity across the landscape, rather than clearcutting large areas of the forest to create large, treeless openings.**

Canopy Removal and Snowmelt Rate:

Similar to long snow retention, slow snowmelt rates are desirable from an ecological and water resource perspective. In Colorado, water demand is highest in July and August (Colorado Water Conservation Board, 2019). If forest management can extend the snowmelt season later into the summer, then this could help to decrease the supply-demand gap during these months. In addition to prolonging the snowmelt season, slow snowmelt allows more moisture to infiltrate into the soil to replenish soil moisture and groundwater storage, which improves soil productivity and can lead to increases in low flows (Pike and Scherer, 2003).

Canopy removal sometimes results in higher snowmelt rates due to increased exposure to solar radiation. One trend that is apparent throughout the literature is that increased snowmelt rate following canopy removal can offset the increases in SWE to create a net zero effect, i.e., the snow disappearance date is the same with or without the treatment (MacDonald and Stednick, 2003). However, this does not nullify the benefits of managing forests to increase snow accumulation, as this can still ultimately increase water yield.

Twenty-six of the 40 papers reviewed looked at the impacts of forest management on snowmelt rate. Of these, 13 were empirical, 5 were model based, 4 used mixed methods, and 4 were literature reviews. Eleven studies found that snowmelt rates increased with canopy removal, 2 found that they decreased, and 13 found mixed results (Figure 9). In all of the "mixed results" studies, snowmelt rate following canopy removal was higher on south-facing slopes, and lower on north-facing slopes. Aspect and slope are highly important because radiation is the driving force for snowmelt, and south-facing slopes in the Rocky Mountain Region are exposed to more shortwave radiation (Musselman et al., 2008; Pomeroy et al., 2008). **These results indicate that canopy removal is likely to decrease snowmelt rate on north-facing slopes, and increase snowmelt rate on south-facing slopes.**

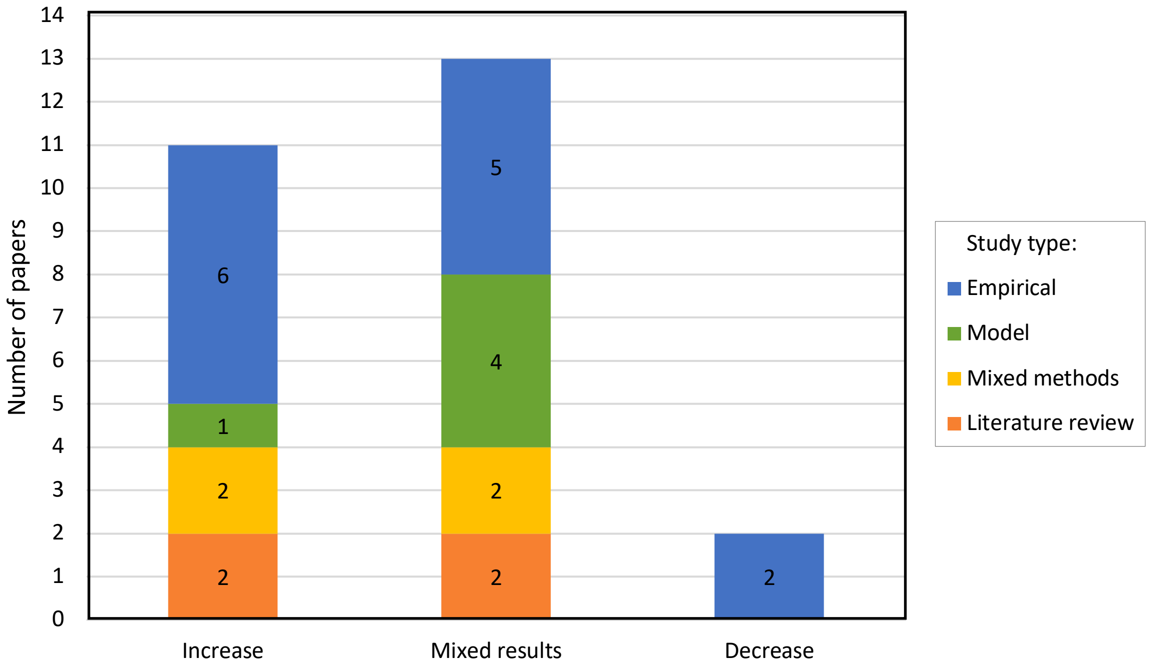


Figure 9. Number of papers associated with increase, mixed results, and decrease for the response of snowmelt rate to canopy removal.

Canopy Removal and Streamflow:

Annual runoff, or streamflow, can be broken down into two parts: peak flows and low flows. Peak flows occur during spring snowmelt and coincide with the highest streamflow volumes of the year. In the Colorado Rockies, peak flows have historically occurred in June (Figure 10), but have been occurring 1-4 weeks earlier in recent years as a result of climate change (Lukas et al., 2014). Peak flows are important during spring and early summer months when agricultural water demand is high. They also provide large quantities of water to refill reservoirs to sustain municipal and industrial water supply throughout the year. Low flows occur during the late summer and winter months and have important ecological benefits such as maintaining soil moisture throughout the year (Pike and Scherer, 2003). Rather than being fueled by snowmelt, low flows are sustained by groundwater storage and surface water discharge (Smakhtin, 2001; Pike and Scherer, 2003). The hydrograph below shows the changes in peak flows and low flows before and after forest treatments in the Fraser Experimental Forest in Colorado (Troendle and King, 1985).

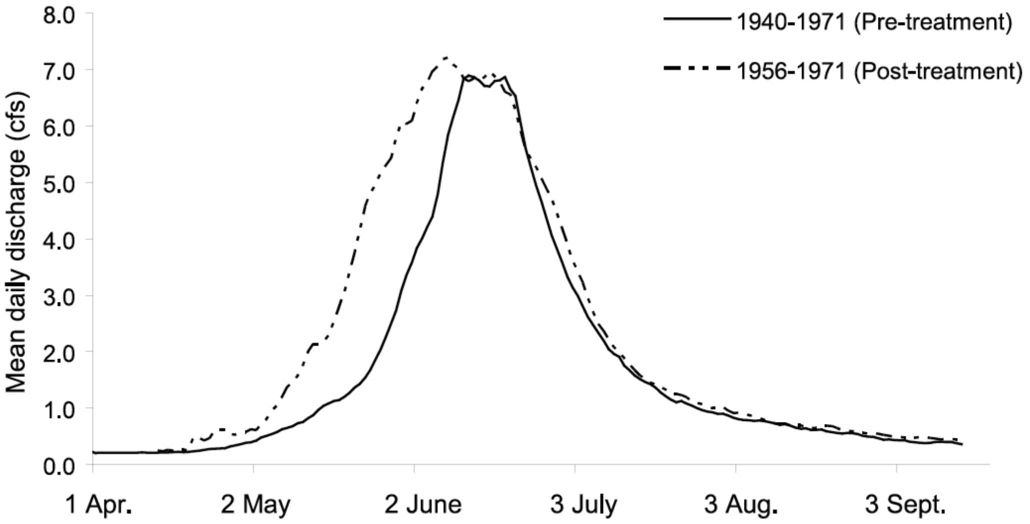


Figure 10. Fool Creek hydrograph before and after forest treatment in the Fraser Experimental Forest, Colorado (Troendle and King, 1985).

The most direct result of an increase in SWE is a subsequent increase in peak flows when the snow melts. When snow melts quickly, there is an especially large peak in the hydrograph. There are benefits to slowing the rate of snowmelt because the slower it melts, the more it is able to slowly infiltrate into the soil and replenish groundwater supplies, which has the potential to increase low flows, along with other ecological benefits (Pike and Scherer, 2003).

Out of the 40 studies reviewed here, 13 looked at the impact of mechanical thinning on streamflow volume. Four were empirical, 3 were model-based, 3 were mixed-methods, and 3 were literature reviews. Ten of these saw an increase in streamflow following canopy removal, 1 saw no change, and 2 saw mixed results (Figure 11). Mixed results were often due to annual precipitation variability.

Only 2 studies in this literature review specifically addressed low flows. Of the 10 studies that reported an increase in streamflow, 1 detected an increase in low flows (Sun et al., 2018). This increase resulted from implementing a gap-thinning treatment, in which 24% of trees were removed to create small gaps throughout the watershed. Pike and Scherer (2003) saw mixed results after reviewing 8 studies that examined the response of low flows to canopy removal, 4 saw an increase in low flow volume, while the other 4 saw no change. Due to the important social and ecological benefits that low flows provide, future forest hydrology research should investigate management practices that have the potential to increase low flows.

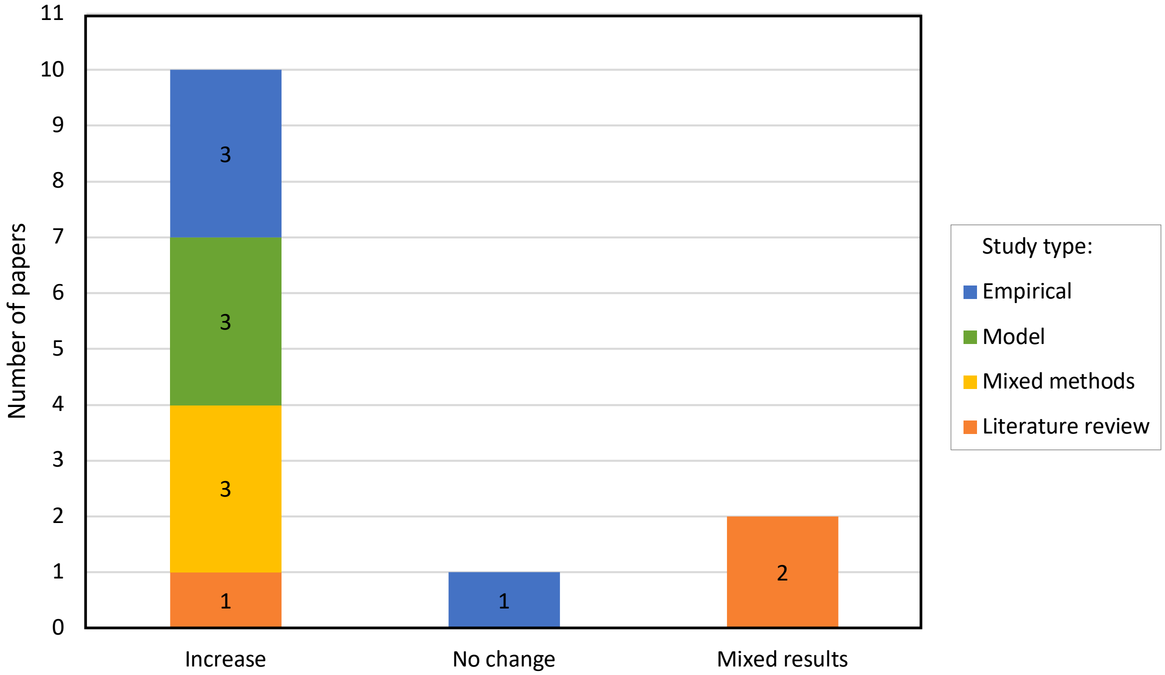


Figure 11. Number of papers associated with increase, no change, and mixed results for the response of streamflow to canopy removal.

Due to the link between soil moisture storage and low flows, 5 of the studies reviewed measured soil moisture response to forest management. Four of these reported an increase in soil moisture storage following thinning, and one reported later timing of peak soil moisture. Four studies were empirical, and 1 used mixed methods.

Collectively, these results indicate that canopy removal has the potential to increase annual streamflow volume and soil moisture storage. Specifically, gap-thinning prescriptions have the potential to increase low flows.

Impact of Slope Aspect on Snow Processes:

Theoretically, there is a threshold at which SWE is maximized and snowmelt rate is minimized, and this is related to aspect and slope (Broxton et al., 2020; Musselman et al., 2008). In North America, more shortwave radiation occurs on south-facing slopes compared to north-facing slopes (Pomeroy et al., 2008). In this literature review 10 studies found that, following canopy removal, snowmelt occurred faster on south-facing slopes compared to north-facing slopes within the same watershed. Ellis et al. (2013) found that snowmelt occurred 20 days earlier on south-facing slopes in Alberta, Canada. In their global meta-analysis, Lundquist et al. (2013) found an overall trend of slower snowmelt rates on north-facing slopes across study sites. Molotch et al. (2016) found the same trend in the Colorado Rockies near Nederland.

Ten studies found that SWE increases following canopy removal were greater on north-facing slopes compared to south-facing slopes. Jost et al. (2007) found a positive correlation between SWE and north-facing slopes, i.e., the more "north-facing" a slope, the higher the SWE. Additionally, 5 studies found that snow retention was longest following canopy removal on north-facing slopes (Figures 12 and 13).

Greenacre (2019) found that maximum snow accumulation and retention, and minimum snowmelt rates occurred in strip-shelterwood plots on north facing plots. This is a result of the canopy edge effect, in which surrounding trees shade adjacent open areas to minimize radiation and prolong snow retention. This treatment is therefore effective for increasing water yield and delaying the timing of peak flows, both desirable outcomes from water resource management and ecological perspectives.

Results from this literature review overwhelmingly suggest that treating north-facing slopes is the best way to simultaneously maximize SWE and minimize snowmelt rate. This finding is supported by previous research claiming that canopy removal on north-facing slopes has the greatest potential to increase water yield (Troendle and Olsen, 1994; MacDonald and Stednick, 2003).

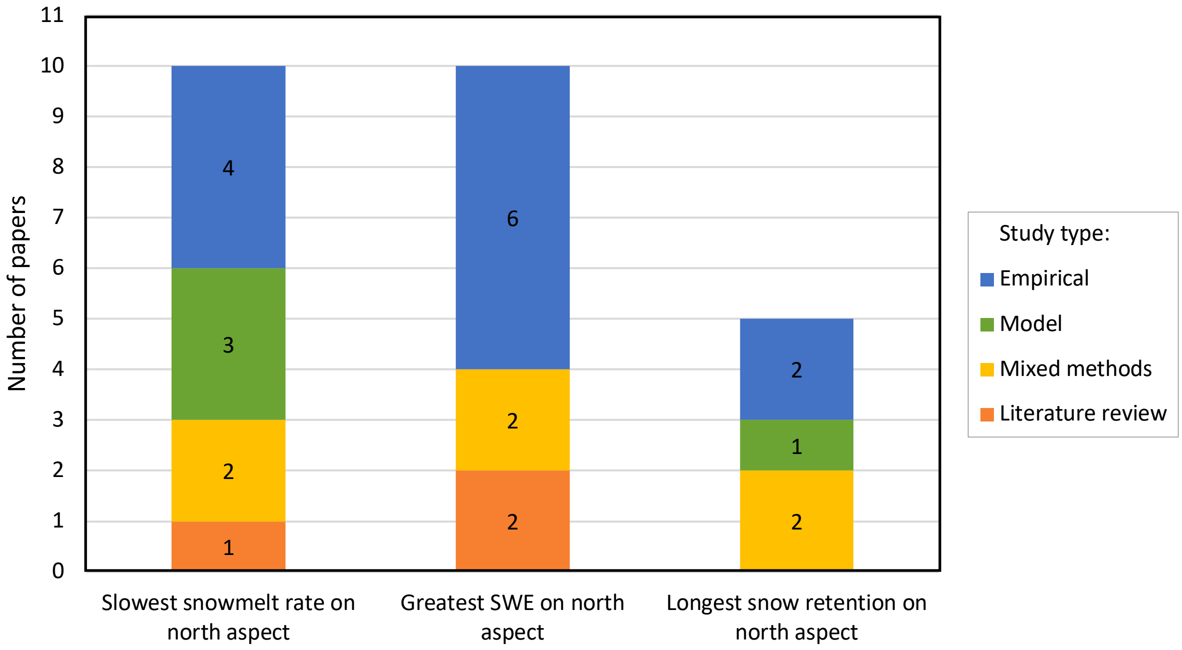


Figure 12. Impact of aspect on snow processes following canopy removal.

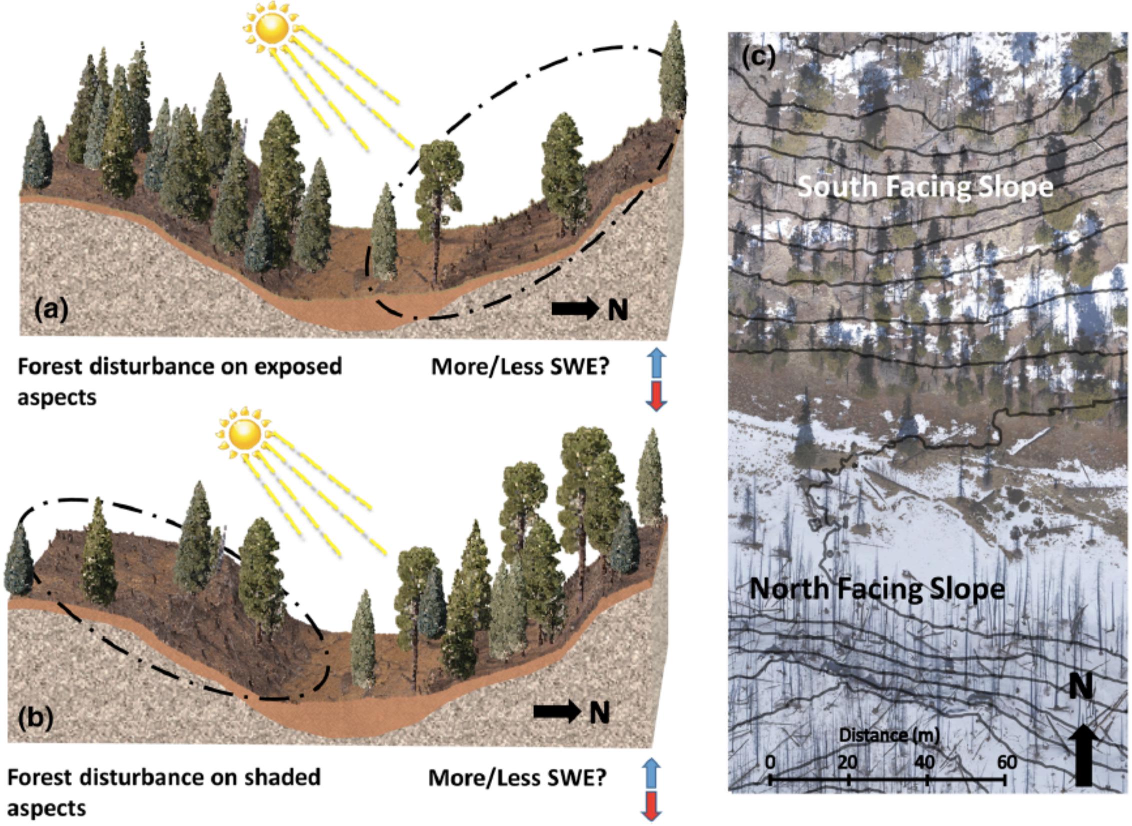


Figure 13. A study conducted by Broxton et al. (2020) in an Arizona watershed showed that, following canopy removal, snow accumulation is greater on north-facing slopes compared to south-facing slopes.

Optimal Residual Canopy Cover to Maximize Water Yield:

Nine studies mentioned an optimal percentage of residual canopy cover following treatment at which snow accumulation and/or water yield were maximized. **Optimal residual canopy cover percentages ranged from 25-70% across studies** (Broxton et al., 2020; MacDonald and Stednick, 2003; Musselman et al., 2008; Pike and Scherer, 2003; Pomeroy et al., 2012; Sankey et al., 2015; Schnorbus and Alila, 2004; Troendle et al., 2010; Veatch et al., 2009; Zhang and Wei, 2014; Appendix D). The wide range can be attributed to individual site characteristics such as latitude, elevation, topography, and climate.

Differences in net radiation along latitudinal and elevational gradients, as well as aspect and slope, will influence how much canopy cover should remain following treatment. As explained by Lundquist et al. (2013), low elevation forests and forests at lower latitudes experience warmer temperatures (e.g., ponderosa pine forests in AZ and NM), and are dominated by longwave radiation. **In these low elevation and low latitude forests, more trees should be removed to maximize water yield. Thus optimal residual canopy cover would be closer to the low end of the spectrum (25%).** For example, Broxton et al. (2020) found that snow accumulation was maximized in a ponderosa pine forest in Arizona at 30-50% residual canopy cover following treatment. A study by Veatch et al. (2009) showed maximum snow accumulation in a ponderosa pine forest in New Mexico at 25-45% residual canopy cover.

On the other hand, high elevation forests at higher latitudes experience colder temperatures (e.g., spruce-fir and lodgepole pine forests in the Colorado Rockies), and are dominated by shortwave radiation. In these forests, the canopy edge effect plays a significant role in increasing snow accumulation and retention by providing shade from surrounding trees. **At higher elevations and higher latitudes, it is important to retain more trees—closer to 70% residual canopy cover.** For example, in the Fraser Experimental Forest in Colorado, which is dominated by lodgepole pine and spruce-fir, maximum water yield increases occurred at 70% residual canopy cover (MacDonald and Stednick, 2003).

Other papers did not specify a percentage of residual canopy cover, but emphasized the importance of retaining trees in high elevation forests, rather than creating large canopy gaps via clearcutting (Goeking and Tarboton, 2020; Lundquist et al., 2013; Tennant et al., 2017; Varhola et al., 2010). This contradicts the previously accepted belief that there is a simple negative correlation between vegetation density and water yield that holds across all densities and all situations.

Additionally, many studies implemented gap-thinning or strip-shelterwood treatments with cleared strips of a certain size. The size of a gap or strip is measured in terms of the average surrounding tree height, H (Figure 14). Eight studies identified the optimal gap size to be 0.5-2H (Baker and Ffolliott, 2003; Broxton et al., 2020; Ellis et al., 2013; Hubbart et al., 2015; Lawler and Link, 2011; Musselman et al., 2015; Seyednasrollah and Kumar, 2014; Sun et al., 2018). According to Sun et al. (2018) **many small gaps distributed throughout the watershed have a greater potential to increase snow retention and water yield than a few large gaps.**

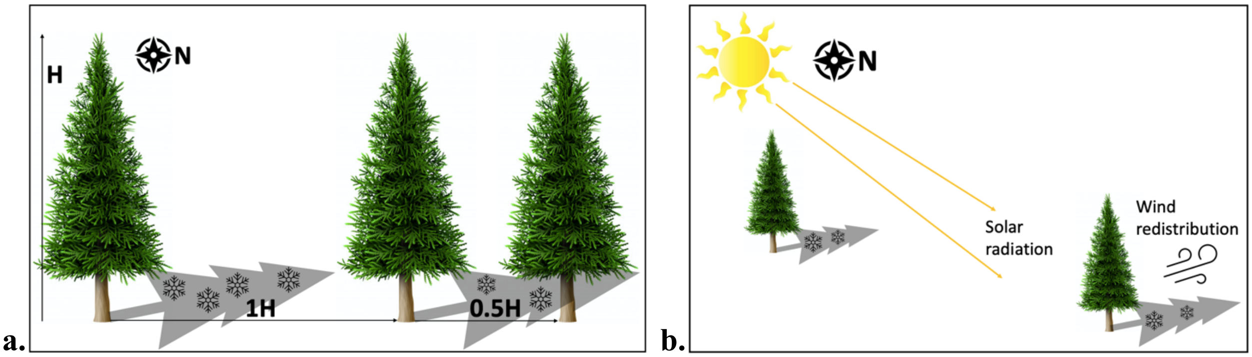


Figure 14. Canopy gap sizes of 1H and 0.5H protect snow from incoming solar radiation by providing shade (a). Large openings expose snow to more solar radiation and wind redistribution, resulting in snow ablation (b).

Interestingly, studies that compared clearcuts to partial cut areas often found greater increases in SWE and/or water yield in the clearcuts (Hubbart et al., 2007, 2015; Du et al., 2016). However, when clearcuts were compared to strip-shelterwood or gap-thinning treatments, the latter always had greater SWE and water yield (Greenacre, 2019). This further demonstrates the importance of the spatial arrangement of trees that are retained, as factors such as the canopy edge effect can greatly influence snow processes.

Collectively, these results indicate that high elevation forests in the Colorado Rockies should be managed in a way that creates spatial heterogeneity and retains trees to maximize the canopy edge effect. Following treatment, the percentage of residual canopy cover in these watersheds should be on the higher end of the spectrum (~70% residual canopy cover), and gap sizes should range from 0.5-2H.

Deciduous vs. Evergreen Forests:

Three studies compared snow processes between deciduous and evergreen forests (LaMalfa and Ryle, 2008; Schneider et al., 2019; MacDonald and Stednick, 2003). All three found greatest snow accumulation in deciduous forests such as aspen and western larch. This increase can be attributed to lower interception rates in deciduous forests due to loss of leaves during winter. LaMalfa and Ryle (2008) compared spruce-fir forests to aspen stands in the Wasatch Mountains in Utah and found that aspen stands had higher SWE, higher soil moisture storage, and overall greater potential for increases in water yield in comparison to the spruce-fir forest. According to LaMalfa and Ryle (2008), there is the greatest potential for increased water yield by creating a mosaic of aspen intermixed with conifers. Aspen also provide valuable wildlife habitat and can act as a fire break (Addington et al., 2018). **These results indicate that managers should promote aspen regeneration and protect existing aspen from overgrazing by ungulates by building exclosures around saplings.**

Elevation:

Eight studies compared the effects of canopy removal in different forest types and at different elevations and found that changes in snow processes are more pronounced at higher elevations (Ellis et al., 2011; Goeking and Tarboton, 2020; Jost et al., 2007; MacDonald and Stednick, 2003; Schnorbus and Alila, 2004; Tennant et al., 2017; Whitaker et al., 2002; Zhang and Wei, 2014). According to Goeking and Tarboton's systematic literature review that compared several different locations and elevations, SWE and water yield increases are more likely to occur at higher elevations following canopy removal (Goeking and Tarboton, 2020). Jost et al. (2007) found elevation to be the single most important predictor for snow accumulation and snowmelt throughout a watershed. **These results indicate that forest management activities that reduce canopy cover should be concentrated in high elevation forests, since these efforts have the greatest potential to increase water yield.**

DISCUSSION AND MANAGEMENT RECOMMENDATIONS

Water supply in Colorado is dependent on the accumulation and retention of snow, and the delivery of snowmelt to downstream users. The results obtained from this literature review demonstrate that there is potential to increase water yield in the Colorado Rockies through specific forest management practices. This report does not suggest a one-size-fits-all approach. Rather, the goal is to provide some general guidelines that can help forest managers determine what treatments may be appropriate based on individual watershed characteristics. Below is a list of management recommendations formulated from the cumulative results of included studies:

- Canopy removal has the potential to increase annual streamflow volume and soil moisture storage.
- Canopy removal via mechanical thinning is the most effective way to increase water yield. Prescribed fire, in combination with mechanical thinning, can have significant impacts on snow processes. However, prescribed fire alone may not alter forest structure enough to influence water yield.
- Treatments should be concentrated in high elevation forests above 2,700 meters, since these efforts have the greatest potential to increase water yield.
- Treatments that retain trees throughout the watershed and maximize canopy edge have the greatest potential to increase water yield in high elevation forests.
- Forests should be managed to enhance spatial heterogeneity by creating many small gaps throughout the watershed rather than a few large gaps. In the high elevation forests of Colorado gap sizes should range from 0.5-2H.
- Treating north-facing slopes is the best way to simultaneously maximize snow accumulation, minimize snowmelt rate, and ultimately increase water yield.
- Forests that are a mosaic of aspen intermixed with conifers have the potential to increase water yield. Managers should therefore promote aspen regeneration and protect existing aspen from overgrazing by ungulates by building exclosures around saplings.

Many of these recommendations overlap with management practices that are already being implemented in current forest restoration projects in Colorado. For example, mechanical thinning and prescribed fire are implemented to reduce hazardous fuels and mitigate wildfire risk (MacDonald and Stednick, 2003). The enhancement of landscape spatial heterogeneity increases forest resilience to climate change and is a goal of the Collaborative Forest Landscape Restoration Program (Addington et al., 2018). Aspen regeneration improves wildlife habitat and can act as a fire break (Addington et al., 2018). Increased moisture retention in forests can decrease wildfire risk by offsetting moisture deficits caused by climate change (Rocca et al., 2014). The recommendations presented in this report would support current management goals while adding the benefit of increased water supply. Of course, best management practices should always be followed when implementing any treatment to ensure the mitigation of negative ecological impacts (Venable et al., 2017; Colorado State Forest Service, 2010).

Managing forests for water resources should ultimately be viewed through an adaptive management lens. Due to the complexity of forest hydrology, the scaling-up of studies presented in this literature review will inevitably present new challenges. The management recommendations presented here can serve as a good starting point, but each forest manager will have to experiment, to a certain extent, to figure out how local topography and climate will influence snow processes in any given watershed.

CONCLUSION

Managing forests for multiple benefits is critical for effectively protecting the ecosystem services that they provide. This report identified forest management practices that have the potential to increase water yield, while also improving forest health and increasing resilience to climate change. Overall, results emphasize the importance of spatial heterogeneity and tree retention to maximize the canopy edge effect. Going forward, forest managers should integrate these recommendations into their management plans to reap additional water yield benefits of restoration efforts. The potential of these management recommendations to increase water yield presents additional funding opportunities from water resource managers such as utilities companies. Ultimately, the successful implementation of large-scale forest restoration projects will require collaboration among water resource managers, conservation groups, and public and private landowners.

APPENDIX

Appendix A: Glossary

Ablation- snow disappearance due to the combination of sublimation, melt, and wind redistribution (NSIDC, 2020)

Evaporation- the transition from liquid to vapor; evaporation can occur from the soil surface, falling precipitation, water bodies, and vegetation surfaces (Pike and Scherer, 2003)

Evapotranspiration- the combined “loss” (return) of water to the atmosphere through evaporation and transpiration (Pike and Scherer, 2003)

Forest canopy cover- usually understood as a percentage in which 0% corresponds to an open field and 100% to a dense forest where there are no gaps between the touching canopies (Varhola et al., 2010)

Hydrograph- graph showing daily mean streamflow throughout the year (USGS, 2020)

Infiltration- the rate at which water enters the soil matrix (Pike and Scherer, 2003)

Interception- the interruption of the downward movement of precipitation; in most cases, interception denotes a “loss” of water, as temporarily stored rain or snow on vegetation surfaces evaporates before reaching the forest floor (Pike and Scherer, 2003)

Longwave radiation- component of solar radiation that is indicated by air temperature (Lundquist et al., 2013)

Low flows- minimum flow or absence of flow in a stream or river during the dry season; in snow-dominated regions, low flows typically occur from late summer through the winter (Pike and Scherer, 2003)

Peak flow- maximum flow in a stream or river; in snow-dominated regions peak flow typically occur during spring snowmelt (Pike and Scherer, 2003)

Residual canopy cover- forest canopy cover that remains following treatment

Shortwave radiation- component of solar radiation that is indicated by solar angle (Lundquist et al., 2013)

Snowpack- the total snow and ice on the ground, including both new snow and the previous snow and ice which have not melted (NSIDC, 2020)

Snow water equivalent (SWE)- the maximum amount of water that is contained within the snowpack before spring snowmelt begins; SWE measurements typically taken on April 1 in North America for standardization purposes (Varhola et al., 2010)

Solar radiation- the total electromagnetic radiation emitted by the sun (NSIDC, 2020)

Sublimation- the transition of a substance from the solid phase directly to the vapor phase, or vice versa, without passing through an intermediate liquid phase (NSIDC, 2020)

Transpiration- the movement of water from the ground through plant leaves (stomata) into the atmosphere (Pike and Scherer, 2003)

Appendix B: Inclusion Criteria

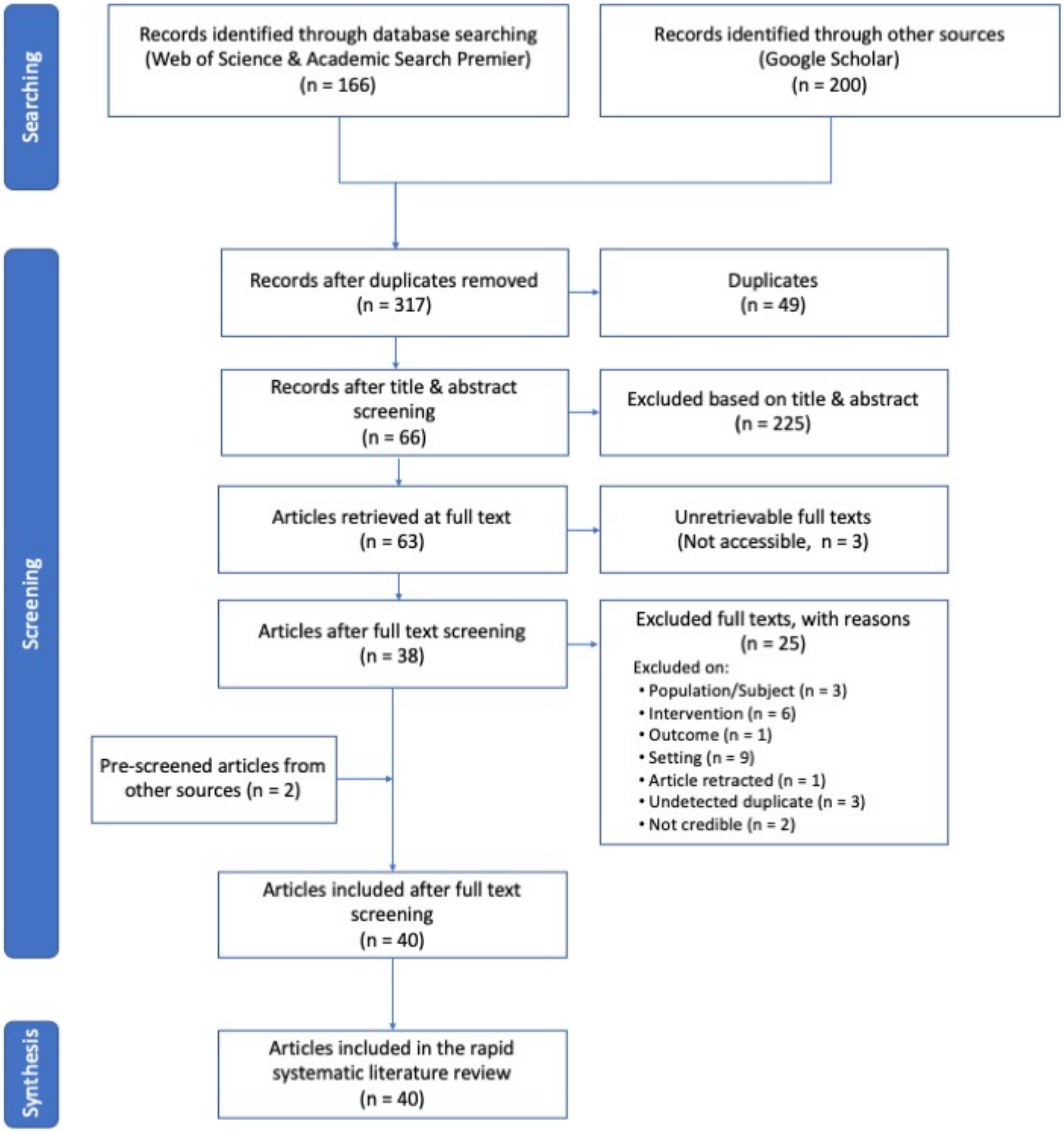
1. Does the TITLE include any derivative of *snow*?
    a. Yes→see #2
    b. No→see #3
2. Does the TITLE include “forest management” OR “forest treatment*” OR “forest cover” OR “forest canopy” OR “canopy cover” OR “forest structure” OR “forest density” OR “vegetation density”?
    a. Yes→See #5
    b. No→Read abstract
3. Does the TITLE include “water yield” OR "water quantity" OR hydrolog* OR hydrograph OR snowmelt OR runoff OR streamflow?
    a. Yes→See #4
    b. No→Exclude
4. Does the TITLE include “forest management” OR “forest treatment*” OR “forest cover” OR “forest canopy” OR “canopy cover” OR “forest structure” OR “forest density” OR “vegetation density”?
    a. Yes→Read abstract
    b. No→Exclude
5. Is the geographic scope in the TITLE within my project’s geographic scope (Rocky Mountain Region)?
    a. Yes→Include
    b. No→Read abstract

If told to read the ABSTRACT, then follow the steps below:

6. Does the ABSTRACT include any derivative of *snow*?
    a. Yes→see #7
    b. No→see #8
7. Does the ABSTRACT include “forest management” OR “forest treatment*” OR “forest cover” OR “forest canopy” OR “canopy cover” OR “forest structure” OR “forest density” OR “vegetation density”?
    a. Yes→see #9
    b. No→Exclude
8. Does the ABSTRACT include “water yield” OR "water quantity" OR hydrolog* OR hydrograph OR snowmelt OR runoff OR streamflow OR “snow water equivalent”?
    a. Yes→see #7
    b. No→Exclude
9. Is the geographic scope in the ABSTRACT within my project’s geographic scope (Rocky Mountain Region)?
    a. Yes→Include
    b. No→Exclude

If the article has made it through to be included, then read the full body text.

Appendix C: Screening Process (flow chart template from Haddaway et al., 2017)



Appendix D: Study Treatments and Outcomes

Author	**Year**	**Location**	**Treatment(s) implemented (treatment plots always compared to control plots)**	**Treatment(s) that maximized snow accumulation and/or water yield**
Baker and Ffolliott	2003	AZ	Mechanical thinning	Max SWE in cleared strips & and gaps <1.5H
Broxton et al.	2015	NM & CO	Mechanical thinning	Max SWE in open areas <15m from canopy edge
Broxton et al.	2020	AZ	Mechanical thinning	Max SWE in medium-size canopy gaps (1-2H) and with intermediate forest density (30-50% residual canopy cover)
Dobre et al.	2012	ID	4 treatments: (1) thinning and mastication, (2) Rx fire, (3) Rx fire with salvage logging, (4) thinning with prescribed fire	Max SWE in treatments that involved mechanical thinning (1&4)
Du et al.	2016	ID	Catchment 1: 50% of area was clearcut (100% tree removal); Catchment 2: 50% of area was partial cut with 50% canopy removal (such that 25% of the total canopy in the drainage was removed)	Max streamflow in Catchment 1 with 50% of watershed clearcut
Ellis et al.	2011	Alberta	Mechanical thinning	Max SWE in openings and longer snow retention on north-facing slopes
Ellis et al.	2013	Alberta	Gap-thinning treatments: 60% of forest replaced by small gaps ranging in size from ¾ – 1¼ H	Max SWE in gaps ~1H; melt was delayed up to 20 days in gaps on north-facing slopes (due to reduced longwave emission from the canopy)
Goeking and Tarboton	2020	Western US & Canada	Forest disturbances including mechanical thinning, wildfire, insect outbreaks (only outcomes from mechanical thinning were considered for this report)	SWE and water yield most likely to increase following canopy removal at high latitudes and high elevations; important to retain some trees at high elevation sites colder than -1°C
Gottfried and Ffolliott	2009	AZ	Mechanical thinning: 47% basal area removed to a create canopy gap of 90 m in diameter	Max SWE in 90 m gap
Greenacre	2019	Alberta	3 treatments: clearcut with tree retention (85% of trees removed, 15% retained), strip-shelterwood (50% of trees removed in parallel strips), and partial cut harvesting (selective logging- removal of ~59% of trees)	Max SWE and snow retention, and lowest snowmelt rates in strip-shelterwood treatment
Harpold et al.	2015	CO	Mechanical thinning	Max SWE in openings
Hubbart et al.	2015	ID	2 treatments: clearcut (100% tree removal in treatment area) and partial cut (50% removal)	Max SWE and snow retention in clearcuts; forest gaps need to be at least 2H to show increase in peak SWE
Hubbart et al.	2007	ID	2 treatments: clearcut (100% tree removal), 50% partial cut (50% tree removal)	Max SWE in clearcuts
Jost et al.	2007	British Colombia	34% of watershed was clearcut	Max SWE in clearcuts, but faster snowmelt rate; positive correlation between “northness” and SWE (i.e., the

				more north the aspect, the higher the SWE)
LaMalfa and Ryle	2008	UT	Aspen vs. conifer	Max SWE and soil moisture in aspen stands; greatest potential for increased water yield by creating a mosaic of aspen intermixed with conifers
Lawler and Link	2011	ID	Gap-thinning treatment: gap sizes ranging from 1H-6H	Radiative minimum in 1-2H gaps due to shading from surrounding canopy (potential to minimize ablation and slow snowmelt with this gap size)
Lundquist et al.	2013	Global	Mechanical thinning: various levels of canopy removal	Greatest potential for water yield increases with treatments that retain trees in cold climates with average winter temperatures < -6°C (e.g., gap-thinning, strip-shelterwood, etc.)
MacDonald and Stednick	2003	CO, WY, AZ	Mechanical thinning with 24-100% canopy removal	Max water yield increases with 70% residual canopy cover in Fraser Experimental Forest, CO; greater potential to increase water yield by thinning on north-facing slopes
Molotch et al.	2016	CO	Gap-thinning treatment	Max SWE in gaps; max snow retention on north side of trees
Molotch et al.	2009	NM	Mechanical thinning	Max SWE in openings, but faster snowmelt
Musselman et al.	2008	NM	Mechanical thinning to various canopy densities	Max SWE with 65% residual canopy cover; max SWE and snow retention on north side of canopy edges (until canopy radius is exceeded- so if canopy radius is 2 m, SWE will be maximized starting at the edge of the canopy until 2 m from the edge due to shading provided by the canopy)
Musselman et al.	2015	Alberta	Gap-thinning treatment	Minimum radiation for small gaps <2H
Pike and Scherer	2003	Western US & Canada	13-40% canopy removal via clearcuts, partial cuts, and strip-shelterwood	Increases in low flows observed with 75% (or less) residual canopy cover
Pomeroy et al.	2008	CO	Forest openings	Greater shortwave irradiance in openings; the greater the opening, the greater the net radiation
Pomeroy et al.	2012	Alberta	Forest disturbances including mechanical thinning, wildfire, insect outbreaks (only outcomes from mechanical thinning were considered for this report)	Max streamflow in clearcuts with tree retention; 40% residual canopy cover resulted in 45% increase in snowmelt volume
Stottlemyer and Troendle	2001	CO	Mechanical thinning	Max SWE in thinned plots
Robles et al.	2014	AZ	2 treatments: strip-shelterwood & patch clearing	Max water yield from both treatments; 20% increase in streamflow compared to control
Sankey et al.	2015	AZ	2 treatments: mechanical thinning & thin-and-burn	Max SWE and snow retention in thin-and-burn plots with 76% residual canopy cover

Schneider et al.	2019	MT	Mechanical thinning to create openings	Max SWE in openings
Schnorbus and Alila	2004	British Colombia	2 treatments: mechanical thinning to remove harvest 33% and 66% of canopy cover	Max streamflow with 33-66% residual canopy cover
Seyednasrollah and Kumar	2014	ID	Gap-thinning treatment to create gaps of 60 m diameter	Minimum radiation for clear sky conditions for gap sizes 0.5-1H, and larger gaps ideal for cloudy sky conditions; Less radiation with canopy removal on north facing slopes, greater net radiation with thinning on south-facing slopes
Seyednasrollah et al.	2013	Conceptual (model data from CO)	Mechanical thinning across varied slopes and aspects	Minimum radiation with thinning on north-facing slopes; importance of retaining trees on south-facing slopes
Sun et al.	2018	ID	Gap-thinning prescription: 24% of watershed thinned to create gaps 50m x 60m in size	Max snow retention in gaps of 2H
Tennant et al.	2017	CO	Mechanical thinning	Max SWE on north-facing slopes; in cold, high elevation sites, tree retention is important to maximize snow processes
Troendle et al.	2010	CO	Strip-shelterwood treatment to remove 40% of canopy throughout watershed	Max SWE in strip-shelterwood treatment and on north-facing slopes; increases in streamflow detected with at least 20% basal area removal throughout watershed
Varhola et al.	2010	North American Rockies	Mechanical thinning	Negative correlation between vegetation density and SWE, and this trend becomes less pronounced at high elevations (again, importance of tree retention at high elevations)
Veatch et al.	2009	NM	Mechanical thinning to create different forest densities	Max SWE at intermediate canopy density, between 25-45% residual canopy cover, and in open areas immediately to the north of trees
Whitaker et al.	2002	British Colombia	Mechanical thinning to remove 1/3 and 2/3 of vegetation	Max SWE and ~10 day delay in snowmelt with thinning
Woods et al.	2006	MT	2 treatments, both removing 50% basal area: 1) residual trees evenly distributed; 2) residual trees in groups	Max SWE in evenly distributed treatment
Zhang and Wei	2014	British Colombia	Mechanical thinning	Max streamflow with 75% residual canopy cover

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