EFFECT OF ALTERNATIVE SILVICULTURAL TREATMENTS ON SNOW ACCUMULATION IN LODGEPOLE PINE STANDS, MONTANA, U.S.A.

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ABSTRACT

Alternative silvicultural treatments such as thinning can restore the productivity and diversity of forested watersheds and reduce wildfire hazards, but the hydrologic effects of these treatments are not well defined. We evaluated the effect of even thinning (SE) and group-retention thinning (SG), both with ~ 60 % basal area removal, on snow accumulation in lodgepole pine stands at the Tenderfoot Creek experimental forest, west-central Montana. In 2003 and 2004, the snow water equivalent (SWE) close to the seasonal peak was measured at >250 locations in the SE and SG treatments, and a control. In both years, the mean SWE in the SE treatment was significantly higher than in the control and the SG treatment ($P<0.0001$). In contrast, the mean SWE in the SG treatment was not significantly different from the control. Spatial variability of SWE was up to 3 times higher in the SG treatment than in the SE treatment or the control. The increased snow accumulation in SE treatments is attributed to reduced interception. In the SG treatment, losses due to wind scour and evaporation offset gains due to reduced interception. These results demonstrate that thinning can have substantially different effects on snow accumulation depending on the spatial arrangement of the treatments.

INTRODUCTION

Snowmelt runoff from high elevation forested watersheds is the primary water source for much of the western United States. Snow accumulation in these watersheds varies with climate, elevation, topography and forest vegetation characteristics (Pomeroy et al., 2002). Canopy structure is an especially important vegetation characteristic because of its effect on the interception component of the water budget and the wind speed and solar radiation flux at the snow surface (Lundberg and Koivusalo, 2003). Forest harvest modifies the canopy structure, and may increase or decrease snow accumulation depending on the balance between gains due to reduced canopy interception and losses due to greater wind scour and evaporation (Golding and Swanson, 1986; Stegman, 1996). In the cold, windy environments typical of the central and northern Rocky Mountains of the western U.S. and Canada, small (2 to 5 tree height diameter) clearcuts accumulate more snow than the surrounding forest because they reduce interception while minimizing losses from the snowpack (Troendle and Leaf, 1980; Troendle and King, 1985; Swanson, 1988). Evenly distributed thinning over small areas also results in a net increase in snow accumulation because of the reduction in interception (Troendle and King, 1987). In contrast, large (more than 20 tree height diameter) clearcuts accumulate less snow than under a closed canopy because scouring and evaporation losses exceed gains due to reduced interception (Troendle and Leaf, 1980).

Natural disturbance events such as wildfire and disease also affect snow accumulation by creating openings in the canopy (Helvey, 1980). However, fire suppression has sharply reduced the frequency of natural disturbance in forests throughout western North America, creating extensive, dense and overstocked stands (Sampson, 1997). By increasing canopy density, fire suppression may reduce snow accumulation in forested watersheds, with a consequent decline in water yield (Matheussen et al., 2000). This is a particular concern for water resource managers in drought prone areas such as the western United States. Wildfire hazards due to increased fuel loads are an additional concern because of the risk to life and property. The widespread use of clearcutting to maintain water yields and reduce wildfire hazards is aesthetically, ecologically and politically undesirable. Alternative silvicultural prescriptions such as thinning offer a potentially more acceptable means of achieving these goals, while also restoring forests to a more natural state by simulating natural disturbance processes. Information on the hydrologic effects of these prescriptions is needed if forests are to be managed in a holistic and ecologically sustainable manner. However, relatively few studies have focused on the hydrologic effects of thinning treatments as compared to the wider literature on the effects of clearcutting.

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Seral, fire-dependent lodgepole pine communities comprise a significant component of mid- to upper- elevation forests in the central and northern Rocky Mountains, and provide wood products, wildlife habitat, livestock forage, water, recreational opportunities and aesthetic benefits (Koch, 1996). However, fire suppression has radically altered the structure of these forests. The USDA Forest Service is investigating the use of alternative silvicultural prescriptions to restore the ecological structure and function of Lodgepole pine forests in the northern Rockies, while also maintaining water yields and reducing fuel loads. We evaluated the effect of two of these prescriptions, even thinning and group-retention thinning, both with ~ 60 % basal area removal, on snow accumulation in Lodgepole pine stands at the Tenderfoot Creek experimental forest in west-central Montana. The objectives were to determine the effect of the two treatments on: 1) the magnitude of winter snow accumulation, and 2) the spatial distribution of snow accumulation at the stand scale. The treatments aimed to simulate the effect of mixed and high severity wildfires, so the study provided a means of assessing the hydrologic effects of natural disturbance events as well as the treatments themselves. Therefore, we plan to use the findings of this study in our efforts to model long-term (decadal to century scale) effects of fire suppression and other management policies on water yields from northern Rocky Mountain forests. This involves linking the SIMPPLLE (Simulating Patterns and Processes at Landscape Scales) vegetation dynamics model (Chew et al., 2002) with the SWAT (Soil and Water Assessment Tool) watershed hydrologic model (Neitsch et al., 2002). The capability of SWAT to model snow accumulation and melt processes in mountainous terrain has recently been greatly improved (Fontaine et al., 2002), but there is a need to further refine this aspect of the model.

STUDY AREA

The 3600 ha Tenderfoot Creek experimental forest (TCEF) lies in the headwaters of Tenderfoot Creek in the Little Belt Mountains of west-central Montana (Figure 1). Elevations in the experimental forest range from 1838 m to 2421 m with a mean of 2205 m. Glaciation has created a broad, basin-like topography in the upper elevations of TCEF, while rock outcrops and talus slopes predominate at lower elevations.

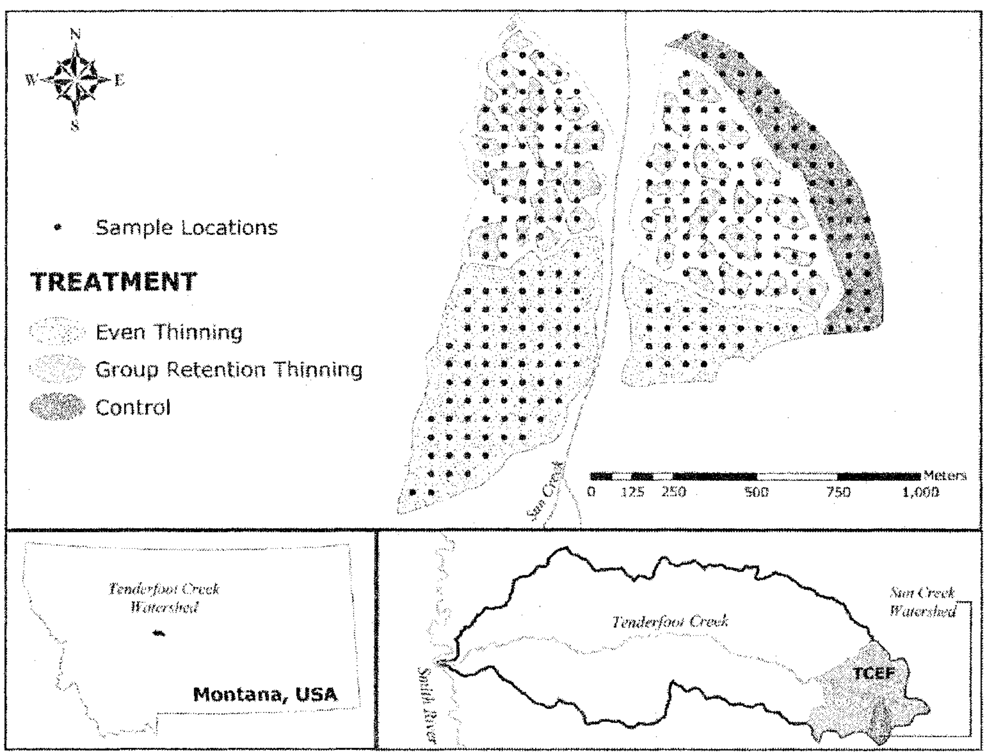


Figure 1. Location of study sites at Tenderfoot Creek Experimental Forest (TCEF), west-central Montana. Main map shows location of treatments and sample locations in the Sun Creek watershed.

The elevation weighted mean annual precipitation at TCEF is 88.4 cm (Farnes et al., 1995). Precipitation is evenly distributed throughout the year, but between October and April most of the precipitation accumulates as snow. The mean peak snow water equivalents (SWE_{max}) at the Stringer Creek and Onion Park SNOTEL sites (elevations 1997 m and 2258 m), both located within TCEF, are 28.2 cm and 37.5 cm, respectively. Peak runoff in Tenderfoot Creek typically occurs between mid-May and early June, and is associated with snowmelt and spring rainfall. The mean annual runoff from the upper part of the Tenderfoot Creek watershed is approximately 30.0 cm. Mean daily temperatures at the Onion Park SNOTEL site range from –8.4 °C in December to 12.8 °C in July.

Lodgepole pine (*Pinus contorta*) is the dominant tree species in each of the four subalpine fir habitat types found at TCEF (Farnes et al., 1995). Other species include subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*), whitebark pine (*Pinus albicaulis*) and quaking aspen (*Populus tremuloides*).

METHODS

Silvicultural Treatments

The silvicultural treatments used in this study were conducted in 1999 and 2000 in the 346 ha Sun Creek subwatershed of Tenderfoot Creek (Figure 1). Two treatments – even thinning (SE) and group retention thinning (SG) – were conducted. In both treatments, approximately 60 % of the basal area was harvested using ground-based felling and yarding methods. The treatment units were located on both east and west aspects and at elevations ranging from 2168 to 2261 m (Table 1 and Figure 1). In the SE treatment, seed tree retention was evenly distributed across the cutting unit. This treatment replicated the effect of a mixed severity wildfire, where many of the mature trees would survive the fire. The SG treatment consisted of an irregular mosaic of uncut 1-2 ha groups of trees, and intervening corridors where all of the trees were removed. This treatment replicated the effect of stand-replacing wildfire where all of the trees would be killed in some areas while other areas would remain largely unburned. The long-term goal of both treatments is to create a two-aged stand structure that is robust to disturbance events such as wildfire, disease and insect infestation.

Table 1. Area, mean aspect, minimum, maximum and mean elevation and mean slope of the even thinning and group retention thinning treatments and the control.

Treatment	Area (ha)	Mean aspect	Elevation (m) Min.	Elevation (m) Max.	Elevation (m) Mean	Mean Slope (%)
Even thinning – east aspect	32	75	2,191	2,259	2,229	9
Even thinning – west aspect	12	297	2,198	2,260	2,230	11
Group retention thinning – east aspect	25	64	2,168	2,234	2,200	12
Group retention thinning – west aspect	32	290	2,176	2,261	2,221	13
Control	13	216	2,175	2,265	2,237	9

Snowpack Measurements

Field measurements of the snowpack were obtained in mid-April 2003 and late March 2004. The measurement periods were scheduled to coincide as closely as possible with the peak snowpack accumulation in the study area. Measurements were conducted in the SE and SG treatments and a comparable 13 ha control plot on the eastern side of the Sun Creek watershed (Figure 1). Sampling locations were selected by delineating a systematic 55 m orthogonal grid of points within each of the treatments and the control using ArcGIS. A 30 m (~2 tree height) buffer was defined around the perimeter of each unit to reduce edge effects. In 2003, the number of sampling points ranged from 45 in the control to 123 in the SG treatment for a total of 270 points. In 2004, there were 21 additional points in the SG treatment, and five fewer in the control, for a total of 286 points. Sample locations were identified in the field using a Geographic Positioning System and a tape and compass, and then marked using plastic wands. In the group retention plots, the position of each sampling point relative to the edge of a group was defined as either inside (SG-I), outside (SG-O), or within 5 m of the edge of a group (SG-IE or SG-OE) to facilitate spatial analysis of snow accumulation patterns. At each location, the snow depth and snow water equivalent (SWE) were measured at three points within 2 m of the marker wand using a Federal snow sampler, and the mean of the three values was recorded.

Ancillary Data

Snowpack data from the Stringer Creek and Onion Park SNOTEL sites were used to determine the magnitude of the 2003 and 2004 snowpacks relative to the mean. The Stringer Creek site, which lies at an elevation of 1997 m and is thus representative of lower elevations in TCEF, was established in 1996. The Onion Park site is at an elevation of 2258 m, close to the mean elevation of the experimental forest, and has snowpack data since 1994.

Data Analysis

Analysis of variance (ANOVA) was used to test for differences among snow depth and snow water equivalent values in the two treatments and the control within each year. Linear contrasts (Ott, 1993) were used to determine which treatments were significantly different, and the Bonferroni adjustment was used to control the experiment-wise error rate at an alpha level of 0.05 (Ott, 1993). Independent sample t-tests were used to test for differences between the two study years in the mean snow depth and SWE values for the two treatments and the control.

RESULTS

Snowfall in Study Area in 2003 and 2004

Winter precipitation at TCEF in both 2003 and 2004 was very close to the long-term mean. In 2003, the peak snow water equivalents (SWE_{max}) at the Stringer Creek and Onion Park SNOTEL sites were 28.2 cm and 36.8 cm respectively, compared to their respective means of 28.2 cm and 37.5 cm (Figure 2). The 2004 SWE_{max} values at these two sites were also close to the mean, at 28.4 cm and 36.1 cm, respectively. The timing of the start of snowmelt differed considerably between the two years. In 2003, the main snowmelt period at the Stringer Creek SNOTEL site began in early April, whereas in 2004 snowmelt began 3 weeks earlier, in mid-March. Snowmelt rates in both years were similar, so there was approximately a 3-week difference in the timing of the end of snowmelt. The difference in the timing of the start of melt was even greater at the Onion Park site, where snowmelt began in late May in 2003 and in mid-March in 2004. However, the 2004 snowmelt rate at Onion Park was lower than in 2003, and there were several late season storms. Consequently, the snowpack at this site did not completely melt until early June, much the same as in 2003.

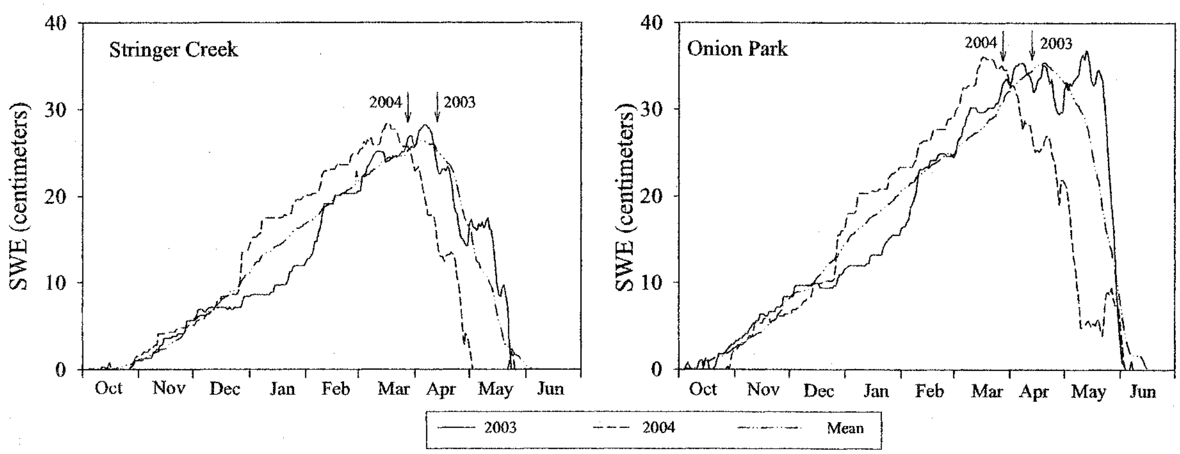


Figure 2. Snow water equivalent (SWE) at Stringer Creek and Onion Park SNOTEL sites in 2003 and 2004 and mean SWE for period of record. Arrows indicate start of 3-day field measurement periods in 2003 and 2004.

The SWE values at the Onion Park SNOTEL site during the two sampling periods (12-14 April 2003 and 27-29 March 2004) were within 10 % of the SWE_{max} in both years (Figure 2). However, the corresponding SWE values at the lower elevation Stringer Creek SNOTEL site were 16 % and 11 % less than the respective SWE_{max} values. In 2003, there was almost 5.0 cm of snowmelt at Stringer Creek in the 5 days between the peak snow accumulation and the start of sampling. In 2004, the time between the peak snow accumulation at Stringer Creek and the start of sampling was 9 days, but there was less than 3.0 cm of melt. Snowmelt at the two SNOTEL sites during the 3-day sampling periods ranged from less than 0.5 cm at Onion Park in 2004 to 2.3 cm at Stringer Creek in 2003.

Snow Accumulation in Treatments

Differences among treatments and between years followed similar patterns for both snow depth and SWE, so only the SWE data are described here. There was no significant difference in SWE between the east and west aspects of either treatment in either year. Therefore, data from the east and west aspects were combined for analysis. In both years, the highest mean snow water equivalent (SWE_{mean}) was in the SE treatment, where the values were 35 % and 20 % higher than the control in 2003 and 2004, respectively (Figure 3 and Table 2). In both years, the difference in SWE_{mean} between the SE treatment and the control was significant (P<0.0001). In contrast, the SWE_{mean} in the SG treatment was within 4 % of the control value in both years, and neither of the differences between treatment and control was significant. The 2004 SWE_{mean} values in both treatments and the control were 22 to 37 % higher than the 2003 values, and all of the differences were significant (P<0.0001).

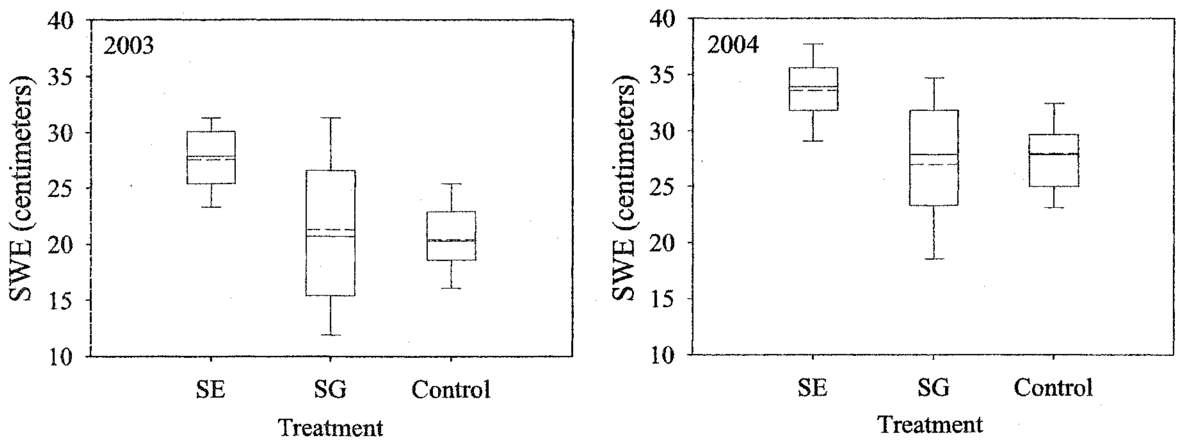
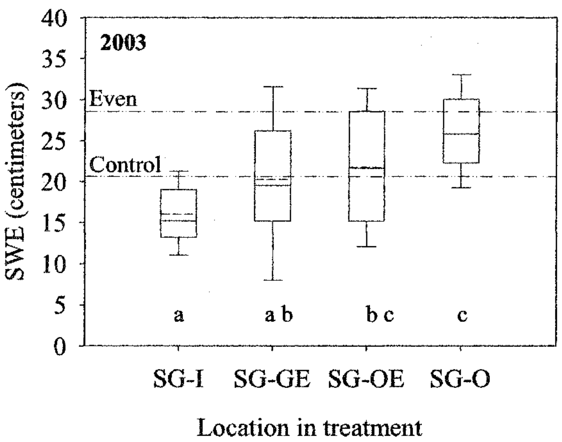


Figure 3. Snow water equivalent in even thinning (SE) and group retention thinning (SG) treatments and control in 2003 and 2004. Solid and dashed lines in boxes indicate median and mean, respectively. Box ends indicate 25th and 75th percentiles. Whiskers indicate 10th and 90th percentiles.

The spatial variability of the SWE measurements in the SE treatment, as indicated by the coefficient of variation (CV), was similar each year, and was slightly lower than in the control in both years (Table 2). In contrast, the SG treatment had SWE values that were 1.5 to 2 times more variable than the control and up to 3 times more variable than in the SE treatment. Much of this increased variability was due to the contrast in snow accumulation between sampling locations inside a group (SG-I) compared to those in the openings between groups (SG-O). The mean of the SWE values in the SG-I sites were 26 % and 25 % less than in the SG-O sites in 2003 and 2004, respectively, and both differences were significant (P < 0.006) (Figure 4). Sites within 5 m of the edge of a group (SG-IE and SG-OE) had mean SWE values that were between those for the SG-I and SG-O locations. In both years, the mean SWE in the SG-I sites was less than the control, and the SG-O sites had a mean that was less than the SWE_{mean} for the SE treatment.

Table 2. Mean and standard deviation, coefficient of variation (CV), minimum and maximum values of snow water equivalent and number of samples (N) in treatment and control sites in 2003 and 2004.

	2003 SWE (cm)			**2004 SWE (cm)**		
Treatment	**SE**	**SG**	**Control**	**SE**	**SG**	**Control**
Mean	27.6	21.3	20.4	33.6	27.0	28.0
Std Dev	3.1	7.1	3.5	3.9	6.3	4.7
CV (%)	11	33	17	12	23	17
Min	19.5	3.8	12.7	15.2	5.1	18.6
Max	36.0	34.7	27.9	43.2	41.5	47.4
N	102	123	45	102	144	40



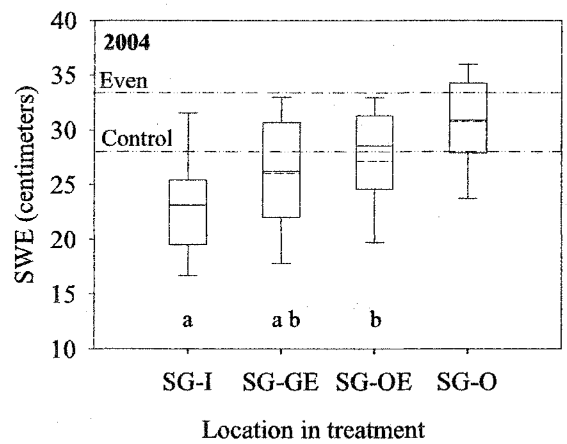


Figure 4. Snow water equivalent in SG treatment inside groups (SG-I), at inside edge of groups (SG-GE), at outside edge of groups (SG-OE) and outside groups (SG-O) in 2003 and 2004. Solid and dashed lines in boxes indicate median and mean, respectively. Box ends indicate 25th and 75th percentiles. Whiskers indicate 10th and 90th percentiles. Dot-dot-dash lines indicate mean SWE in even thinning treatment and control. Treatments with same letter (a, b etc.) have means that are not significantly different at $P = 0.05$.

DISCUSSION

Studies of the hydrologic effects of clearcutting have shown that the effect on snow accumulation depends on the spatial arrangement of harvest units, and particularly the size of individual openings in the canopy (Golding and Swanson, 1978; Troendle and Leaf, 1980; Troendle and King, 1985). The results of our study demonstrate that the effect of thinning on snow accumulation also depends on the spatial arrangement of the treatments. Both of the thinning treatments used in this study involved the removal of approximately 60 % of the stand basal area. However, in the even thinning treatment, tree removal was conducted evenly across the stand, leaving seed trees spaced 5 to 10 m apart. In the group retention treatment, the thinning operation involved removal of all the trees in some areas, while 1 to 2 ha groups of trees were left intact elsewhere. The even thinning treatment resulted in an increase of up to 35 % in the mean snow water equivalent relative to the control, while the group retention thinning treatment had no significant effect on the magnitude of snow accumulation when measured at the stand scale. We attribute this to differences in the way that the spatial arrangement of the two thinning treatments affected canopy interception, wind scour and evaporation from the snowpack.

Canopy interception is a primary control on snow accumulation in forested watersheds. Consequently, snow water equivalent is inversely proportional to the canopy density (Harestad and Bunnell, 1981; Gary and Troendle, 1982; Moore and McCaughey, 1997; Winkler, 2001; Teti, 2003), and partial removal of the canopy by thinning results in an increase in SWE (Gary and Watkins, 1985; Troendle and King, 1987). The 56 to 72 mm (21 to 35 %) increase in SWE in our even thinning (SE) treatment is very similar to results reported from a doghair Lodgepole pine stand in Wyoming, where SWE increased by 53 mm (30 %) after thinning (Gary and Watkins, 1985). The results are also comparable to those reported for a 41 ha shelterwood cut in Colorado, where a 40 % reduction in basal area resulted in a 48 mm increase in SWE (Troendle and King, 1987). Although the magnitude of the increase at our study site is greater than that for the Colorado site, it is in proportion to the 20 % greater reduction in basal area.

The lack of a significant treatment effect in the SG treatment is probably due to greater exposure to wind scour, resulting in losses that offset gains due to decreased interception. Two lines of evidence support this conclusion. First, the mean SWE in the openings was less than that for the evenly thinned treatment, despite the greater reduction in interception. Second, we observed bare areas on the windward side of ridge crests and wind-formed ripples on the snow surface in the openings between groups whereas these features were not observed in the control stand. Bare areas and ripples were particularly evident in openings that were oriented parallel to the prevailing wind. The effect of reduced snow accumulation in the openings in the SG treatment is similar to that observed in large (> 20 tree height) clearcuts in windy areas, which tend to accumulate less snow than adjacent uncut areas despite the reduced interception (Troendle and Leaf, 1980). In the group retention thinning treatment used in this study, wind scouring may have been accentuated by the corridor-like structure of the openings, resulting in a funneling effect on wind blowing through the treatment. An additional factor contributing to the reduced snow accumulation in the clearings in the SG treatment may have been that most of the slash was removed after logging. Snow accumulation in large openings is generally greater if the surface roughness is increased by slash retention (Pomeroy et al., 1997).

Wind scouring losses may also explain the lower snow accumulation inside groups compared to the control. The groups are all less than 2 ha in area, so the maximum distance from the edge of a unit to the interior is approximately 80 m. However, wind effects can extend up to 240 m from clearings into the adjacent forest in fragmented forest landscapes (Chen et al., 1995). Redistribution of windblown snow from the forest can supplement gains in SWE in adjacent clearings in areas where patch clearcutting was used as the silvicultural prescription (Schmidt and Troendle, 1989; Stegman, 1996). In contrast, in the SG treatment used in this study, redistributed snow from the forest may have been blown out of the clearings, so that it did not contribute to the total SWE.

The higher spatial variability of SWE values in the SG treatment is primarily due to the contrast in snow accumulation between sites in openings and within the groups of uncut trees (Figure 4). However, sites located close to the edge of clearings (SG-GE and SG-OE on Figure 4) had higher variability in SWE than sites either fully inside or fully outside the groups, and we observed clear differences in snow depth between sites on the north and south sides of the groups. These results and observations suggest that drifting on the windward side and shading of the snowpack on the north side of groups may contribute to the higher variability in SWE in the SG treatment. Differential melting around the edges of the groups may also explain the higher variability in the SWE of the SG-GE and SG-OE sites in 2003, which had more melting prior to the measurement period than 2004. The higher spatial variability in snow accumulation in the SG treatment, together with different rates of melting in under-canopy and open areas during the melt phase, will likely result in more prolonged snowmelt in this treatment as compared to the SE treatment.

Three critical assumptions were made in our interpretation of the study results. First, we assumed that spatial differences in canopy interception were insignificant prior to treatment. Since the treatment watershed has never been logged, the main influence on canopy density and hence on canopy interception is natural disturbance by fire. Fire history data for the Tenderfoot Creek Experimental Forest indicates that most of the treatment and control units last burned 130 years ago, although about 30 % of the SG treatment is in a stand that burned 239 years ago (Barrett, 1993). Moore and McCaughey (1997) reported only a 10 to 20 mm difference in April SWE between a 123-year-old and a 270-year-old Lodgepole pine stand at TCEF, suggesting that pre-treatment differences in canopy interception in our study site were minimal.

The second assumption was that SWE losses due to snowmelt prior to the measurement period were insignificant. Differences in snow accumulation between forest harvest treatments may be confounded by differential snowmelt rates prior to measurement (Lundberg and Koivusalo, 2003). Although there was more melting of the snowpack prior to the measurement period in 2003 compared to 2004, a greater treatment effect was observed in the SE treatment in 2003. Since melting occurs earlier and more rapidly in open areas compared to sites under a closed canopy (Pomeroy and Granger, 1997), this indicates that pre-measurement melting did not affect the outcome of the study. In fact, the contrast between the SE treatment and the control in 2003 was probably even greater at the time of peak snow accumulation than at the time of measurement.

The last assumption was that differences between treatments due to aspect, elevation, and topography were minimal. The maximum contrast in snow accumulation due to aspect effects is typically between north and south facing slopes. However, the treatments and the control lie primarily on east and west facing slopes, and there was no significant difference in SWE within treatments for sites located on these two aspects. Therefore, differences in SWE between treatments due to aspect are expected to be minimal. The winter precipitation lapse rate in the study area, based on the peak SWE values at the Stringer Creek and Onion Park SNOTEL sites is 3.6 cm / 100 m. Mean elevations in the SE treatment and control are 2211 and 2237 m, respectively, so the contrast in SWE that can be attributed to the elevation differences is 0.9 cm. Since the minimum treatment effect was an additional 5.6 cm of SWE in the SE treatment, differences in elevation do not explain the observed contrast in SWE. Topographic effects in the study area are also expected to be insignificant because of the limited relief within the treatments and the absence of prominent ridgelines or depressions, which accumulate less and more snow than flat areas, respectively (Lundberg and Koivusalo, 2003).

CONCLUSIONS

Forest harvest has been proposed as a means of increasing water yield from forested watersheds in drought prone areas such as the western U.S. while also reducing wildfire hazard. However, such proposals are controversial because of the potential aesthetic and environmental impacts when clearcutting is used as the primary silvicultural prescription. Thinning treatments offer a potentially more acceptable means of increasing water yields and reducing wildfire hazard while also restoring the ecological structure and function of forested areas. The results of this study demonstrate that thinning can have substantially different effects on snow accumulation depending on the spatial arrangement of the treatments. If forest harvest is to be conducted with a view to maximizing water yield, then the even thinning treatment is the most appropriate because of the significant increase in snow accumulation. In some cases it may be more desirable to minimize the hydrological effects of harvesting, in which case the group retention treatment is more appropriate because of its limited effect on total snow accumulation and, presumably, water yield.

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