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Snow accumulation in thinned lodgepole pine stands, Montana, USA

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Abstract

Alternative silvicultural treatments such as thinning can be used to restore forested watersheds and reduce wildfire hazards, but the hydrologic effects of these treatments are not well defined. We evaluated the effect of two shelterwood-with-reserve silvicultural prescriptions, one leaving residual trees evenly distributed (SE) and the second leaving residual trees in groups (SG), both with ~50% basal area removal, on snow accumulation in lodgepole pine stands at the Tenderfoot Creek Experimental Forest, west-central Montana. 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 2003, 2004 and 2005. Reduced interception in SE resulted in significant ($P < 0.0001$) 7.2 and 5.6 cm increases in SWE relative to the control in 2003 and 2004, respectively, and a 1.7 cm increase in 2005. Predictive models for the mean peak SWE in the control and the SE treatment were based on an inverse-exponential relationship between interception efficiency and mean storm intensity, and the average percent deviation for the two models was 9.4 and 7.6%, respectively. In the SG treatment, increased solar radiation and wind resulted in sublimation losses that offset gains due to reduced interception in the openings between groups. Consequently, SG always accumulated significantly less snow than SE ($P < 0.0001$), and the SG treatment and control means were not significantly different. Differences in snow accumulation between groups and openings and between the north and south sides of groups meant that the SWE in SG was up to three times more variable than in either SE or the control. The contrasting responses in the SE and SG treatments demonstrate that thinning can have substantially different effects on snow accumulation depending on the spatial arrangement of tree removal.

Keywords: Forest hydrology; Snow accumulation; Interception; Thinning

1. Introduction

Snowmelt runoff from high elevation forested watersheds is the primary water source for much of western North America. Snow accumulation in these watersheds varies with climate, elevation, topography and canopy structure characteristics (Pomeroy et al., 2002). Canopy structure is an especially important control on snow accumulation because of its effect on the interception component of the water budget and the wind speed and solar radiation flux at the snow surface (Harestad and Bunnell, 1981; Marks et al., 1998; Lundberg and Koivusalo, 2003). Tree removal during forest harvest or fuel reduction efforts may increase or decrease snow accumulation depending on the relative magnitude of gains due to the reduced canopy interception and losses due to increased wind scour and sublimation (Golding and Swanson, 1986; Stegman, 1996; Winkler et al., 2005).

In windy environments such as the high-elevation forests of the central and northern Rocky Mountains of western North America, snow accumulation varies with the size of the individual cutting units (Pomeroy et al., 2002; MacDonald and Stednick, 2003). Small (2–5 tree height diameter) clearcuts accumulate the most snow because the exposure to wind is minimized (Troendle and Leaf, 1980; Troendle and King, 1985; Swanson, 1988). Similarly, evenly distributed thinning over small areas results in a net increase in snow accumulation (Troendle and King, 1987). In contrast, large clearings in wind-swept areas may accumulate less snow than the surrounding forest (Troendle and Leaf, 1980). In less windy environments, opening size is less important and factors such as the amount of slash retention play a greater role in determining snow accumulation (Pomeroy et al., 1997).

Natural disturbance events such as wildfire and disease also affect snow accumulation by creating openings in the canopy

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(Helvey, 1980). 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 and western Canada. 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, particularly since the treatments must be repeated periodically to maintain any increase in water yield. Alternative silvicultural prescriptions such as thinning offer a potentially more acceptable means of maintaining water yield and reducing fuel loads while also restoring forests to a more natural state by simulating natural disturbance processes. In order that forests can be managed in a holistic and ecologically sustainable manner, information is needed on the effects of thinning on both the magnitude and spatial variability of snow cover. The former controls the amount of available runoff while the latter is a major factor in the timing of runoff contributions from different areas. However, relatively few studies have focused on the hydrologic effects of thinning treatments as compared to the wider literature on the effects of clearcutting.

Seral, fire-dependent lodgepole pine (*Pinus contorta*) 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). Fire suppression has altered the structure of these forests by allowing in-growth of competing species such as subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*). The United States Department of Agriculture, Forest Service, Rocky Mountain Research Station 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. As part of these investigations, we evaluated the effect of two shelterwood-with-reserve prescriptions, one leaving residual trees evenly distributed and the other leaving residual trees in groups, on snow accumulation in lodgepole pine stands on the Tenderfoot Creek Experimental Forest in west-central Montana. The objectives were to: (1) determine the effect of the two treatments on the magnitude of winter snow accumulation and

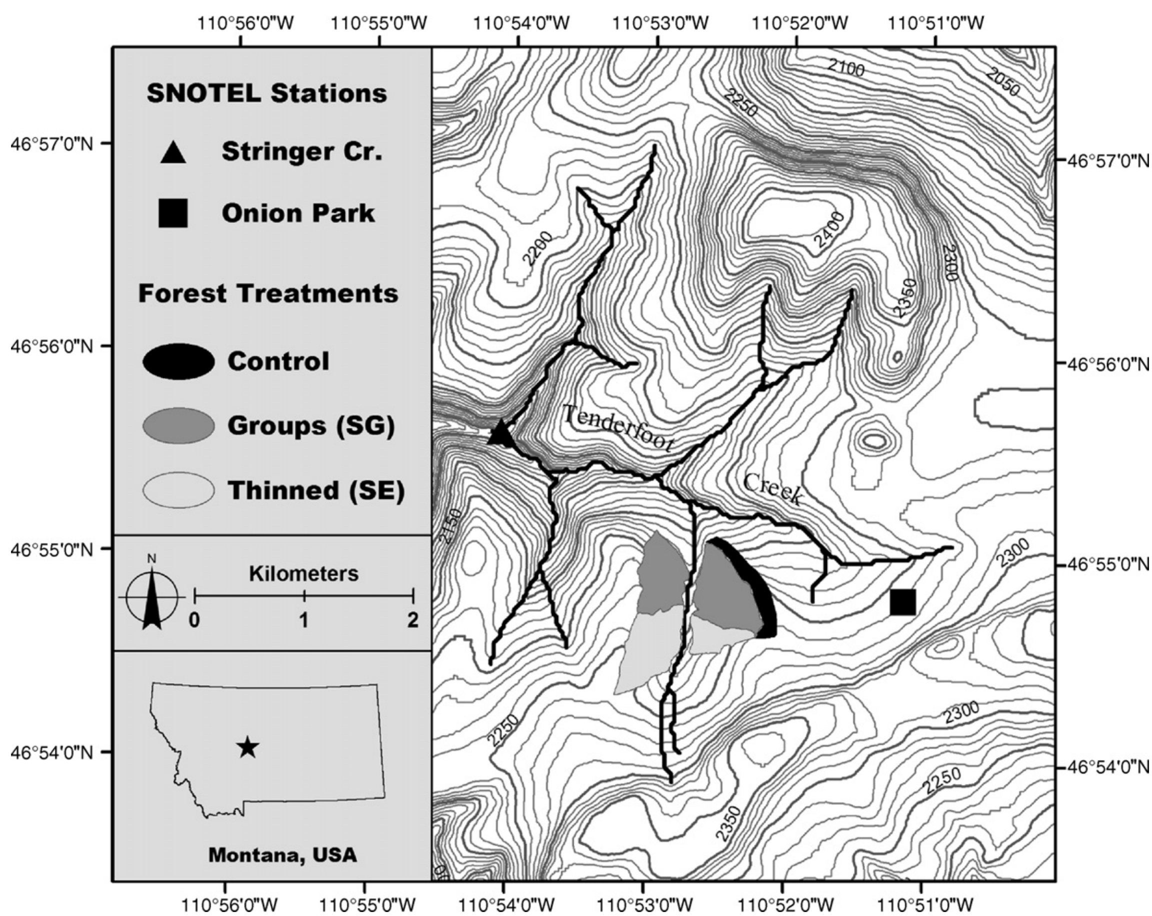

Fig. 1. Location of study sites at Tenderfoot Creek Experimental Forest in west-central Montana. Main map shows location of treatments in the Sun Creek subwatershed, and the Onion Park and Stringer Creek SNOTEL stations. Contour interval is 10 m.

(2) understand how the treatments affect the spatial distribution of snow accumulation at the stand scale. The results of this study will be of value to hydrologists concerned with modelling of snow accumulation processes in forested watersheds and determining the hydrologic effects of both forest management and natural disturbance events.

2. 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 (Fig. 1). Elevations in the experimental forest range from 1838 to 2421 m with a mean of 2205 m. Glaciation and subsequent fluvial erosion has produced a landscape in which broad, rounded ridgelines separate steep-sided stream valleys with frequent rock outcrops and talus slopes. Lodgepole pine 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, Engelmann spruce, whitebark pine (*Pinus albicaulis*), Douglas-fir (*Pseudotsuga menziesii*) and quaking aspen (*Populus tremuloides*). Tree height averages 15 m, and leaf area index (LAI) values range from 2.8 to 3.2.

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 and 2258 m), both located within TCEF, are 28.2 and 37.6 cm, respectively (Fig. 1). On average, snowfall comprises 40 and 47% of the annual precipitation at Stringer Creek and Onion Park, 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. Winds are typically out of the west. Mean daily temperatures at the Onion Park SNOTEL site range from minus 8.4 °C in December to 12.8 °C in July.

3. Materials and methods

3.1. Silvicultural treatments

Two silvicultural treatments were installed in 1999 and 2000 in the 346 ha Sun Creek subwatershed of Tenderfoot Creek (Fig. 1). The treatments were shelterwood-with-reserve prescriptions with ~50% basal area removal, and followed procedures for structural retention harvest outlined by Forest Ecosystem Management Assessment Team (1993) and Franklin et al. (1997). In the first treatment (SE), the residual trees were evenly distributed, and in the second (SG) the residual trees were in 0.2–0.8 ha groups with intervening corridors where all of the trees were removed. Ground-based felling and yarding methods were used for both treatments. The treatment units were located on both east and west aspects and at elevations ranging from 2168 to 2261 m (Table 1 and Fig. 1). The SE treatment replicated the effect of a low-intensity mixed-severity wildfire, where many of the mature trees survived the fire. The SG treatment emulated the effect of stand-replacing wildfire where all trees were killed in swaths or corridors while groups remained largely unburned. The long-term goal of both treatments is to create two-aged stand structures that are robust to disturbance events such as wildfire, disease and insect infestation (Forest Ecosystem Management Assessment Team, 1993).

3.2. Snowpack measurements

Field measurements of the snowpack were obtained in mid-April 2003, late March 2004 and mid-March 2005. The measurement periods were scheduled to coincide with the peak of the snowpack accumulation in the study area. Measurements were conducted in the SE and SG treatments and a comparable 13 ha control area on the eastern side of the Sun Creek watershed (Fig. 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 thinned stand and the control stand to reduce edge effects. The number of sampling points ranged from 270 in 2003 to 286 in 2004 because of modifications to the sampling grid between years. Sample locations were identified in the field using a Geographic Positioning System (GPS) 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.

Table 1
Area, mean aspect, minimum, maximum and mean elevation, and mean slope of the even and group retention shelterwood-with-reserve treatments and the control

Treatment	Area (ha)	Mean aspect (°)	Elevation (m)			Mean slope (%)
			Minimum	Maximum	Mean	
Even thinning—east aspect	32	75	2191	2259	2229	9
Even thinning—west aspect	12	297	2198	2260	2230	11
Group retention thinning—east aspect	25	64	2168	2234	2200	12
Group retention thinning—west aspect	32	290	2176	2261	2221	13
Control	13	216	2175	2265	2237	9

Field observations in 2003 and 2004 indicated that the snowpack depth and snow water equivalent varied within the SG treatment depending on the location relative to the edge of the retention groups. To investigate the effect of position within the treatment, snow depth measurements were collected at 5 m intervals along north-south and east-west transects extending across nineteen of the retention groups in 2005. Transects started in openings between groups and extended through the center of a group and into the opening on the other side.

3.3. Ancillary data

Snowpack data from the Onion Park SNOTEL site were used to determine the magnitude of the 2003, 2004 and 2005 snowpacks relative to the mean. 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.

Descriptive data for each of the sampling locations within the treatments and the control were obtained to determine which site factors control snow accumulation. Site location and elevation was obtained using a GPS and slope and aspect were measured with a clinometer and compass, respectively. The surface roughness was rated on a categorical scale of 0–4, with higher values indicating the presence of more roughness elements such as vegetation and slash. The percent open canopy and the effective leaf area index at each of the snow measurement locations were calculated from hemispherical photographs taken with a Fuji Finepix digital camera equipped with a fisheye lens and processed using the Gap Light Analyzer software (Frazer et al., 1999).

3.4. Data analysis

Analysis of variance (ANOVA) was used to test for differences in the snow depth and snow water equivalent values between the two treatments and the control within and between years. Linear contrasts 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 (Dunn, 1961).

Predictive models for snow accumulation in the SE treatment and the control were developed by applying a canopy interception function to the observed snow accumulation in the open at the Onion Park SNOTEL site during each storm. Canopy interception rates in conifer forests may be constant (McNay et al., 1988) but more commonly they decrease at varying rates with increasing snowfall (Harestad and Bunnell, 1981; Calder, 1990; Hedstrom and Pomeroy, 1998; Pomeroy et al., 1998). Both constant canopy interception rates and rates that declined as both inverse linear and inverse exponential functions of total storm snowfall and mean storm intensity (cm SWE day^{-1}) were evaluated. A storm was defined as a period of one or more consecutive days when snowfall was recorded at the Onion Park SNOTEL site, and storm intensity was the mean of the daily snow water equivalent totals during the storm.

The model-predicted snowfall totals in the control and the SE treatment for each storm were summed over the period prior to sampling in 2003, 2004 and 2005 and compared to the observed mean snow water equivalents. Model fit was evaluated using the average percent deviation statistic (Martinec and Rango, 1989).

A least squares stepwise multiple regression procedure was used to develop a predictive model for the 3-year mean SWE at each site in the treatments and the control. The independent variables in the model were the percent open canopy, the effective leaf area index, slope, aspect, elevation and surface roughness. Pearson and Spearman rank correlation matrices were used prior to regression modelling to test for multicollinearity among the independent variables. If two independent variables were correlated, the variable that had the lowest linear relationship with SWE was removed from the analysis.

4. Results

4.1. Snowfall during the study period

Snow accumulation at TCEF was close to average during the 3-year study period. The peak snow water equivalent at the Onion Park SNOTEL site was within 1.5 cm of the mean of 37.6 cm in all 3 years (Fig. 2), and averaged 84% of the total snowfall. Sampling of the snowpack in 2003 took place almost a month before the peak snowpack, but the SWE at Onion Park was less than 3 cm below the SWE_{max} of 36.8 cm (Fig. 2). In 2004, the snowpack sampling was conducted 9 days after the peak, when the SWE at Onion Park had decreased 1.3 cm from the SWE_{max} of 36.1 cm. In 2005, the snowpack sampling was conducted approximately 1 month prior to the peak snow accumulation at the Onion Park site, and there was considerable late season snowfall. Consequently, the SWE during the 3-day sampling period (18–20 March 2005) was 9.4 cm less than the SWE_{max} of 38.6 cm.

4.2. Snow accumulation in treatment and control plots

Differences among the treatments and control plots, within and between years, followed similar patterns for both SWE and snow depth. The highest snow accumulation values in the

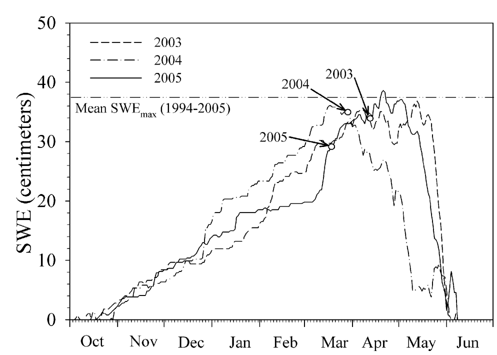

Fig. 2. Snow water equivalent (SWE) at the Onion Park SNOTEL site in 2003, 2004 and 2005. Labeled circles indicate the start of each 3-day measurement period in each year.

Table 2
Snow water equivalent (cm) at the Onion Park SNOTEL site and in the treatments and the control at the time of sampling in 2003, 2004 and 2005

	2003 (34.0[a])			2004 (34.8[a])			2005 (29.2[a])			Average (32.7[a])		
	SE[b]	SG[b]	Control[b]	SE	SG	Control	SE	SG	Control	SE	SG	Control
Mean	27.6	21.3	20.4	33.6	27.0	28.0	20.1	17.8	18.4	27.1	22.0	22.3
Standard deviation	3.1	7.1	3.5	3.9	6.3	4.7	3.0	5.4	2.9	3.3	6.3	3.7
CV (%)	11	33	17	12	23	17	15	30	16	13	29	17
Minimum	19.5	3.8	12.7	15.2	5.1	18.6	11	5.9	11	15.2	4.9	14.1
Maximum	36.0	34.7	27.9	43.2	41.5	47.4	27.9	30.5	23.7	35.7	35.6	33.0
N	102	123	45	102	144	40	99	142	40	101	136	42

Values for the treatments and control are the mean of all sample locations, along with the standard deviation, coefficient of variation (CV), minimum and maximum values and number of samples (*N*).
[a] Onion Park.
[b] Treatment.

treatment and control plots were measured in 2004, when the mean snow water equivalent values were 22–37% higher than in 2003 and 52–67% higher than in 2005 (Table 2). Although both 2003 and 2004 had similar snow accumulation at Onion Park, there was almost 8 cm more snow water equivalent in the control plot in 2004, which had a similar number of storms to 2003 but more days with heavy snowfall.

There was no significant difference in SWE between the east and west aspects of either treatment in any year. Therefore, data from the east and west aspects were combined for analysis. Differences in snow accumulation between the control and the Onion Park SNOTEL site indicated seasonal interception rates of between 20 and 40% for the intact canopy (Table 2). In all 3 years, the highest mean snow water equivalent was in the SE treatment, where the values were 7.2, 5.6 and 1.7 cm higher than the control in 2003, 2004 and 2005, respectively (Fig. 3 and Table 2). The difference in SWE_{mean} between the SE treatment and the control was statistically significant in both 2003 and 2004 ($P < 0.0001$), but not in 2005. The SWE_{mean} in the SE treatment was significantly greater than the SG treatment in all 3 years ($P < 0.0001$). In contrast, the SG treatment mean was within 1.0 cm of the control value in all 3 years, and none of the differences in SWE_{mean} between the SG treatment and the control was significant.

The 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 (Table 2). In contrast, the SG treatment had SWE values that were 1.5–2 times more variable than the control and up to three times more variable than in the SE treatment. Part of this variability was due to a strong contrast in snow accumulation between sampling locations inside a group (SG-I) compared to those in the openings between groups (SG-O). The SWE_{mean} in the SG-I sites was 26, 25 and 35% less than in the SG-O sites in 2003, 2004 and 2005, respectively, and all of the differences were significant ($P < 0.006$) (Fig. 4). The SG-I SWE_{mean} was also significantly less than that in the control in all 3 years, and the SG-O sites had a SWE_{mean} that was significantly less than in the SE treatment. Sites within 5 m of the edge of a group (SG-IE and SG-OE) had mean SWE values that were intermediate between those for the SG-I and SG-O locations (Fig. 4).

The data from the snow depth transects conducted in the SG treatment in 2005 also showed a strong contrast between snow depths in the groups and in the openings (Fig. 5). The mean snow depth for transect locations in the openings (109 cm) was significantly greater than that for locations in the groups (73 cm).

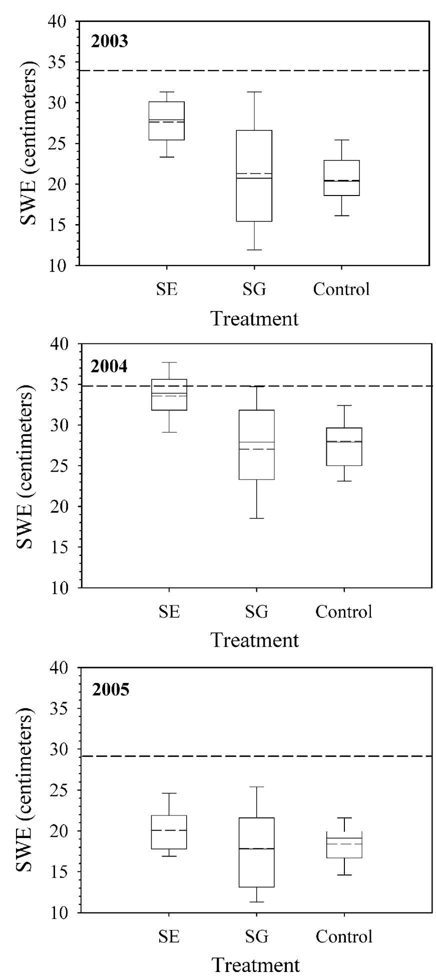

Fig. 3. Snow water equivalent (SWE) in even (SE) and group retention (SG) shelterwood-with-reserve treatments and control in 2003, 2004 and 2005. Solid and dashed lines in boxes indicate median and mean, respectively. Box ends indicate 25th and 75th percentiles. Whiskers indicate 10th and 90th percentiles. Horizontal dashed lines indicate the SWE at the Onion Park SNOTEL site at the start of the sampling period.

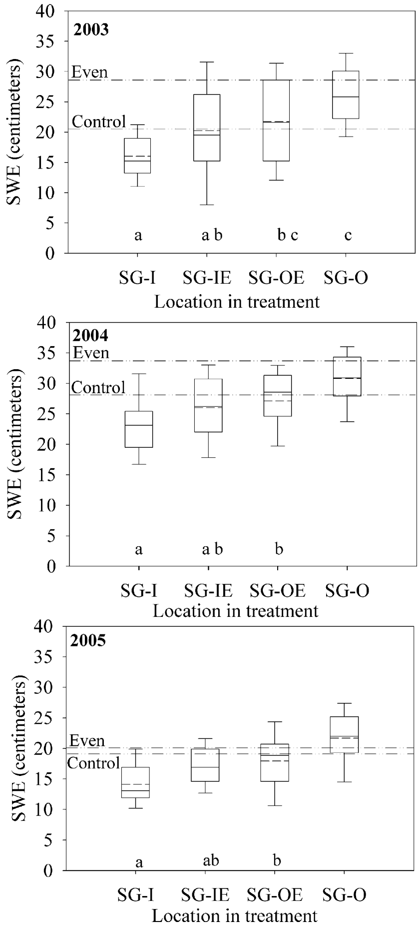

Fig. 4. Snow water equivalent in shelterwood-with-reserve group treatment inside groups (SG-I), at inside edge of groups (SG-IE), at outside edge of groups (SG-OE) and outside groups (SG-O) in 2003, 2004 and 2005. Solid and dashed lines in boxes indicate median and mean, respectively. Box ends indicate 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 $P = 0.05$.

Snow accumulation within the SG treatment varied with distance from the edge of a group, both inside the groups and in the openings, and this resulted in even greater overall spatial variability. The snow depths measured along the transects within the groups decreased with distance between the north and south facing edges, so that snow depth on the southern edge of groups was less than half that measured on the northern edge (Fig. 5). Similarly, the mean snow depth in the openings within 30 m of the south side of groups (108 cm) was significantly less than that in the openings within 30 m of the north side of a group (116 cm) ($P < 0.0001$). There were no comparable trends in snow depth, either in the groups or in the openings, along the west to east transects.

4.3. Interception models

The best models for predicting the cumulative snow accumulation prior to sampling in each year were obtained when the interception rates in the control (I_{con}, %) and SE treatment (I_{SE}, %) were calculated as inverse exponential functions of mean storm intensity (S, cm SWE day^{-1}):

$$I_{con} = 13.46 + 158e^{(-3.5S)} \quad (1)$$

$$I_{SE} = 10.25 + 120e^{(-3.5S)} \quad (2)$$

Eq. (1) predicts that the interception rate in the control stand decreases from more than 70% for mean storm intensities of less than 0.3 cm SWE day^{-1} to less than 20% for storm intensities of more than 1.0 cm SWE day^{-1}. Eq. (2) predicts that the storm interception rate in the SE treatment is less than in the control, ranging from over 60% for storm intensities of less than 0.25 cm SWE day^{-1} to less than 15% for storm intensities greater than 1.0 cm SWE day^{-1}. When these interception functions were used to predict seasonal snow accumulation totals in the control and the SE treatment, the average percent deviation values for the 3-year study period were 9.4 and 7.5%, respectively (Table 3).

Table 3
Observed and model predicted values for the mean snow water equivalents (cm) in the control and the SE treatment in 2003, 2004 and 2005

Year	Control			SE treatment		
	Observed	Predicted	Difference	Observed	Predicted	Difference
2003	20.4	23.9	+3.5	27.6	27.6	0
2004	28.0	25.5	−2.5	33.6	28.6	−5.0
2005	18.4	18.1	−0.3	20.1	21.2	+1.1
D_v (%)	9.4			7.5		

D_v is the average percent deviation from the observed values.

4.4. Regression analysis

The only significant variable in the stepwise multiple regression analysis of the influence of site factors on the mean SWE at a site was the percent open canopy (CAN):

$$SWE = 11.6 + (0.16 \times CAN) \quad (3)$$

This regression model is statistically significant ($F = 215.1$, $P < 0.0001$), and explains 51% of the variability in SWE among sites in both of the treatments and the control. Effective leaf area index (LAI_{eff}) was dropped from the regression because it was significantly correlated with the percent open canopy ($P < 0.0001$, $r^2 = 0.98$). There was no relationship between the mean SWE and slope, aspect, elevation or surface roughness.

5. Discussion

Previous research on the hydrologic effects of forest management has shown that the effect of complete tree removal on snow accumulation depends on the spatial arrangement and size of the cutting units (Golding and Swanson, 1978; Troendle and Leaf, 1980; Troendle and King, 1985). Similarly, the results of the present study demonstrate

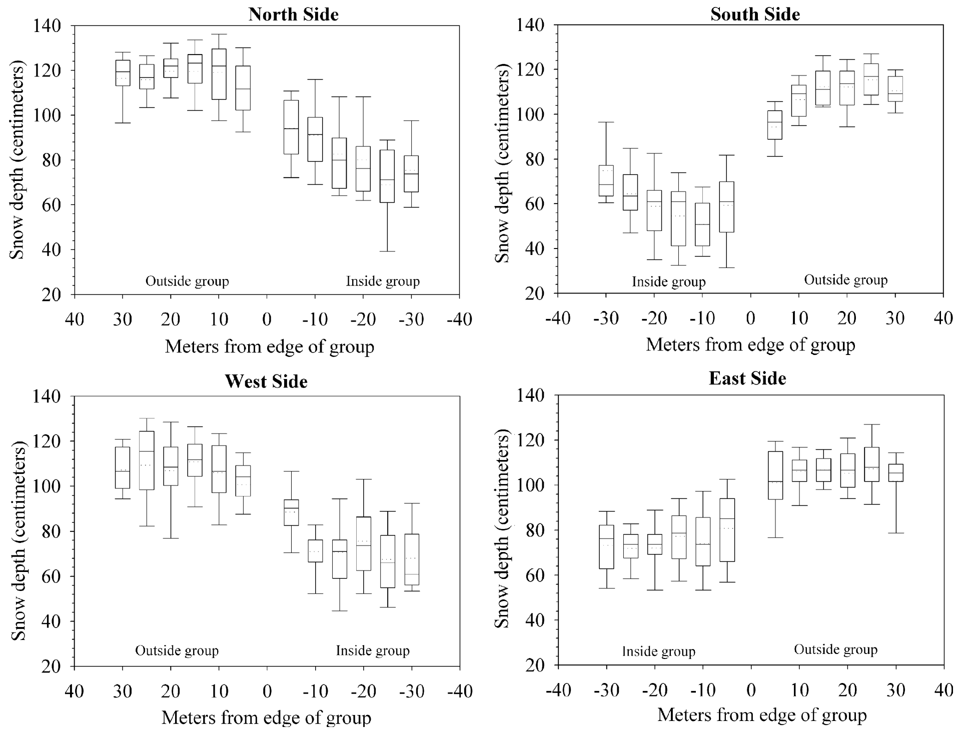

Fig. 5. Snow depth along transects on north, south, west and east sides of 19 retention groups in 2005. Solid and dashed lines in boxes indicate median and mean, respectively. Box ends indicate 25th and 75th percentiles. Whiskers indicate 10th and 90th percentiles.

that the effect of partial tree removal (thinning) on snow accumulation depends on the spatial arrangement of the residual trees within the treatments. Both of the thinning treatments used in this study involved the removal of approximately 50% of the stand basal area. However, in the even distribution treatment, tree removal was conducted evenly across the stand, leaving trees spaced 5–10 m apart. In the group retention treatment, the silvicultural prescription involved the removal of all the trees in some areas with 0.2–0.8 ha groups of trees left intact elsewhere. The SE treatment resulted in an increase of up to 35% in the mean snow water equivalent relative to the control, while the SG 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 and size of the groups affected canopy interception, sublimation and wind scour.

Precipitation and canopy interception are the primary controls on snow accumulation in forested watersheds. Consequently, snow water equivalent during the accumulation phase 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 evenly spaced thinning generally results in an increase in SWE (Haupt, 1979; Gary and Watkins, 1985; Troendle and King, 1987). The increase in SWE in the SE treatment relative to the control, which averaged 4.8 cm (21%) over the 3 years, is identical in magnitude and similar in proportion to the 4.8 cm (16%) increase in SWE observed following a 41 ha shelterwood cut in Colorado that reduced the basal area by 40% (Troendle and King, 1987). The increase is also similar to that reported from a very dense lodgepole pine stand in Wyoming, where the mean SWE increased by 5.3 cm (30%) after thinning (Gary and Watkins, 1985). In both of these studies the increase in SWE was attributed primarily to reduced interception, and a similar conclusion is appropriate for the present study.

The interception functions used to calculate storm-by-storm snow accumulation in the control and the SE treatment (Eqs. (1) and (2)) resulted in a reasonably good fit between the observed and predicted values for the corresponding seasonal snow accumulation totals. The inverse relationship between the interception rate and average storm intensity contained in these models is generally consistent with other snow interception studies (e.g. Strobel, 1978; Harestad and Bunnell, 1981; Calder, 1990; Hedstrom and Pomeroy, 1998). The low interception efficiency for storm intensities of greater than 0.5 cm SWE day^{-1} can be attributed to the sparse canopy cover and widely spaced branches in the high-elevation lodgepole pine forest present in the study area.

Interannual differences in snow accumulation in the control and the SE treatment can be explained in terms of the interception models and differences between years in the storm characteristics. The snow accumulation totals at Onion Park in 2003 and 2004 differed by less than 1 cm, but in 2004 there was 7.6 cm more SWE in the control and an additional 6.0 cm in the SE treatment. The higher snow accumulation below the canopy in 2004 was because more of the snow was delivered on days with high snowfall, when interception captured proportionally less of the total: there were 18 days in 2004 when the snowfall exceeded 0.5 cm SWE compared to just 15 days in 2003.

Based on the interception models (Eqs. (1) and (2)) the three highest daily snowfall totals in 2004 accounted for an additional 6.0 cm of SWE in the SE treatment and the control, respectively. Thus, snow accumulation under a forest canopy can vary considerably between years with similar gross precipitation depending on the distribution of daily snowfall totals.

In 2005, there was less snowfall overall than in 2003 or 2004, and this was the primary reason for the reduced snow accumulation in the treatments and the control. There was also a greater relative difference in snow accumulation in the SE treatment and the control compared to Onion Park, and this was due to a reduced number of days with heavy snowfall. There were just 11 days when the snowfall exceeded 0.5 cm SWE, so that the overall canopy interception in both the SE treatment and the control was proportionally higher than in 2003 or 2004.

The interception functions developed for this study may be used to predict snowfall under the canopy in similar forested areas elsewhere in the northern Rocky Mountains. However, like all empirically based models in snow hydrology, the models may not perform well when the climatic and land surface conditions are different from those on which the model is based. The study encompassed 3 years with similar snowfall totals that were very close to the long-term average, so the best model performance would be expected under similarly ''average'' conditions.

The absence of a significant treatment effect in the SG treatment was due to increased sublimation losses from the retention groups and in the openings between groups, which offset gains due to decreased interception in the openings. Evidence for increased sublimation from the retention groups comes from the fact that the mean SWE inside the groups (SG-I) was less than in the control, despite the similarity in canopy density. Snow depth decreased along the north to south transects within the groups, indicating that increased sublimation of snow in the canopy was largely due to increased exposure to solar radiation, with the greatest effect occurring on the more exposed south side of the groups. Snowpack temperature and snowmelt data collected for a related study indicates that mid-winter melt generally does not occur in the treated stands, so the observed losses can only be due to sublimation (Sappington, 2006).

Sublimation losses from the retention groups may have been enhanced by higher wind speeds within the canopy. Snow blown from a forest canopy is subject to increased sublimation because of the increased exposure and ventilation of the snow crystals (Pomeroy et al., 1998). The retention groups are all less than 0.8 ha, so that the maximum distance from the edge of a group to the center is about five times the average tree height. Increased wind speeds have been measured at distances of up to five times the dominant tree height from forest edges in fragmented forest landscapes (Chen et al., 1995).

In 2003 and 2004 the mean SWE in the openings in the SG treatment (SG-O) was less than in the SE treatment, despite the absence of canopy interception, suggesting that sublimation losses also occurred in the openings between groups. As in the retention groups, blowing snow may have increased the sublimation rate. There were signs of wind scour in the openings, such as bare areas on the windward side of ridge crests and wind-formed ripples on the snow surface, particularly in openings oriented parallel to the prevailing westerly wind. However, there was no evidence that this snow was being re-deposited elsewhere in the treatments.

The removal of slash from the openings when the treatments were installed may have increased the losses due to blowing snow. Slash and surface vegetation help to retain snow in logged openings, while the removal of these surface roughness elements generally results in increased blowing snow sublimation and wind scour (Pomeroy et al., 1997). Regrowth of surface vegetation within our treatment plots may have increased the surface roughness, resulting in an increase in snow retention. This could explain why, in contrast with the two previous years, the mean SWE in the openings in 2005 was greater than in the SE treatment. Annual snow accumulation measurements in the treatments and the control are continuing, and these data will be used to distinguish the effects of vegetation regrowth from interannual differences in climate.

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 indicate 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 1–2 cm 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 did not affect the outcome of the study. Differences in snow accumulation between forest harvest treatments may be confounded by differential snowmelt rates prior to measurement (Lundberg and Koivusalo, 2003). Melting generally occurs earlier and more rapidly in open areas compared to sites under a closed canopy (Pomeroy and Granger, 1997). The only years potentially affected by snowmelt prior to the measurements were 2003 and 2004, which had 1.3 cm of melt at Onion Park prior to the start of sampling. Differences between the treatments and the control in these 2 years may have been partly due to differential snowmelt. However, more rapid melt in the SE treatment would tend to decrease rather than increase the difference in SWE relative to the control. In the SG treatment, melt rates may have been higher than at the Onion Park SNOTEL site due to the presence of significant edge effects. However, even with an additional 1–2 cm of SWE in this treatment there would still have been a significant difference between the SE and SG treatments in 2003 and 2004.

The last assumption was that differences between treatments due to topography were minimal. Snow accumulation patterns in mountainous areas can be significantly altered by redistribution due to the interaction between wind and topography (e.g. Winstral et al., 2002). However, the similar elevation and aspect distributions of the treatments and the absence of prominent ridgelines or depressions, which accumulate less and more snow than flat areas, respectively (Lundberg and Koivusalo, 2003) suggests that topographic effects are likely to be less important here than in other areas.

6. Conclusions

Alternative silvicultural treatments such as thinning have been proposed as a means of increasing water yield and reducing wildfire hazard in forested watersheds in drought prone western North America, while also restoring the ecological structure and function of forested areas. This study evaluated the effect of two shelterwood-with-reserve silvicultural prescriptions, one leaving residual trees evenly distributed (SE) and the other leaving residual trees in groups (SG), both with ~50% basal area removal, on snow accumulation in lodgepole pine stands at the Tenderfoot Creek Experimental Forest in west-central Montana. Reduced interception in the SE treatment resulted in an increase of up to 7.2 cm in SWE relative to the control. In contrast, in the SG treatment increased exposure to solar radiation on south facing group edges and greater wind speeds both inside and outside the groups resulted in sublimation losses that offset gains due to reduced interception in the open. Consequently, SG always accumulated significantly less snow than the SE treatment and the SG treatment and control means were not significantly different. Differences in snow accumulation between groups and openings and between the north and south sides of groups meant that the SWE in SG was up to three times more variable than in either SE or the control. The contrasting responses in the SE and SG treatments demonstrate that the effect of thinning on snow accumulation largely depends on the spatial arrangement of tree removal.

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