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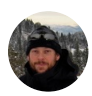

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Forest Canopy Reduction and Snowpack Dynamics in a Northern Idaho Watershed of the Continental-Maritime Region, United States

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Full understanding of snowpack dynamics in forested mountainous terrain of the western United States remains one of the greatest uncertainties in forest and water management in the region. The effect of forest canopy removal (i.e., 100% clearcut, 50% partial cut) on snow deposition and ablation dynamics was studied in a northern Idaho watershed. For the water year tested, results indicate that 85% of the annual precipitation (132 cm) occurred during the snow deposition and ablation months (October–May). Peak snow water equivalent (SWE) was approximately 57, 30, 17, and 34 cm in clearcut, 50% basal area partial cut, undisturbed, and riparian valley bottom forest sites, respectively. The number of days to melt-out from peak SWE ranged from 53 to 36 days in the clearcut and full forest, respectively. Clearcutting resulted in almost 3 times the snowpack as full forest and prolonged snowpack depletion by 3 weeks. Snow interception in the full forest, partial cut, and valley bottom forested sites was approximately 60, 43, and 32% of annual snow deposition, respectively, assuming negligible meltwater drip. Results indicate high variability in snowpack dynamics at snow course sites, suggesting that site-specific microclimate variations within treatments (due to canopy cover, aspect, elevation, and other factors) are important. Ultimately, assuming snow cover uniformity may lead to considerable errors in the computed quantity and timing of runoff pre- and postharvest in the climatologically complex and topographically diverse landscapes of the continental-maritime region of the United States.

Keywords: snowmelt, forest hydrology, Idaho, timber harvest, snow water equivalent

Snow deposition in the mountainous regions of the western United States accounts for 50–90% of total precipitation. The seasonal snowpack is consequently the largest annual water reservoir in the northwestern United States (Mote et al. 2005, Molotch et al. 2009, Veatch et al. 2009) and supplies a critical resource for ecosystem and human uses. The volume and timing of snowmelt are especially critical for seasonal drought periods when evaporation and transpiration exceed precipitation (Hicks et al. 1991, Bales et al. 2006). To date, the physical processes controlling the rate, magnitude, and spatial variability of snow accumulation and ablation under vegetation canopies remain among the greatest uncertainties in snowmelt computations. This is largely due to difficulties related to obtaining the necessary data in topographically complex and remote locations, with distinct climate regimes and harsh winter conditions (Link and Marks 1999a, Anderton et al. 2002, Bales et al. 2006, Winkler and Moore 2006, Varhola et al. 2010). Geographically variable climate differences are the greatest determinant of site-specific snow accumulation and ablation processes (Lundquist et al. 2013); there is therefore an ongoing need for focused regional studies that will lead to improved understanding of snow deposition and ablation dynamics and consequently the management of this critical seasonal resource in mountainous vegetated terrain.

Both anecdotal observations and research results agree that snow accumulation increases with elevation and decreases with canopy cover. Topographic variability can alter the patterns of snow accumulation and consequently the rate and timing of melt (Gray and Male 1981, Molotch et al. 2009, Varhola et al. 2010). For example, redistribution of snow by wind can produce a high degree of variability in accumulation and melt patterns and subsequent runoff characteristics (Gray and Male 1981, Winstral et al. 2002, Winstral and Marks 2002, Molotch and Bales 2005, Varhola et al. 2010). Complex interactions of these factors have made determining the exact relationships between canopy cover, topography, and microclimate challenging (Chamberlin et al. 1991, Bales et al. 2006), which coupled with forest management practices only become further confounding. It is understood that large forest openings collect and store snowpacks that are typically deeper than in surrounding forest stands (Schmidt and Troendle 1989). Golding and Swanson

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(1986) indicated that forest gaps need to be at least 2 times the average surrounding tree height to show increases in peak snow water equivalent (SWE). Large openings also tend to be subject to higher ablation rates than snowpacks under dense canopies (Golding and Swanson 1978, Harr 1980, 1986, Berris and Harr 1987, Golding 1987) due to lower canopy snowfall interception and increases in both radiant and turbulent heat fluxes (Harr 1986, Chamberlin et al. 1991, Marks 1998, Link and Marks 1999a, 1999b, Storck et al. 2002). Woods et al. (2006) showed that 50% basal area removal resulted in 7.2-, 5.6-, and 1.7-cm increases in SWE relative to that of an unharvested lodgepole stand in west-central Montana in 2003, 2004, and 2005, respectively. Troendle and King (1985) reported that peak SWE was 9% greater and peak snowmelt flows were 20% higher in central Colorado after a forest was harvested by alternating cut and leave strips 1–6 tree heights wide. In larger clearings of the boreal forest, ablation rates were noted as being higher relative to those of the adjacent forest due to increased radiation-driven snowmelt and energy exchange at the snow surface (Link and Marks 1999a, 1999b). A recent investigation by Lawler and Link (2011) further illustrated the importance of spatial and temporal variability on all-wave radiation and potential melt dynamics across a range of forest gap openings. To understand the complex interactions of land use, canopy structure, climate, and topography and hence improve hydrologic predictions of snow accumulation, peak SWE, and ablation in a wide range of climatic and mountainous terrain conditions, it is critical to characterize the spatial variability of snowpack dynamics, especially under different canopy structures (Moore et al. 1993, Durand et al. 2008).

Snowpack deposition and ablation have been studied in the panhandle region of Idaho since the 1940s at the Priest River Experimental Forest (Packer 1962, 1971, Cline et al. 1977, Haupt 1979a). Haupt (1979a, 1979b) reported that clearcutting on a south facing slope led to a 56% increase in SWE, whereas SWE increased by 37% for a north facing slope. Hubbart et al. (2007a) estimated 36% (272 mm/year), and 23% (145 mm/year) increases in annual water yield after clearcutting and partial cutting (50% canopy removal), respectively, in the Mica Creek Experimental Watershed (MCEW) located in northern Idaho. These changes were largely attributed to increased snow deposition and evapotranspiration reductions in clearcut and partial cut catchments, leading to relatively large increases in annual water yield. The following work builds on the water yield findings of Hubbart et al. (2007a) by providing additional information assessing the impact of forest harvest on snowpack dynamics. This work addresses an expressed need for improved understanding of snow deposition and ablation dynamics in mountainous terrain (Moore et al. 1993, Bowling et al. 2000, Varhola et al. 2010). It also quantitatively characterizes snowpack hydrology within the continental-maritime region of the Pacific Northwest, thus providing further understanding of forest management implications on snowpack dynamics. This is of particular interest in the region, given that snowpack dynamics remain largely unknown and may respond differently to land use (i.e., contemporary timber harvest), climate, and topography relative to the responses of other regions. The main purpose of this study was to improve the understanding of the variability of SWE and ablation rates in the complex terrain of the continental-maritime climate region. Specific objectives were to assess differences in snow accumulation and peak SWE between clearcut, partial cut, undisturbed, and riparian forested conditions, to quantify the variability of meteorological conditions due to altered canopy cover, and to assess differences in ablation rates and timing between treatments.

Methods

Study Site

The MCEW is located in Shoshone County, northern Idaho, approximately 25 km southeast of St. Maries, Idaho (47.17°N latitude, and 116.25°W longitude) (Figure 1) . A tributary to the St. Joe River, the experimental watershed encompasses the Mica Creek and the West Fork of Mica Creek (2,700 ha) catchments. Average water year (WY) temperature was 5.0° C, and precipitation was 147 cm recorded at the Mica Creek SNOTEL station (Natural Resource Conservation Service, site 623, 1,295 m above sea level) from 1991 to 2013. At the time of this study, current vegetation community status was the result of natural reforestation after extensive logging that took place during the 1920s and 1930s. Since the completion of logging in the early 1930s, there were no major anthropogenic disturbances in the watershed until 1997 when preharvest roads were constructed in portions of the watershed, followed by timber harvest approximately 4 years later. Fully forested vegetation at the site consists of 70- to 80-year-old naturally regenerated mixed-species conifer stands (approximate average tree height of 30 m) composed of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), western larch (*Larix occidentalis* Nutt.), western redcedar (*Thuja plicata* Donn ex D. Don), grand fir (*Abies grandis* Donn ex D. Don), western white pine (*Pinus monticola* Donn ex D. Don), and Engelmann spruce (*Picea engelmannii* Parry ex Engelm). The understory vegetation is largely composed of grasses, forbs, and shrubs (Hubbart et al. 2007b).

The MCEW was designed with paired and nested watersheds to enable the assessment of the effects of contemporary timber harvest practices on hydrologic dynamics. Clearcut harvest took place on north (~23 ha) and southeast (~43 ha) facing slopes, whereas partial cut harvest (50% basal area removal of the main canopy) took place on northeast (~34 ha) and southeast (~49 ha) facing slopes (Figure 1). Valley bottom forests, located in headwater riparian zones, were not previously harvested and consisted of the species composition listed above but were dominated by old-growth cedar. Within clearcut treatment areas, tree seedlings were replanted to a fully stocked condition in May 2003, with the planted component composed primarily of Douglas-fir, western larch, and western white pine seedlings. Natural forest regeneration species included western hemlock, western redcedar, grand fir, and Engelmann spruce. At the time of this study (WY 2006), young trees had grown to approximately 1 m in height. Therefore, leaf area index (LAI)-related interception of snow and impacts to snowmelt processes were assumed to be negligible or nonexistent, in particular after the snowpack covered them. Average LAI for the treatments was estimated by transect using the ceptometer method (Monserud and Marshall 1999) with an extinction coefficient of 0.52 (Duursma et al. 2003), resulting in average LAIs of 0.0, 3.8, 5.3, and 7.0 in the clearcut, partial cut, valley bottom, and full forest (corroborated in Du et al. 2013), respectively.

Both continental and maritime weather systems influence the watershed. Winters are generally characterized by oscillations between the two conditions, which can result in midwinter warming and rain-on-snow (ROS) events. The watershed varies in elevation from 1,000 to 1,600 m at the headwaters and receives approximately 1,450 mm annual precipitation. The average annual temperature is

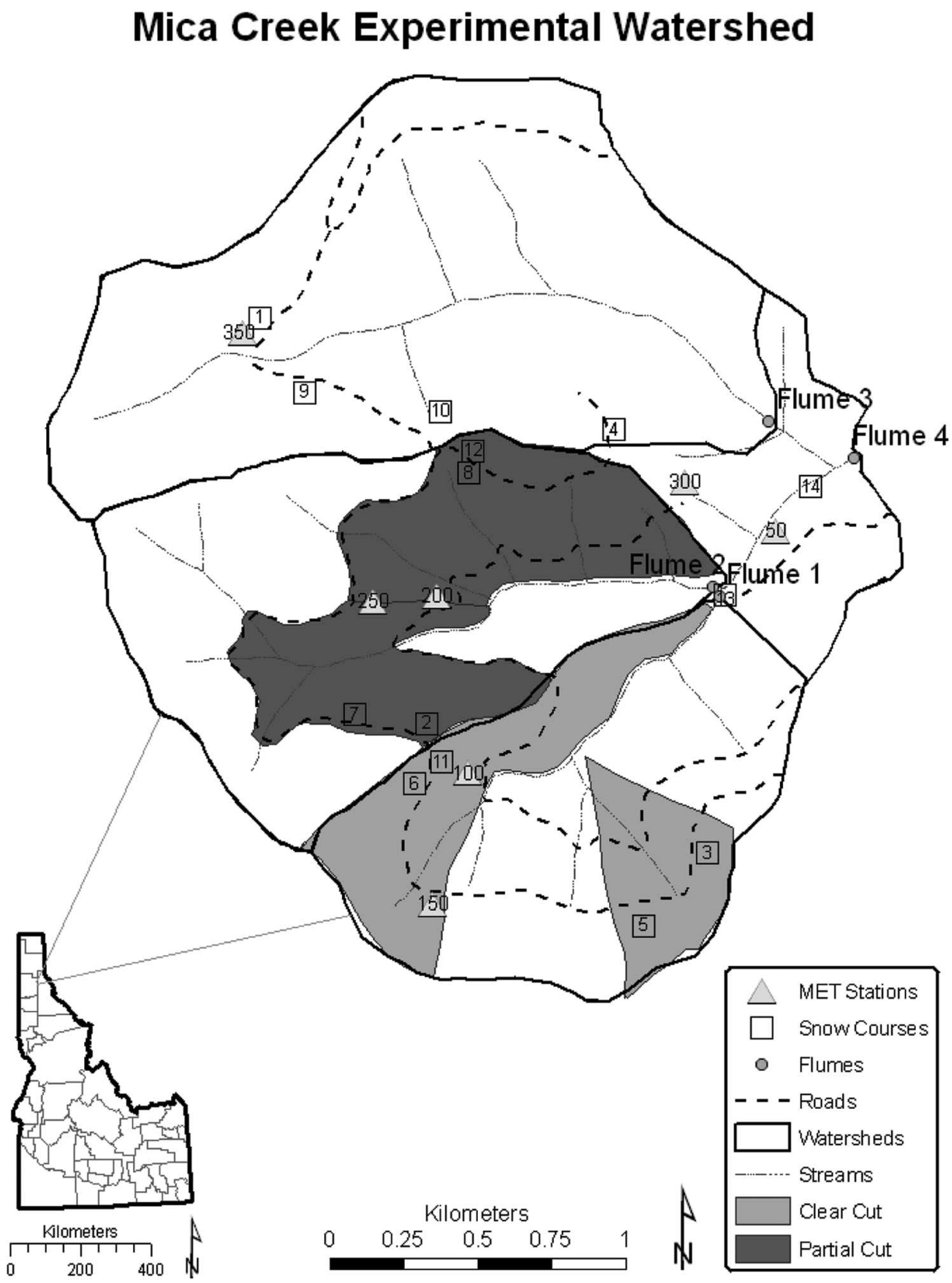

Figure 1. Location of the MCEW in northern Idaho, USA, including forest treatments (clearcut, partial cut, and full forest) and sampling sites: snow courses and meteorological (MET) stations.

approximately 4.5° C, and the majority of precipitation falls from November to May, with >70% of all precipitation falling as snow (Hubbart et al. 2007a).

Instrumentation and Data Processing

Precipitation was recorded at the Mica Creek SNOTEL site. The SNOTEL site is located at 1,448 m above sea level, in a 50-m wide clearing on the lee side of prevailing winds and includes a large-volume Alter-shielded precipitation gauge that is 3.7 m high, with a 30.5-cm diameter orifice. The SNOTEL site is located within the MCEW and near the median elevation approximately 1 km from the catchments in this study and was therefore assumed to provide a reasonable estimate of spatially averaged precipitation for the experimental area.

Seven meteorological stations (Tables 1 and 2; Figure 1) were installed in the catchment, stratified by canopy structure (i.e., clearcut, partial cut, undisturbed full forest, and valley bottom riparian) and elevation to capture key microclimate differences. It is recognized that because meteorological sites were chosen to cover the range of expected conditions, data may reflect localized processes including drifting. Similarly, it is worthy of note that the watershed has a generally northeast aspect but includes a mix of aspects across the catchments. Snow depth was recorded at each station with a sonic snow depth sensor (Judd Communications, Inc., Logan, UT). Soil temperature was monitored at 15 cm depth using thermistors (model CS107, Campbell Scientific, Inc., Logan, UT). Air temperature and relative humidity were monitored with combination temperature/humidity probes in Gill radiation shields (Vaisala,

Table 1. Local topographic characteristics for seven climate stations monitored within the MCEW in northern Idaho, USA.

Station no.	Treatment	Elevation (m)	Slope (%)	Aspect (°)	Aspect categorized
50	Valley bottom	1,208	Level		
100	Clearcut	1,365	44	46	NE
150	Clearcut	1,424	30	304	NW
200	Partial cut	1,340	20	117	ESE
250	Partial cut	1,403	29	56	NE
300	Full forest	1,299	25	82	E
350	Full forest	1,453	30	134	SE

Table 2. Local topographic characteristics for climate variables monitored within the MCEW in northern Idaho, USA.

Variables sensed at all climate stations	Sensor model
Precipitation (SNOTEL)	NRCS, 12 in. AS storage gauge
Snow depth	Judd, ultrasonic depth sensor
Shortwave radiation (ridge solar site)	Kipp & Zonen, CM3
Air temperature/relative humidity	Vaisala, HMP45C
Longwave radiation (ridge solar site)	Middleton, SK08
Wind speed/direction	Met-One 034B
Soil volumetric water content	CS 616
Soil temperature	CS 107

NRCS, Natural Resouces Conservation Service; AS, alter shielded, all season; CS, Campbell Scientific.

Table 3. Local topographic characteristics for 14 20-m snow courses within the MCEW in northern Idaho, USA.

Snow course	Treatment	Elevation (m)	Slope (%)	Aspect (°)	Aspect categorized
3	Clearcut	1,418	30	258	W
5	Clearcut	1,438	41	345	N
6	Clearcut	1,418	32	99	E
11	Clearcut	1,393	38	82	E
2	Partial cut	1,359	25	98	E
7	Partial cut	1,393	38	1	N
8	Partial cut	1,384	38	194	S
12	Partial cut	1,409	38	206	SW
1	Full forest	1,452	30	134	SE
4	Full forest	1,376	35	71	E
9	Full forest	1,457	28	348	N
10	Full forest	1,405	26	291	W
13	Valley bottom forest	1,224			
14	Valley bottom forest	1,194			

HMP45C; Campbell Scientific, Inc.). Wind speed and direction were monitored with integrated cup anemometers and wind vane sensors (Met One 034B; Campbell Scientific, Inc.). Shortwave (Middleton SK08) and longwave (CM3; Kipp & Zonen, Inc., Delft, the Netherlands) radiation were measured at a height of approximately 10 m and elevation of 1,460 m at the southern boundary of the MCEW on the top of a prominent ridge (latitude, 47.14°N; longitude, 116.25°W) (Gravelle and Link 2007, Hubbart et al. 2007b, Koeniger et al. 2008). Data gaps less than 3 hours in length (<2% of the total record) were filled by a 3-point spline interpolation technique (Akima 1978). Data gaps exceeding 3 hours (<1%) were filled by substituting values estimated via linear regression ($R^2 > 0.95$) with data from a nearby station.

Fourteen snow courses (Table 3) were established to monitor snowpack depth and SWE on a weekly basis starting from peak SWE through the end of the melt season. Snow courses were 20 m in length, running parallel to the slope, and were located through the treatment watersheds and stratified by elevation, aspect, and canopy structure. Snow depth was measured and a snow core was collected every 2 and 4 m, respectively, using a standard Federal snow tube and weighed with a calibrated spring balance, resulting in direct estimates of SWE (in.). Errors associated with the Federal snow sampler may be attributed to scale calibration, scale interpretation, and the relative quality of a given snow core. It was suggested that the Federal snow sampler yields estimates of SWE that tend toward a positive bias relative to gravimetrically obtained estimates (Work et al. 1965, Peterson and Brown 1975), for which maximum errors were shown to range from 7 to 12% for snow densities >25% and SWEs from 1 to 217 cm (Peterson and Brown 1975, Goodison et al. 1981). In a recent assessment of snow sampling instruments, Dixon and Boon (2012) showed that the Federal snow sampler produces SWE values closest to snow pit measurements (i.e., gravimetric method). Regardless of minor potential errors, this device is widely accepted for this type of work and was therefore deemed appropriate for use in this research. To ensure accuracy, care was taken to be certain that the snow tube was clear of snow and soil before each sample. Snow depth and SWE samples were collected by the same survey team to reduce operator measurement bias. The bottom of the snow tube was examined with each sample to be sure it had reached the soil surface. At least two measurements were made when snow depths were between 15 and 25 cm to validate weight. Snow cores were not collected below depths of 15 cm. Descriptive statistics were calculated for snow course SWE to quantify sampling heterogeneity (e.g., SD and coefficient of variation). One-way analysis of variance (ANOVA) was used to detect significant differences ($P < 0.05$) in mean SWE values between snow courses in terms of treatment and aspect. When significant differences occurred, ANOVA was followed with post hoc multiple comparison tests of specific means using the Tukey honestly significant difference test, which is a broadly accepted multiple comparison procedure for such data set structures (Smith 1971, Keselman et al. 1989). Snow depth and SWE data collected from snow courses were averaged by treatment. Snow density was calculated from depth and SWE and subsequently multiplied by the snow depth at meteorological stations in complementary treatments to estimate hourly time series density and SWE.

Results and Discussion

Climate

Weather during the period of study (Oct. 1, 2005–May 31, 2006) was characterized by relatively normal precipitation, low incoming shortwave radiation, and high longwave radiation (cloudy conditions). Total precipitation for WY 2006 in the MCEW measured at the Mica Creek SNOTEL was 1,320 mm. This total was less than the 23-year (WY 1991–2013) average (approximately 1,470 mm, SD ±270 mm), which was well below the individual annual maximum (2,096 mm, 1997) and well above the individual annual minimum (930 mm, 1994). Total precipitation during the period of study (Oct. 1, 2005–May 31, 2006) was 1,130 mm. Thus, approximately 85% of annual precipitation fell during the snow deposition and ablation months of WY 2006. Figure 2 shows hourly time series of climate variables from the meteorological monitoring sites (Table 2) from Oct. 1 to May 31 of WY 2006. Average air temperatures were close to 0.0° C and oscillated above and below freezing during the winter months. Wind speeds were low with exposed sites averaging slightly above 1 m/s. There were very few early season melt events, and no notable ROS events during the snow season. For purposes of this work, the snow season was defined

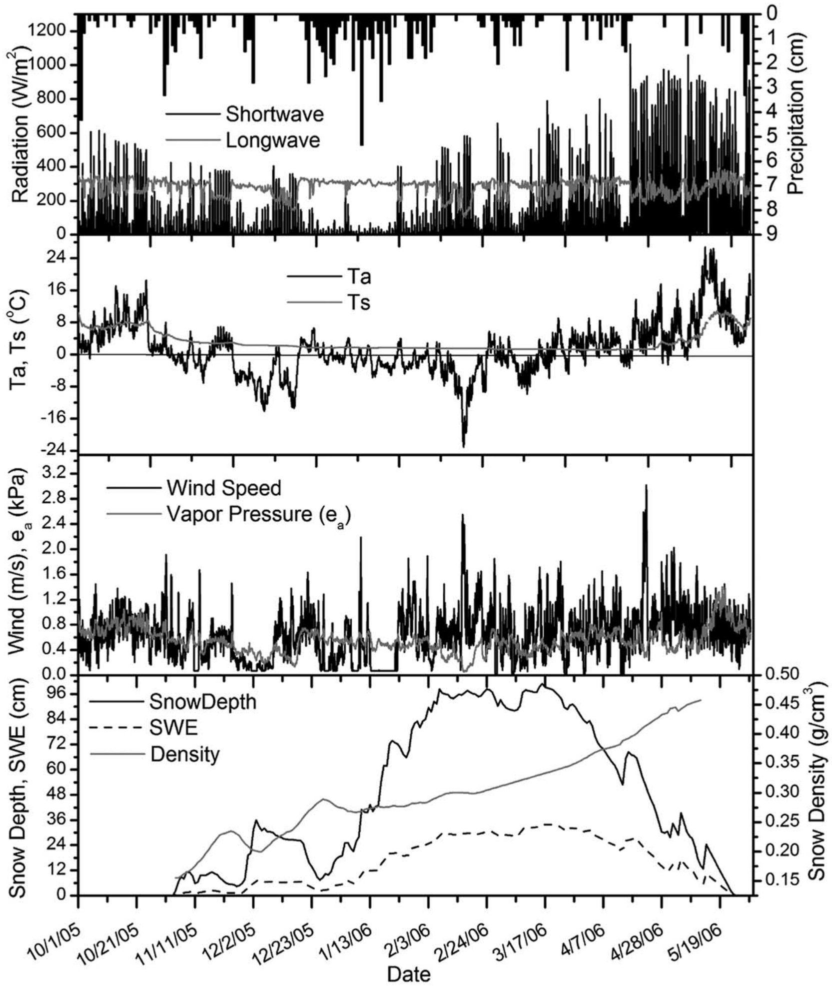

Figure 2. Hourly time series of average climate variables for each of the climate monitoring sites listed in Table 1 from Oct. 1 to May 31 of WY 2006. The snow depth, SWE, and density graph reflects conditions at the high elevation clearcut site. Data were collected within the MCEW in northern Idaho, USA. T_a, air temperature; T_s, soil temperature; e_a, vapor pressure.

as the period of continuous snow cover at any of the meteorological stations (Nov. 4–May 25).

Figure 3 shows October through May (WY 2006) descriptive indices for climate variables monitored in each of the four land-use types of this study. Radiation and climate data for the valley bottom forest reflect a single location (see Methods), whereas all other data reflect averages of two climate stations for each treatment (Table 1). During the snow accumulation and ablation period (Nov. 4–May 25, WY 2006) average air temperature ranged from −0.5° C in the full forest to 0.8° C in the clearcut site (Table 4). Within treatment areas, there was between a 0.6 and 0.8° C variability in average air temperature between the 2 clearcut sites (range: site 100 = 51.0° C and site 50 = 51.6° C) and partial cut sites (range: site 200 = 50.5° C and site 250 = 51.0° C), which may be attributable to minor differences in exposure, elevation, and/or topographic shading. Average vapor pressure ranged from 506.6 to 579.4 Pa in the clearcut and valley bottom forest, respectively. The slightly higher vapor pressure in the valley bottom forest is not unexpected given the low elevation sheltered conditions with low wind speeds. Average wind speed was highest (approximately 1.3 m/s) at the high elevation clearcut site (150), which recorded 5 times greater wind speeds than those at the valley bottom forest (0.3 m/s). Average wind speed from all climate monitoring sites was 0.6 m/s. Average soil temperature ranged from 1.5 to 4.1° C in the high elevation clearcut and undisturbed forest sites, respectively, so frozen soils were not present at the monitoring sites during the course of this study. It is worth mentioning that although soil temperature observations exhibited minor variations, soil heat flux is typically a relatively minor component of the snow cover energy balance but has been noted to be large in maritime climates based on simulations (Mazurkiewicz et al. 2008).

Snow Distribution and Melt Variability

The first measured snowfall of WY 2006 occurred in the MCEW on Nov. 4. Maximum snow depth for the season was 161 cm measured in the high clearcut site (station 150) (Table 1 and data not shown). Peak SWE occurred between March 15 and March 23 at all snow courses and climate stations and ranged from 17 to 57 cm (n = 14) (Table 5). Average peak SWE from four replicate snow courses in each treatment ranged from 43.1 cm in the clearcut site to 23.9 cm in the undisturbed full forest. Peak SWE was notably higher in the clearcut treatments by nearly a factor of 2 than in undisturbed full forest (Figures 4, top, and 6). Snow sampling campaigns (n = 9; Jan. 19, Mar. 23, Mar. 30, Apr. 7, Apr. 13, Apr. 20, Apr. 27, May 5, and May 12) included 20-m transects with SWE measurements

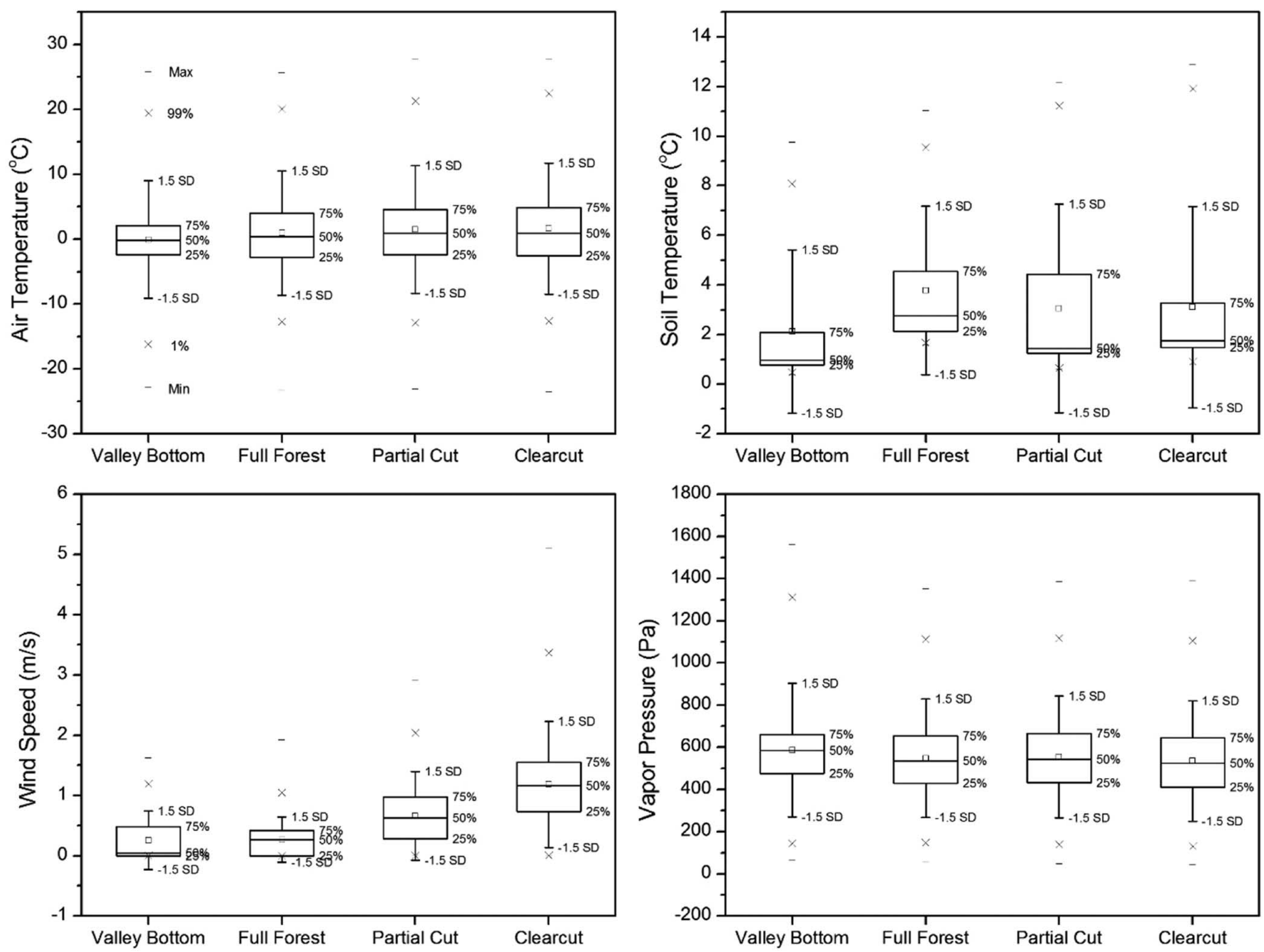

Figure 3. Climate characteristics for each of four treatment sites (valley bottom forested, clearcut, partial cut, and fully forested) over the snow season of WY 2006 within the MCEW in northern Idaho (valley bottom, *n* = 1; other sites, *n* = 2).

Table 4. Average meteorological conditions at each of the climate monitoring sites listed in Table 1 over the snow season (Nov. 4–May 25) for water year 2006 within the MCEW in northern Idaho, USA.

	Average snow season climate differences by monitoring site[a]						
Clinical parameter	50	100	150	200	250	300	350
Air temperature (° C)	−0.2	0.8	0.2	−0.2	0.6	−0.5	−0.5
Vapor pressure (Pa)	579.4	517.0	506.6	532.1	531.0	529.7	515.2
Soil temperature (° C)	2.0	3.5	1.5	2.5	2.4	2.9	4.1
Wind speed (m s^{-1})	0.3	1.1	1.3	0.5	0.8	0.0	0.5

[a] 50, riparian; 100 and 150, clearcut; 200 and 250, partial cut, 300 and 350, fully forested control.

every 4 m (n = 6/transect). The number of sampling dates completed at each transect varied from 7 to 9, depending on the timing of complete snow ablation. To better understand the variability of SWE within transects, the population mean, SD, and coefficient of variation (CV) were calculated for each transect and each campaign. Average SD and CV within transects by treatments were 5.71 and 0.35 for full forest, 5.54 and 0.27 for partial cut, and 5.13 and 0.21 for clearcut, respectively. The SD and CV within transects by general aspect were 0.41 and 0.17 for western slopes, 3.61 and 0.28 for northern slopes, 1.79 and 0.30 for eastern slopes, and 0.84 and 0.33 for southern slopes. The CV for most transects increased for the last half of April, which is not surprising considering active melt during this time, spatially varying canopy distribution, and hence variable net melt energy at relatively fine scales (Hubbart et al. 2011). Penn et al. (2012) showed that SWE was significantly greater in openings (P = 0.021) than in forests on north facing plots but not on south facing plots. However, this distinction became less consistent with advancement of the melt season, thus illustrating the spatial and temporal variability of deposition/ablation processes, as reflected in the current investigation. In the current work, one-way ANOVA of average SWE for each snow course (n = 14) per sampling date indicated a significant difference between the snow courses ($P <$ 0.001). The Tukey post hoc multiple comparison test detected significant differences between snow courses nos. 5 (clearcut) and 2 (partial cut), 3 (clearcut), 4 (full forest), 6 (clearcut), 8 (partial cut), 10 (full forest), and 12 (partial cut) ($P <$ 0.01). In addition, average

Table 5. **Average snow course (n = 14) and climate monitoring site (n = 7) results for peak SWE, total melt period, and melt per day in the MCEW in northern Idaho, USA.**

Treatment	Site description	SWE Peak (cm)	SWE Date	Ablation end date	Days to melt	Average melt/day (cm)
SNOTEL	(NRCS)	60.8	Mar. 27	May 15	49.0	1.2
Clearcut	Snow course	43.1	Mar. 23	May 3	41.3	1.0
Clearcut	Climate station	56.5	Mar. 16	May 7	52.5	1.1
Full forest	Snow course	23.9	Mar. 23	May 9	47.0	0.5
Full forest	Climate station	17.0	Mar. 16	Apr. 20	35.5	0.5
Partial cut	Snow course	32.6	Mar. 23	May 1	39.5	0.8
Partial cut	Climate station	29.5	Mar. 15	Apr. 28	44.5	0.7
Valley bottom forest	Snow course	31.2	Mar. 23	May 24	62.0	0.5
Valley bottom forest	Climate station	34.2	Mar. 16	May 24	69.0	0.5

NRCS, Natural Resouces Conservation Service.

SWE for each sampling date at the Mica Creek SNOTEL site was significantly different from all average snow course SWE values except 13 and 14 (both riparian).

Results of ANOVA indicated a significant difference between snow course mean SWE ($P = 0.003$) and treatment types. Results of the Tukey post hoc multiple comparison test indicated statistically significant differences between the clearcut and SNOTEL ($P = 0.01$) and the control (fully forested) and SNOTEL sites ($P = 0.002$). These findings are in agreement with research findings across a broad range of forested systems (Troendle and King 1985, Golding and Swanson 1986, Talbot et al. 2006, Woods et al. 2006) where increases in snow deposition and peak SWE in forest openings after harvest practices were reported. Pomeroy et al. (1998) showed that as much as 70% of the spatial variation in SWE under a boreal forest canopy was related to winter leaf area. Varhola et al. (2010) reviewed 33 snow deposition and ablation studies, indicating that snow cover accumulation and ablation decrease with increasing forest cover. In the current study, 100% clearcut (average climate station peak SWE 57 cm) and 50% basal area (partial cut, LAI of 3.8, average climate station peak SWE 30 cm) reduction resulted in a clear inverse relationship between canopy cover and SWE (Table 5). Statistical analyses showed that in many ways intra-snow course variability was greater than inter-snow course variability. This is a critical finding that justifies the current work and highlights the need for further spatiotemporal snow deposition and melt research in complex vegetated terrain. Despite the intra-snow course SWE variability, results of the current work show a very strong treatment and aspect effect. It is notable that in terms of statistical differences (confidence interval [CI] = 0.05), the Mica Creek SNOTEL site may exhibit SWE values that are more similar to the riparian forest SWE values than to the hillslope full forest values. This is an important observation because in the current work, riparian areas (snow courses 13 and 14) were shown to have generally deeper snowpacks and a longer time to total melt-out relative to those of any of the hill slope sites (irrespective of treatment or aspect).

A key driver of snowmelt is shortwave and longwave radiation. Previous work showed that in forested catchments, radiation is the dominant energy source for snowmelt, and vegetation has a direct influence on the snowcover energy balance by reducing shortwave and increasing longwave radiation relative to those in open areas (Link and Marks 1999, Sicart et al. 2004, Talbot et al. 2006). This finding was confirmed in a recent review of 33 snow deposition and ablation studies by Varhola et al. (2010), who concluded that forest cover is a very strong predictor of snow deposition and melt processes. Recently, Molotch (2009) showed that simulated net shortwave radiation can account for as much as 65% of total radiative flux and as much as 58% of total modeled energy exchange. Rasmus (2013) showed statistically significant (CI = 0.05) differences between open (greater depth and density) and full forest conditions from approximately 150 snow survey points in Finland. Lundquist et al. (2013) provided a global analysis indicating that during the winter months (December through February) with average temperatures above −1° C, forest cover results in reduced snowpack duration by as much as 2 weeks relative to that of open areas, whereas snow persisted longer under forest canopies in colder environments. Ultimately, there remains little question that canopy density determines the magnitudes of the net shortwave and longwave radiation components that are probably the primary driver of variations in melt dynamics observed between the different forest treatments in this investigation.

According to snow course and climate station observations, the beginning of snowmelt occurred synchronously across the MCEW. Conceivably, clearcut sites could have started melting earlier because of increased radiation exposure; however, based on weekly snow course observations, beginning melts for all study sites were within a few days of each other (Figure 5). This is not surprising considering the relatively small spatial extent of the watershed (i.e., approximately 600 ha), allowing for a clearer interpretation of the melt period and melt rates between each of the treatments. The average total days to melt among all snow courses ranged from almost 40 days in the partial cut to 60 days in the valley bottom riparian forest, with average melt per day ranging from approximately 0.5 cm/day in the undisturbed and valley bottom forest to 1.0 cm/day in clearcut treatments (Table 5). To avoid erroneous average daily melt computations due to differing dates of completed ablation (i.e., snowpack depletion) and hence different micrometeorological melt drivers, snowmelt rates were calculated earlier in the melt season (Mar. 23–Apr. 13 [data not shown]). Average total melt ranged from more than 14 cm to approximately 5.4 cm between the clearcut and valley bottom forest, respectively. Average daily melt was 0.7 cm/day for clearcut and partial cut treatments and 0.5 and 0.3 cm/day for fully forested and valley bottom forest, respectively. This analysis resulted in somewhat different estimates of daily melt relative to those calculated over the entire melt period; however, the overall trend was similar with the exception that the partial cut had daily melt rates similar to those for the clearcut treatment (0.7 cm/day) earlier in the season. This observation is not surprising considering increased that radiation loading leads to increased melt rates in clearcut forests later in the season (Figure 5). However, these

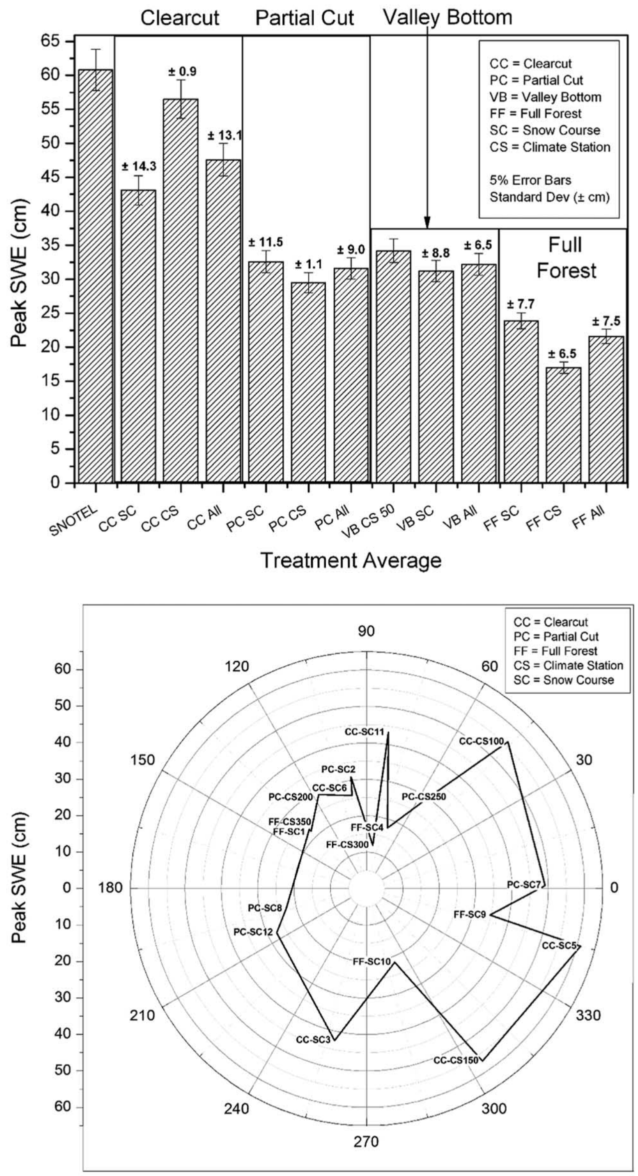

Figure 4. Top: Average peak SWE (cm) for each of four treatments (clearcut [CC], partial cut [PC], full forest [FF], and valley bottom forest [VB]; *n* = 4 replicates per treatment), for snow courses (SC) and climate stations (CS; *n* = 2 replicates per treatment) and averages for both snow courses and climate stations combined relative to that for the Mica Creek SNOTEL SWE (*n* = 1). Bottom: Peak SWE (cm) versus aspect (degrees) for 12 snow courses and 6 climate stations (Tables 1, 2, and 3) for snow season WY 2006, within the MCEW in northern Idaho, USA.

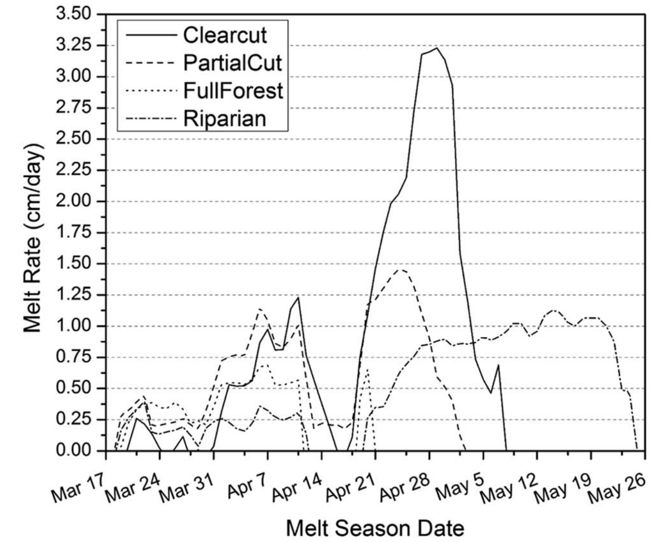

Figure 5. Melt rates (cm/day) versus time for each of four treatment sites (valley bottom forested, clearcut, partial cut, and fully forested) during the late accumulation and melt season for WY 2006 within the MCEW in northern Idaho, USA.

results have important implications for forest managers wishing to mitigate increased melt rates and erosion potential (often associated with clearcutting) by using partial cut or uneven-aged harvesting practices.

Results indicate that although differences between 100 and 50% harvest were notable in terms of snow deposition and peak SWE (here SWE was approximately 40% greater in the clearcut than in the partial cut treatments), melt rates were similar in the clearcut and partial cut sites through the melt season. Comparisons of SWE at each of the climate monitoring sites showed a high degree of variability among treatments. In the undisturbed, valley bottom, partial cut, and clearcut forests, peak SWE was approximately 17, 34, 30, and 57 cm, respectively (Table 4). Other recent studies have also reported a high degree of spatial variability in SWE. DeBeer and Pomeroy (2009) investigated a 0.6 km^2 alpine cirque in the Canadian Rocky Mountains using premelt measured data and modeling techniques, which showed considerable variability of SWE and melt rates between slopes. Jackson and Prowse (2009) reported challenges predicting spatial distribution and snowmelt rates under variable forest canopies and variable elevation in the Okanagan Basin of western Canada. These findings were supported by radiation simulations provided by Seyednasrollah et al. (2013), who noted the importance of understanding snow distribution and melt variability processes related to land-use practice (e.g., canopy cover) to modulate the timing of snowmelt in mountainous environments. Previous studies clearly highlighted the need for improved understanding of snowpack development and melt variability (slope, elevation, and aspect), canopy cover modulation of melt processes, and the need for better spatial characterization (direct measure and automated sensors) to improve the predictive modeling ability (Varhola et al. 2010, Penn et al. 2012, Lundquist et al. 2013, Schelker et al. 2013).

Average peak SWE in the clearcut treatments was 340% higher than peak SWE in the undisturbed full forest and 200% higher than peak SWE in the valley bottom forest and the partial cut treatments. The maximum snow density occurred on May 12, 2006, when the average of the seven meteorological stations was estimated to be 0.46. The time required to completely melt the snowpack was on average 53, 45, 36, and 69 days for clearcut, partial cut, full forest, and valley bottom forest, respectively (Table 4), further illustrating that the amount of canopy cover dramatically affects the amount of snow deposited, ablation rate, and duration.

One of the greatest quantifiable discoveries of this work is the large degree of variability in microclimate due to treatments, which led to considerable differences in melt rate across the MCEW. Although this general observation may not be surprising, given the outcomes of previous work (e.g., Boon 2012, Lundquist et al. 2013), the current investigation specifically shows an approximate 3- and 4-week lag to complete snowpack depletion in clearcut and

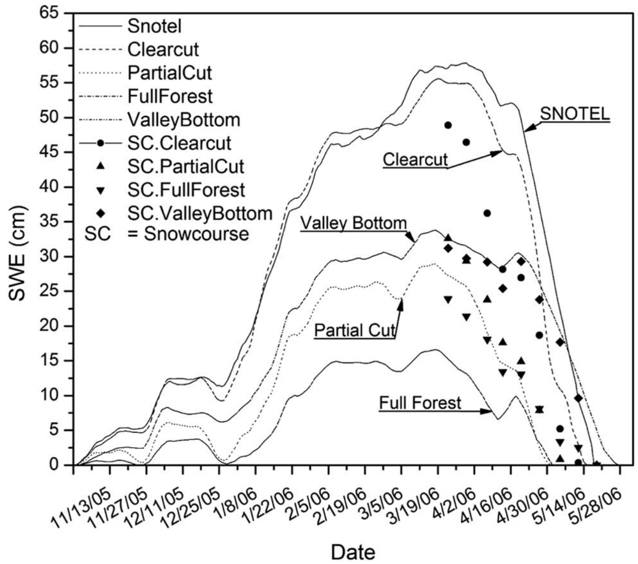

Figure 6. Average SWE (cm) time series for each of four treatments (clearcut, partial cut, undisturbed full forest, and valley bottom forest), and the Mica Creek SNOTEL and weekly snow course (SC) results for the snow season, for WY 2006, within the MCEW in northern Idaho, USA.

valley bottom forests, respectively, relative to that for the undisturbed forest (Figures 5 and 6). The partial cut (50% canopy removal) site fully ablated only 1 week before full snowpack depletion in the clearcut site. The valley bottom forested site fully ablated more than 2 weeks after the clearcut treatments, probably because of topographic shading, wind sheltering, and/or potential persistent cold-air drainage phenomena (see Hubbart et al. 2007b). The timing of complete ablation in relation to the different harvest treatments and stand locations also has important implications for the timing of seasonal stream temperature increases and associated ecological processes. This is because stream temperatures typically do not rise substantially until most of the snow has completely ablated within the watersheds (Gravelle and Link 2007), and hence the alteration of snow dynamics due to timber harvest and retention of snow in valley bottom forests may delay the onset of stream temperature increases.

The average melt rate of all seven climate monitoring sites was estimated to be 0.6 cm/day. Compared with the average melt rates calculated for the fully forested catchments (0.5 cm/day), this may seem to be a negligible difference over that for the watershed. However, the relative localized impacts on melt, erosion, water availability, and quality may be large. Murray and Buttle (2003) noted that wetter soils in clearcut forests coupled with increased snowmelt rates can result in decreased soil infiltration efficiency and thus increased surface runoff, therefore having important implications for erosion and biogeochemical dynamics. Karwan et al. (2007) noted that in the MCEW, the highest suspended sediment concentrations and loads occurred in the absence of snow and during intense rainfall events. Schelker et al. (2013) showed that clearcutting in the boreal forest of Sweden resulted in an approximately 29 mm (27%) increase in SWE. Similar to the current work, Schelker et al. (2013) found that accelerated timing of snowmelt in clearcut forests resulted in increased stream response during most years, reflecting increased snowmelt-related runoff by 39 and 27% in 2008 and 2009, respectively. Hubbart et al. (2007a) noted a significant ($P <$ 0.05) increase in water yield after timber harvest in the MCEW. The current work shows that despite the increased snowpack and thus increased water yield, melt was only prolonged by approximately 3 weeks in clearcut relative to that in the unharvested control forest. This result implies that increased water supplies may not be available later in the year when most needed for ecosystem and human use unless the excess snow water recharges groundwater resulting in higher base flows. Recently, Musselman et al. (2008) made similar observations when they estimated 46% lower ablation rates under canopy relative to those in open areas, resulting in equivalent snow cover durations in undisturbed locations despite substantially less snowpack. Determining the exact nature of these relationships in different canopy covers and climate regimes provides impetus for future work.

Snowmelt and Slope Orientation

The influences of elevation, slope, and aspect are very important for hillslope snow dynamics because they directly affect snow accumulation and snowmelt energetics (Carey and Woo 1998, Pomeroy et al. 2003). Results of the current work were corroborated in the work of Jost et al. (2007), who showed that the combination of elevation, aspect, and forest cover explained about 80–90% of the large-scale variability in snow accumulation in the spring of 2005 and 2006 in the Cotton Creek Watershed, Kootenay Mountains, Southeastern British Columbia. Many other studies showed that relative to canopy thinning, small-scale elevation differences on the order of those in this study play a less important role in terms of snowmelt (Talbot et al. 2006, Molotch 2009, Veatch et al. 2009). However, Varhola et al. (2010) indicated in their review of 33 empirical snowpack studies that elevation was the strongest predictor of snow accumulation and melt after forest cover. Jackson and Prowse (2009) showed that melt-out occurred first at lower elevations, whereas open sites were snow free 2–5 days earlier than forested sites at the same elevation despite higher areal SWE in the Okanagan Basin of British Columbia. This study was not designed to directly test the effects of elevation and the full range of aspect variability, but rather focused on treatment effects (i.e., clear and partial cuts), since aspect was generally controlled for by replicated snow courses. However, based on observed SWE from snow transects, aspect appears to play a key role in snow deposition and ablation rates across the watershed. Results of ANOVA showed that average SWE by aspect for each snow course for each sampling date (riparian not included) was significantly different ($P < 0.001$). In general, northern aspects, irrespective of treatments were significantly different in terms of average SWE (CI = 0.05, $P < 0.01$). Specifically, SWE on northern aspects was significantly different from that on southern ($P = 0.001$) and eastern ($P = 0.02$) aspects. The clearcut treatments in the MCEW are no more than a few hundred meters in width. However, a given slope could experience preferential deposition of snow due to both forest clearing and orientation. This is probably the case for northerly facing slopes in the MCEW where snow depths and SWE were greatest (Figure 4, bottom) and is probably attributable to winter storms that typically originate from the South or Southwest. For example, minor drifting and/or preferential deposition was observed in a small area of the high elevation north facing slope in the full forest near snow course 9 (Table 3). Veatch et al. (2009) reported shallower snowpacks on western aspects, a result generally corroborated in the current study despite the different locations. Other researchers have reported similar results, further suggesting that afternoon surface heating and increased exposure to turbulence (Winstral et al. 2002, Rinehart et al. 2008) may lead to observed snowpack depletion patterns. However, windspeeds remained low during the period of this study (Table 3). Regardless, this observation illustrates the complexities of this environment and the possibility that some preferential snow deposition may occur in the lee sides of ridges (independent of canopy structure) as has been observed in more extreme terrain (Mott et al. 2014). While providing valuable information regarding aspect (Figure 4, bottom), which is of use to land managers, future investigations should focus on the extent that topographic features including slope and aspect play in controlling snowpack dynamics.

Interception/Sublimation

Recent studies indicate that sublimation losses from intercepted snowfall may dramatically reduce annual water available for runoff in snow-dominated systems (Hedstrom and Pomeroy 1998, Essery et al. 2003, Molotch et al. 2007, Pomeroy et al. 2012), ranging from 28 to 83% (Martin et al. 2013). In the current work, interception was estimated by the difference in snowfall at the reference site (SNOTEL) and the estimated snowfall (based on snow depths at snow courses and climate stations) in the full forest, partial cut, and valley bottom forested sites. Results indicate that snow interception and sublimation may play important roles in this system. Average snow interception was estimated to be approximately 60, 43, and 32% of annual snow deposition in full, partial cut, and valley bottom forested sites, respectively, during the period of study. Notably, these values indicate that interception (not interception loss) and differences are presumably due to a combination of sublimation and meltwater drip from the canopy intercepted snow load. Values reported here are similar to the value reported by Molotch et al. (2007) who reported 68% interception (LAI of 4.2) in an Engelmann spruce and lodgepole pine forest at Niwot Ridge Forest, Ameriflux site in Colorado. Storck et al. (2002) and Pomeroy and Schmidt (1993) reported 60% snow interception in mixed-conifer forests of Oregon and Colorado, respectively. Pomeroy and Schmidt (1993) reported sublimation losses as high as 40% for coniferous canopies in subalpine boreal forests (continental climate). Schmidt and Troendle (1992) reported that all of the intercepted snow (30% of the total snowfall on average) was lost to sublimation in dense conifer canopies. Musselman et al. (2008) reported interception of annual snowfall of 24% in full canopy conditions and a 56% increase in snow depth in open versus full forest conditions at maximum snow depth in a montane forest of the Valles Caldera National Preserve in the Jemez Mountains, New Mexico. These findings are also consistent with those of Koeniger et al. (2008) who identified enrichment of ^{18}O in subcanopy snowpacks relative to that of open site snowpacks at the MCEW, suggesting greater enrichment in denser canopies because of longer term exposure and thus sublimation of canopy snow loads. Based on the residual computation, at the MCEW, 50% canopy removal resulted in an average 43% sublimation loss (assuming no meltwater drip). Schmidt and Troendle (1992) suggested that when winter storms are small (5–25 mm water equivalent), 50% of the snowfall may be intercepted when conifer crown closure is 50% or more. Despite the limitations of the method (i.e., residual computation), these observations may be reasonable for the MCEW where the mixed-conifer canopy, structural alteration by harvest, and climate (particularly low wind speeds) result in snow packs that generally accumulate slowly and steadily over the season.

Whereas release of intercepted snow loads as melt water drip can occur during warming events after snowfall (Storck et al. 2002), there are several supporting observations, suggesting that the observed SWE differences at the MCEW during WY 2006 were caused primarily by sublimation losses. For example, observations during snow surveys indicated that snow persisted in the forest canopy for an extended period and much longer than would be expected under windier or warmer conditions. A larger proportion of snowmelt drip could occur at the MCEW during warmer years especially with ROS events. However, significant ROS events did not occur during the WY 2006 winter, with only a small event occurring in late December. Shallow (15 cm) soil water content (SWC) trends recorded at the climate stations (data not shown) indicated sporadic increases ($n = 5$ events, $<5\%$) in SWC in the forested areas relative to those in open areas, probably reflecting meltwater drip that subsequently flushed through the snowcover and infiltrated. However, based on available data (air and soil temperature and SWC), during the majority of the snow accumulation phase, there were no obvious canopy drip events, and if so, they were probably minor in terms of sublimation offsets during the WY 2006 snow season. Despite this information, peak SWE and melt rates varied dramatically among treatments and aspects, which was the core objective of this current investigation. Additional information pertaining to canopy snow interception, sublimation processes, and the spatial distribution of snow and snowmelt relative to variable microclimates is necessary to better partition snow interception to the water mass balance. However, the estimates provided from the current study supply previously unavailable information and thus a basis for future research.

Modeling Implications

Hydrologic and climatological models rely on parameterizations for snow accumulation, ablation, forest cover, and meteorological conditions. Results of the current work supply baseline data to pursue new methods to map and model snowpack properties, such as that suggested by Melloh et al. (2008), using pinched cone-shaped solution mapping for distributed modeling. Regional climate and numerical weather models typically operate at scales that would treat areas the size of the MCEW and larger as a single grid cell. The use of uniform snow cover and energy balance was previously shown to potentially lead to considerable errors in computed snow cover over much of the melt period, resulting in inaccurate surface energy balance values for open, northern environments (Essery 1997, Pohl and Marsh 2006). Although the energy balance was not explicitly assessed in the current work, findings pertaining to the spatial variability of snow mass are relevant to modeling needs. Du et al. (2013) indicated discrepancies of model outputs of the distributed hydrology soil-vegetation model between simulated versus measured snow distribution values in the MCEW, illustrating the importance of observed data to improve process-based modeling. Given the relatively small size of the MCEW yet highly variable snow deposition and ablation rates across the catchments, the current work suggests concerns for understanding snow deposition and ablation processes in many forested regions of the inland Pacific Northwest and other regions where forests cover is spatially and/or temporally variable. Hubbart et al. (2011) assessed approaches to adjust meteorological data and canopy parameters to improve the Water Erosion Prediction Project snowmelt predictions at the MCEW. Schelker et al. (2013) indicated that stream response to snowmelt is governed by interception, sublimation, and loss of melt water (e.g., evaporation during melt). Although those general processes hold true in the current study, spatial, temporal, and canopy variability coupled to a distinct climate regime controls the relative contributions of radiation and turbulent energy fluxes and remains a challenge in the continental-maritime climate region and many other locations globally. Results confirmed that in complex heterogeneous landscapes such as the MCEW, site-specific climate and canopy parameters produce the most accurate simulations. Methods were proposed that improve model predictions; however, it was concluded that improvements in simulation accuracy are needed to improve model predictive confidence for forest management in the complex forested ecosystems of the Pacific Northwest. Previous research findings imply that relatively small (30 m) grid-based approaches may be required to account for snowpack process spatial variability in this complex physiographic region, an assertion echoed in recent work by Jost et al. (2012) in the Cotton Creek Experimental Watershed in British Columbia. Clearly, the development of process-based models is often confounded in complex mountainous forested environments by a general lack of adequate mechanistic understanding, resulting in modeling errors and spurious conclusions (Winkler 1999, Hudson 2000, Woo and Thorne 2006, Bales et al. 2008). The current work provides invaluable baseline data (a need expressed by Molotch 2009), to improve physically based snowmelt algorithms in complex vegetated watersheds.

Conclusions

Distinct differences in snow accumulation and melt rates can be expected with forest cover heterogeneity in the interior Pacific Northwest of the United States. In this study, following conventional timber harvest practices, peak SWE was shown to be approximately 3.4 and 2 times greater in clearcut catchments (57 cm) than in undisturbed (17 cm) and partial cut (30 cm) forests, respectively. The highest snowmelt rates occurred in clearcut treatments where seasonal average melt rates (1.1 cm/day) were nearly twice the average melt rates of the partial cut (0.66 cm/day), control (0.5 cm/day), and riparian (0.5 cm/day) monitoring sites. The number of days required to completely melt the snowpack ranged from 36 to 69 days for full forest and riparian valley bottom, respectively (clearcut, 53 days; partial cut, 45 days). Results indicate that dates of complete ablation took nearly 2 and 3 weeks longer in the partial cut (May 3) and clearcut (May 8) forests than in the undisturbed forest (April 21). Thus, clearcutting resulted in almost 3 times the snowpack as that in full forest, but snowpack depletion was only prolonged by 3 weeks relative to that in the full forest. Snow interception estimates by residual computation, assuming negligible meltwater drip, indicated that undisturbed, partial cut, and riparian valley bottom forests intercepted and sublimated as much as 60, 43, and 32% of annual snow deposition, respectively.

With four different land cover types (i.e., clearcut, partial cut, full forest, and valley bottom forest), the results from this work show that timber harvest can lead to large increases in SWE, as well as much higher, sustained melt rates across highly diverse terrain. In the current work, snow deposition and ablation were largely controlled by canopy cover and aspect, both of which affect preferential deposition and radiation loading. The results are further explained by elevation and topographic shading, highlighting the high degree of spatial variability of intact fully forested stands, which are also complicated by higher deposition and relatively slower melt rates in valley bottom forested stands that often exhibit spatially varying stand structure relative to upland sites.

This work showed preferential deposition on northern slopes and persisting snowpacks in lowest elevations. This latter result is counter to what most watershed modelers might expect but demonstrates the need to simulate spring snowmelt at smaller spatial and temporal scales and expressly identifies the need to better understand snow ablation variability in complex mountainous topography. Understanding the mechanisms that control the observed snow deposition and ablation variability in the interior Northwest under variable forest types and hydrometeorological conditions will provide essential information for process-based watershed hydrologic and snowmelt models, leading to improved predictability of snowmelt-generated streamflow and erosion processes in hydroclimatologically diverse mountain landscapes of the Intermountain West.

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