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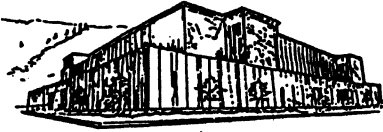
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SNOW ACCUMULATION AND SNOWMELT IN THINNED AND
UNTHINNED LODGEPOLE PINE STANDS, WEST CENTRAL
MONTANA

By
Jason Sappington

B.S. University of Montana, 2003

presented in partial fulfillment of the requirements

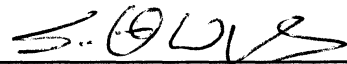
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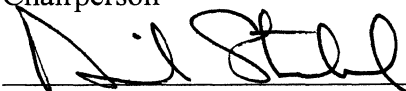
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Snow Accumulation and Snowmelt in Thinned and Unthinned Lodgepole Pine Stands, West Central Montana

Chairperson: Scott Woods *SW*

Alternative thinning treatments can be used to restore the health of forested watersheds and reduce the risks associated with wildfires, but the hydrologic effects of these treatments are largely unknown. In this research I investigated the effects of two silvicultural prescriptions in lodgepole pine stands, one leaving residual trees evenly distributed, (SE) and the other leaving residual trees in 0.2-0.8 ha retention groups, (SG), on snow accumulation and snowmelt in lodgepole stands in Tenderfoot Creek Experimental Forest (TCEF), west central Montana east of the continental divide. I also tested the ability of several snowmelt models to predict melt in the treated stands. Snow accumulation was measured in 2004 and 2005 at 286 points throughout the two treatments and a 13 ha control unit. Snowmelt was measured in twelve lysimeters that were installed in the two treatments and the control in 2004. In 2004, reduced interception resulted in a 20% increase in snow accumulation in the SE treatment relative to the control. In 2005, total snowfall was lower and snow accumulation in the SE treatment was just 9% greater than the control. Increased sublimation on the southern edges of the groups along with wind scour in the openings in the SG treatment offset gains from reduced canopy interception. Consequently, the SG units accumulated less snow than the SE units, and there was no increase in snow accumulation relative to the control unit. There was no difference in the timing of the beginning and end of snowmelt among the treatments, and the average daily melt rates in the treatment and the control were similar. However, the SG treatment had a maximum daily melt rate of 4.4 cm day⁻¹ for sites located in the open compared to 2.6 cm day⁻¹ for sites in the control. A hybrid temperature index model with radiation inputs adjusted for canopy cover was the best way to model snowmelt under varying forest canopy coverage. The contrasting responses in the SE and SG treatments illustrate that alternative harvesting can have substantially different effects on snow accumulation and snowmelt. Management prescriptions for silvicultural treatment of forest stands should take these differences into account.

Acknowledgements

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Most importantly I would like to thank my wife Kate for her constant support and encouragement. Without her support this research would not have been possible. It is to her this thesis is dedicated.

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Introduction

Runoff from the winter snowpack in forested upland watersheds is the primary water source in the western United States, and is critical for the survival of many organisms in the region due to a lack of summer precipitation. Streamflow varies depending on the amount of snow accumulation and the rate and timing of snowmelt, both of which can be altered by human activities such as forest harvest and fuel reduction and by natural disturbance due to fire, insect infestation and disease. Understanding and predicting the effects of forest management and natural disturbance on snow accumulation and melt is an important element of watershed management in the western United States.

Snow accumulation in forested watersheds

Snow accumulation in forested watersheds is dependent on canopy structure characteristics, topography, elevation and climate (*Pomeroy et al., 2002*). The forest canopy intercepts a portion of the snowfall, subjecting it to redistribution and sublimation. In general, snow accumulation rates are inversely proportional to canopy density and the difference in snow accumulation between open areas and areas under the forest canopy increases with increasing snowfall in the open (*Harestad and Bunnell, 1981 ; Lundberg and Koivusalo, 2003*). Losses due to wind scour and evaporation are generally lower under the canopy, and this may offset the reduced net snowfall caused by interception.

Topography is an important control on snow accumulation because south and west facing slopes absorb greater inputs of solar radiation and tend to be drier than north and east facing slopes. South facing slopes may also have sparser canopies

allowing more wind and solar inputs to affect the snow pack. Elevation lapse rates control what form precipitation is in when it falls to the earth's surface; higher elevations generally receive more of the precipitation as snow.

Tree removal during forest harvest or fuel reduction efforts may increase or decrease snow accumulation depending on the relative magnitude of gains due to reduced canopy interception and losses due to increased wind scour and evaporation (*Golding and Swanson, 1986; Stegman, 1996*). In the cold, windy environment of the central and northern Rocky Mountain Region, small clearcut openings have been shown to accumulate more snow than under (*Troendle and King, 1985; Koivusalo and Kokkonen, 2002*) because of reduced interception and redistribution of snow from the adjacent forest (*Hover and Leaf, 1967*). Redistribution is a direct result of changes in the aerodynamics of a forest stand after harvesting. Openings in the forest create wind eddies that scour snow from the lee side of the adjacent forest and redistribute it in the opening (*Gary, 1980*). In larger openings, the reduction of interception may be offset by increased wind scour and evaporation, leading to an overall reduction in snow accumulation.

Snowmelt in forested watersheds

Snowmelt rates are a function of the depth of snow accumulation, the solar and thermal radiation flux, and the wind speed. Snow accumulation varies depending on the factors previously described and, in general, snow will take longer to melt in areas with deeper snow (*Anderton et al., 2004*). The presence of snowdrifts can prolong the snowmelt period by several weeks compared to a more uniform snowpack distribution (*Tarboton et al., 2000*).

Net radiation – the sum of net solar and net thermal radiation – provides the energy necessary for snowmelt. Solar radiation or shortwave radiation is the energy from the sun, and is made up of a range of wavelengths that include visible light as well as ultraviolet and near infrared. Thermal or longwave radiation is the energy re-emitted from vegetation, clouds and topography and consists of wavelengths from 3.0 μm to 50 μm . The importance of each of the radiation components for snowmelt varies depending on the time of year and the physical properties of the site. When shortwave radiation enters the atmosphere it is absorbed, scattered, and reflected by terrestrial objects. When it hits a snowpack, shortwave radiation can be absorbed and transformed into sensible heat to be used for melt purposes. A portion of shortwave radiation is reflected, and the ratio of reflected to incoming shortwave radiation is the albedo. The albedo decreases as the season progresses as the snow surface becomes covered in debris such as pine needles and dirt. The decreased albedo allows more absorption of shortwave radiation thus increasing the importance of shortwave radiation for snowmelt.

Longwave radiation re-emitted from the forest canopy, branches and stems is a major source of energy for snowmelt under a forest canopy. Additional energy for snowmelt under the canopy comes from direct solar radiation passing through gaps in the canopy. In the winter months, low sun angles and short days reduce the amount of direct solar radiation reaching the forest and snowpack. During this time the thermal radiation from the atmosphere and surrounding terrestrial objects is the primary source of energy available for melt.

Wind blowing across the snow surface can transfer energy to the surface by turbulent transfer of latent and sensible heat, providing additional energy for melt.

Turbulence will also lift individual grains of snow and physically transport them across a landscape. Vegetation, debris, and topography will disrupt the transporting of the snow, by wind, causing the snow to accumulate as snowdrifts.

The physical factors controlling snowmelt are complex, spatially variable and interact with each other in a multitude of ways. The result is that snowmelt is also spatially variable at scales ranging from just a few meters to tens of kilometers. Understanding and modeling this variability represents a challenge for snow hydrologists. The challenge is particularly great when dealing with forest stands that have been manipulated by thinning or harvest. Forest harvest and thinning operations contribute to the complexity of melt by affecting the distribution of snow and the energy inputs to the snowpack. When trees are removed, the snowpack is exposed to increased solar inputs, turbulent heat transfer, and redistribution, while thermal radiation inputs from the trees are reduced.

Snowmelt modeling provides a means of predicting the rate and magnitude of snowmelt based on meteorological measurements such as solar radiation flux, air temperature and wind speed. There are three main approaches to snowmelt modeling: the temperature index method, methods based on the energy budget of the snowpack, and hybrid methods that are based on a combination of temperature index and energy budget approaches. While snowmelt models have been widely applied in open areas, calibration for the effects of a forest canopy remains problematic.

Current concerns in forest management

Natural disturbances such as wildfires, beetle infestations, and disease have similar effect on snow accumulation and melt to forest management in that they can periodically reduce canopy density and create openings. These disturbance events may add temporal variability to the rate and timing of runoff from forested watersheds. Decades of fire suppression along with climatic variability has resulted in western forests growing into more uniform and dense stands, thus reducing the amount and variability in snowmelt runoff. In addition, these dense stands are susceptible to catastrophic wildland fires, which can lead to severe erosion and risks to human life and property.

In recent years there has been a move towards proactive restoration of forests affected by fire suppression through a combination of thinning and prescribed fire. Thinning treatments have the advantage of providing an immediate reduction in canopy density and fuel loads without the risks associated with using prescribed fire as a management tool. Thinning can also provide an economic benefit if the cut timber is commercially viable, and is generally more acceptable than clearcutting as a management tool. Information on the hydrologic effects of thinning prescriptions is needed if forests are to be managed in a holistic and ecologically sustainable manner. However, relatively few studies have focused on the hydrologic effects of thinning treatments as compared to the wider literature on the effects of clearcutting.

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 and climatic variability may have radically altered the structure of these forests. 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 a part of these investigations, two silvicultural prescriptions, one leaving residual trees evenly distributed and the other leaving residual trees in groups were applied to lodgepole pine stands on the Tenderfoot Creek Experimental Forest in west-central Montana in 1999 and 2000. The objectives of the study described here were to: 1) determine the effect of the treatments on the magnitude and spatial variability of winter snow accumulation, 2) determine the effect of the treatments on the timing, rate and spatial variability of snowmelt, and 3) develop a simplified melt model to predict snowmelt in treated stands using readily available site metrics.

Study Area

The 3600 ha Tenderfoot Creek Experimental Forest (TCEF) lies in the headwaters of Tenderfoot Creek in the Little Belt Mountains of west-central Montana (Figure 1). TCEF was established in 1961 for watershed research but its scope was expanded in 1980 to include all aspects of landscape level forest management. Elevations in the experimental forest range from 1838 m to 2421 m. A broad basin like topography in the upper elevations gives way to talus slopes and steep-sided canyons in the lower elevations. Lodgepole pine is the dominant tree species in the four subalpine fir habitat types that occur within the forest. Other

Figures

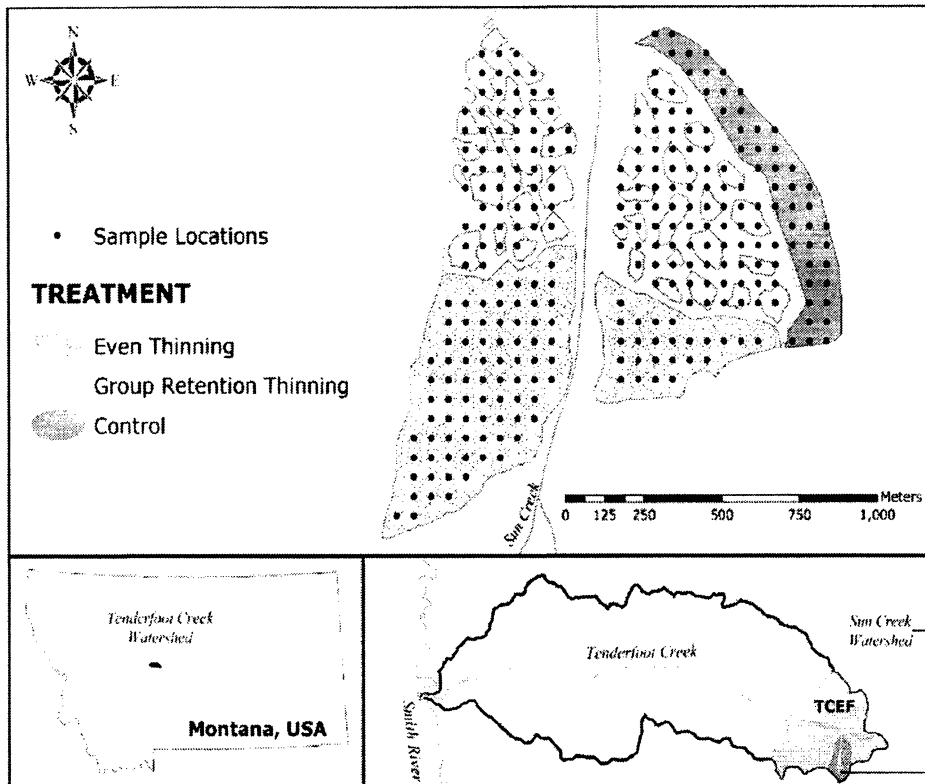


Figure 1. Location map of study site. Inset map on lower left shows location of the Tenderfoot Creek watershed in west-central Montana. Inset map on lower right shows the location of Tenderfoot Creek Experimental Forest (TCEF). Main map shows the Sun Creek watershed in TCEF, with the experimental thinning treatments.

species included subalpine fir (*Abies lasiocarpa*), Englemann spruce (*Picea engelmannii*), whitebark pine (*Pinus albicaulis*), and quaking aspen (*Populus tremuloides*). The elevation weighted mean annual precipitation at TCEF is 88.4 cm (Farnes *et al.*, 1995). Between October and April most of the precipitation falls as snow, forming a winter snowpack that melts between early May and late June. The mean monthly temperature at the Onion Park Snotel site within TCEF ranges from -8.4°C in December to 12.8°C in July.

Methods

Thinning Treatments

In 1999 and 2000, two experimental thinning treatments were applied in the 346 ha Sun Creek subwatershed of Tenderfoot Creek (Figure 1). Each of the forest thinning treatments reduced the average basal area from 200⁻¹ acre to 60⁻¹ acre, but the configuration of the tree removal varied between the two treatments. In one of the treatments (SE), tree removal was conducted evenly across the unit (Figure 2), while the other treatments (SG) comprised uncut 0.2 to 0.8 ha groups of trees with intervening areas where all of the trees were removed (Figure 3). In both treatments the trees were removed using ground based felling and yarding systems. Both treatments were designed to simulate wildfire scenarios; the SG treatment simulated a stand replacing fire that left a mosaic of patches of trees with intervening areas where all the trees were killed, while the SE treatment replicated the effects of a mixed severity wildfire where many of the mature trees would survive the fire.



Figure 2. Even thinning treatment in the Sun Creek watershed, April 2003

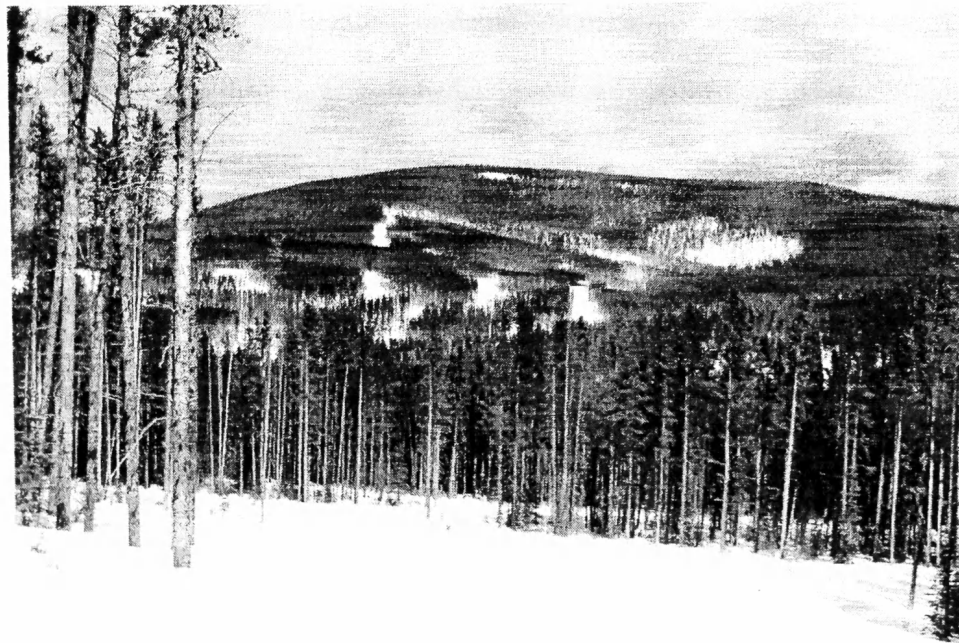


Figure 3. Group retention thinning treatment in the Sun Creek watershed, April 2003. Foreground is an opening between groups. Open corridors in the distance are part of the group retention treatment on the opposite hill slope.

Snow Accumulation Measurements

Snowpack measurements were conducted near the peak of the seasonal snow accumulation in 2004 and 2005 in both of the treatments and an uncut 13 ha control stand on the east side of the Sun Creek watershed. The control stand is at a similar elevation to the treatment plots. The measurements were conducted on a systematic 55 m grid oriented in the cardinal directions. The grid was created using ArcGIS and then transferred to the field using a Geographic Positioning System (GPS) and a tape and compass. A 30-meter buffer zone was defined around the edge of the units to reduce edge effects. Approximately 286 points were sampled in each of the two study years. Survey point locations were marked with a 4 ft tall PVC pipe. In the SG treatment, locations inside an uncut group of trees were designated as “group” sites (SG-I) while those that fell in the opening were designated as “open” sites (SG-O). At each survey location, SWE and snow depth was measured at three locations within two meters of the pole using a Federal snow sampler and the average of the three measurements was recorded.

Measurements conducted in 2004 suggested that snow accumulation varied with position relative to the edge of the retention groups in the SG treatment. Therefore in 2005, snow depth was measured along north-south and east-west transects extending through 19 of the retention groups in the SG treatment. Each transect started 30 meters from the edge of a group and ended 30 meters from the edge in the opening on the opposite side of the group. Snow depth measurements were taken every 5 meters using a Federal Snow Sampler.

Snowmelt Measurements

Twelve snowmelt lysimeters were installed in TCEF in 2004 and 2005 to investigate the effects of the treatments on the rate and timing of snowmelt. The lysimeter locations were chosen to capture the various elevations, aspects, and canopy coverage within the two treatments and the control (Figure 4). Three lysimeters were placed in the control unit, three in the SE treatment, and six in the SG treatment. The lysimeters in the control unit were placed at least 50 m from any natural or man-made openings to reduce edge effects. In the SG treatments the lysimeters were paired, with one lysimeter inside a retention group and the other located at the same elevation and aspect in an adjacent opening.

Each lysimeter was a 1 m x 1 m steel pan with a 10 cm high rim welded around the outside and a drain near the front center. A grid of expanded steel was placed in the bottom of the lysimeter and a screen was placed over the drain hole to reduce the possibility that needles, branches and other debris would block the drain. Snowmelt percolating into the pan was routed to a tipping bucket mounted in a cooler buried beneath the ground surface in front of the pan. Each tip of the tipping bucket mechanism indicated approximately 0.3 mm of melt ($\sim 300 \text{ cm}^3$ of melt water). A Hobo® Event Logger recorded the date and time of each tip. Data from the event loggers was downloaded twice each year, at the time of the snow accumulation survey and after snowmelt was complete. The tipping bucket mechanisms were calibrated prior to deployment in the field, in October of each year and after the final snowmelt season in July 2005. Field calibrations were performed by allowing approximately 40 L of water, equivalent to 40 mm of melt, to run into the lysimeter over a 2-3 hr time period.

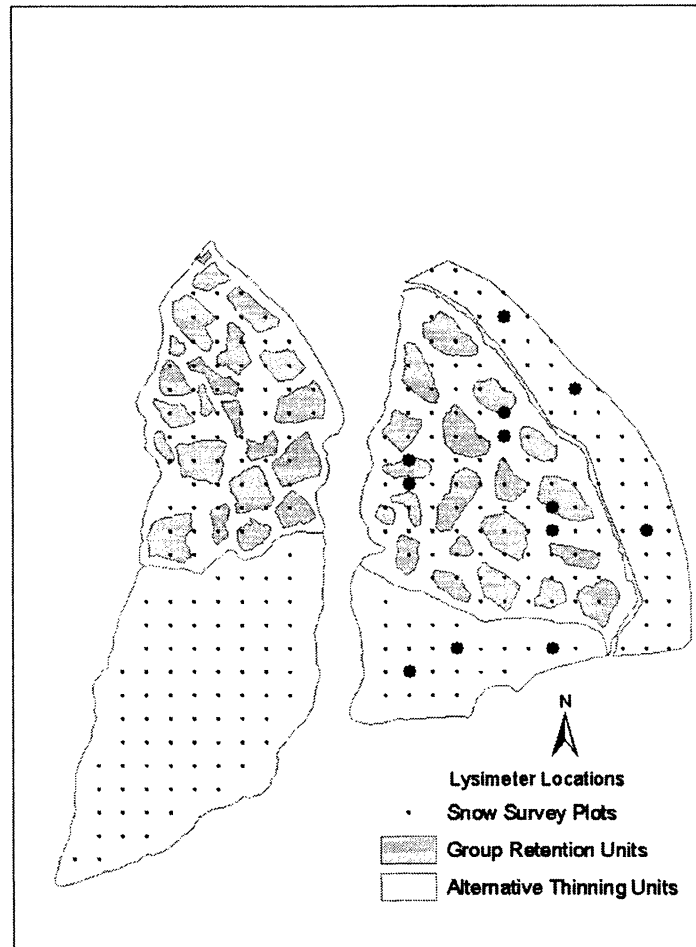


Figure 4. Location of the twelve lysimeters (shaded circles) in the two treatments and in the control.

Ancillary Field Data

Data from the Onion Park SNOTEL site, which is located within TCEF at a similar elevation to the treatment and control units, was used to compare the winter snowpack characteristics in 2004 and 2005 to the long-term average.

An automated weather station was installed in the SE treatment during the winters of 2004 and 2005. Upward and downward facing CM3 pyranometers measured the incoming and reflected solar radiation, and a NR-Lite net radiometer measured the net radiation. Wind speed, air temperature and relative humidity were measured using Campbell Scientific electronic sensors. Output from the sensors was recorded each hour by a Campbell Scientific CR10-X data logger equipped with a solar panel power source.

In 2005, I-Button temperature sensors were installed at each of the lysimeters, one at ground level and one two meters above the ground. These sensors recorded temperature values every hour throughout the melt period.

Canopy density at each of the snow survey and lysimeter locations was determined from hemispherical photographs taken with a Fuji Finepix digital camera equipped with a fisheye lens. All photos were processed using the Gap Light Analyzer (GLA) software package. Effective Leaf Area Index (ELAI) and the percent open canopy were obtained from the photographs. Elevation, aspect, latitude, longitude, and slope were recorded at each site. A geographical positioning system was used to collect the elevation and spatial coordinates of each site. A clinometer and a compass were used to measure slope and aspect, respectively.

Snowmelt Modeling

Three types of model were used to predict snowmelt in TCEF; a temperature index model, a hybrid model, and an energy balance model. A prototype for each model was first calibrated to daily snowmelt data from the Onion Park SNOTEL station. The calibrated models were then used to predict the melt at each of the lysimeters. Model fit was evaluated using the Nash - Sutcliffe, R_{NS}^2 (Nash and Sutcliffe, 1970):

$$R_{NS}^2 = 1 - \frac{\sum_{i=1}^N (Q_i - \hat{Q}_i)^2}{\sum_{i=1}^N (Q_i - m_Q)^2} \quad (1)$$

where Q_i is the i^{th} observed value, \hat{Q}_i is the i^{th} predicted value, m_Q is the mean of the observed values and $i=1,2,3$ etc. Values for R_{NS}^2 between 0 and 1 indicate that the modeled values provide a better estimate than a simple average of the observed values.

Temperature index method

The basic form of the temperature index model (*Martinec, 1989; Davies, 1997; Hock, 2003*) is:

$$M_f = C_f (T_{ave} - T_b) \quad (2)$$

where M_f is the depth of daily melt (*cm*), and C_f is the coefficient of melt ($cm \text{ } ^\circ C^{-1}$), T_{ave} is the average daily temperature ($^\circ C$), and T_b is the base temperature, which is usually taken to be $0^\circ C$. Correctly estimating C_f is critical for accurate

prediction of the melt rate using the temperature index method. In this study separate values for C_f were calculated for April, May and June using historical snowmelt and temperature data from the Onion Park SNOTEL site. For each year in the period of record all the positive values for daily average temperature during a month were summed and plotted against the total melt for the month. The total melt was calculated as the overall decrease in SWE plus the daily rainfall over the period. The melt coefficient for each month was the slope of the linear regression of total melt versus the summed positive daily temperature values.

Hybrid method

Brubaker et. al. (1996) and Kustas et al. (1994) proposed the following hybrid model for predicting snowmelt:

$$M = a_r T_{ave} + m_Q Rn \quad (3)$$

where M is melt ($cm d^{-1}$), a_r is a restrictive degree-day factor, m_Q is a conversion factor for energy flux density to snowmelt depth ($cm d^{-1} (Wm^{-2})^{-1}$), and Rn is the net radiation (Wm^{-2}). By incorporating the net radiation, the hybrid model should provide a better estimate of melt than the temperature index method, without the complexity involved in using the energy balance approach. Daily site-specific values for a_r can be calculated using wind speed, humidity, and temperature or the model can be calibrated using a single value to represent the entire snowmelt period. In this study both seasonal and daily a_r values were used and their ability to accurately predict melt was compared. Climate data for the hybrid equation was obtained from the weather station installed in the SE treatments.

Energy budget method

The general form of the energy budget equation is:

$$S = (k + L) + H \pm (LE) + R + G \quad (4)$$

where S is the energy available to melt snow, $(k+L)$ is the net radiation, H is the turbulent exchange of energy, (LE) is the exchange of latent heat, R is the energy input from rainfall, and G is the energy input from the ground. The melt rate (ΔW) is calculated from:

$$\Delta W = \frac{S}{\rho_w \cdot \lambda_f} \quad (5)$$

where ρ_w is the density of water, and λ_f is the latent heat of fusion. The energy budget model is the most data intensive method for calculating melt, but it is also usually assumed to be the most accurate because it directly quantifies the physical, energy-based processes that result in snowmelt. All the climate data used to calculate the melt rate was obtained from the weather station located in the treatment units.

Modeling of canopy effects

To adjust the hybrid and energy budget models for canopy effects, radiation under the canopy was calculated in accordance with USACE (1956). Longwave and shortwave data was collected in the opening for melt years 2004 and 2005. Net longwave radiation under the canopy (L_{NC}) was calculated from:

$$L_{NC} = F \times (\sigma T^4 - (\sigma T^4 - 2.5)) + (1 - F) \times L_{open} \quad (6)$$

where F is a measure of forest canopy, σ is the Stefan-Boltzmann constant, and L_{open} is the net longwave radiation in the open. Net shortwave radiation under the canopy (K_{NC}) was calculated from:

$$K_{NC} = K_{open} \times \exp^{(-3.91 \times F)} \quad (7)$$

where K_{open} is the shortwave radiation measured in the opening and F is a measure of forest cover. Net radiation under the canopy Rn_{can} was calculated from:

$$Rn_{can} = K_{NC} + L_{NC} \quad (8)$$

The calculated values for net radiation under the canopy were used in the hybrid and energy balance models to calculate snowmelt at the lysimeter situated under the forest canopy.

Results

Snow accumulation and melt at Onion Park SNOTEL site

The seasonal maximum snow water equivalent (SWE_{max}) values at the Onion Park SNOTEL site were within 4% and 3% of the 10-year mean in 2004 and 2005, respectively (Figure 5). The primary difference between the two years was that in the spring of 2004 snowmelt began over four weeks earlier than in 2005. However, several cool periods and spring snow slowed the rate of snowmelt in 2004, so that the end of snowmelt occurred at near the same time in both years. The 2004 snow survey in Sun Creek was conducted 9 days after the peak snow accumulation at Onion Park, when the SWE was approximately 97% of the SWE_{max} . In 2005, the

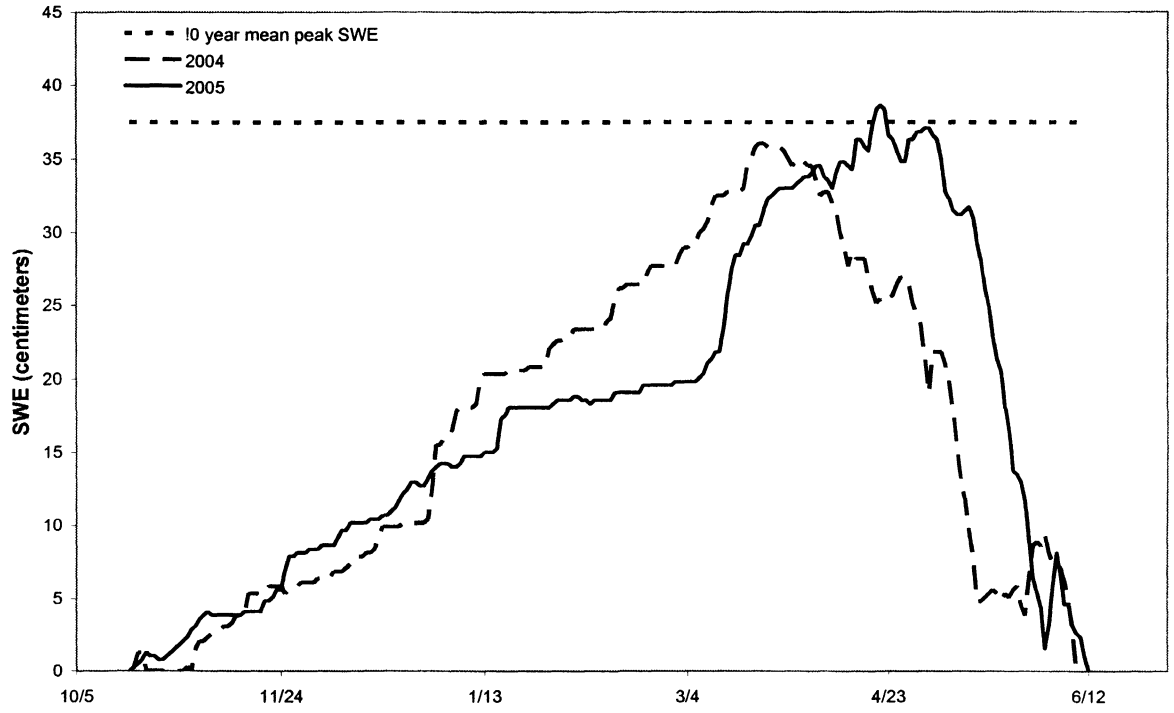


Figure 5. Snow water equivalent at the Onion Park SNOTEL site in 2004 and 2005.

survey was conducted approximately a month before to the peak snow accumulation, when the SWE at Onion Park was just 76% of the SWE_{max} .

Snow accumulation in treatments in 2004 – 2005

Differences in snow accumulation between the treatments and the control followed similar patterns in both 2004 and 2005. However, the mean SWE in the treatments and control was 35 to 40% higher in 2004 than 2005 (Table 1), primarily because the 2004 snow survey was conducted nearer the maximum snow accumulation. In both years, the mean SWE in the SE treatment was higher than in either the SG treatment or the control (Table 1), presumably due to the decrease in interception associated with thinning. The largest difference was in 2004, when the SE treatment had 20% more SWE than the control.

In contrast with the SE treatment, the mean SWE in the SG treatment was within 3 and 1% of the control in 2004 and 2005, respectively (Table 1). There was a strong contrast between the SWE inside the retention groups (SG-I) and in the openings (SG-O). The average SWE for the SG-O sites was 25% higher than for the SG-I sites in 2004 and 35% higher in 2005. Although, the canopy density was similar for sites in the retention groups and in the control, the mean SWE inside the groups was less than the mean SWE for the control in both years. In addition, the mean SWE for sites in the open in the SG treatment was up to 7.2 cm less than in the SE treatment, despite the absence of a canopy in the former. The snow depth measurements conducted in 2005 along transects extending through 19 of the retention groups confirmed the results of the SWE measurements; the mean snow

Table 1. Mean, standard deviation, coefficient of variability (CV), maximum and minimum snow water equivalent in the two treatments and the control in 2004 and 2005.

	2004			2005		
<i>Treatment</i>	<i>SE</i>	<i>SG</i>	<i>Control</i>	<i>SE</i>	<i>SG</i>	<i>Control</i>
<i>Mean</i>	33.5	27.2	28.0	20.1	17.8	18.0
<i>STDEV</i>	3.9	6.3	4.7	3.1	5.4	3.0
<i>CV(%)</i>	11.5	23.1	16.9	15.2	30.3	16.7
<i>Min</i>	15.2	5.0	18.6	11.0	5.9	11.0
<i>Max</i>	43.2	41.5	47.4	27.9	30.5	23.7
<i>N</i>	102	144	40	101	143	45

depth in the openings was 109cm compared to just 73 cm in the interior of the groups.

Variability of SWE, as indicated by the coefficient of variation (CV) of the snowpack measurements, was slightly lower in the SE treatment than in the control in both years (Table 1), while the CV in the SG treatment was considerably higher than in the SE treatment or the control (Table 1). Much of the increased variability in the SG treatment was due to a strong contrast in snow accumulation between the SG-I and SG-O sites. However, the transect based measurements indicated that snow depths also varied with position within the retention groups, and this added to the overall variability of the SWE. Snow depth consistently decreased along the north – south transects, so that snow depth on the south-facing side of the groups was half that on the north– facing side. Similarly, sites in the open within 30m of the north facing edge had a mean snow depth of 116cm compared to 108cm for sites in the open within 30m of the south-facing edge (Figure 6). No such patterns were observed for snow depth along the west-east transects, suggesting that the differences were due to the greater exposure of south-facing edges to solar radiation.

Snowmelt in treatments

In 2004, seven of the twelve lysimeters functioned properly, two in the control, one in the thinned unit, and four in the group unit. Two of the functional lysimeters in the group unit were inside the groups and two were in opening between groups. In 2005, seven of the twelve lysimeters collected data: two in the thinned treatment and five in the group treatment. However, all of the lysimeters were

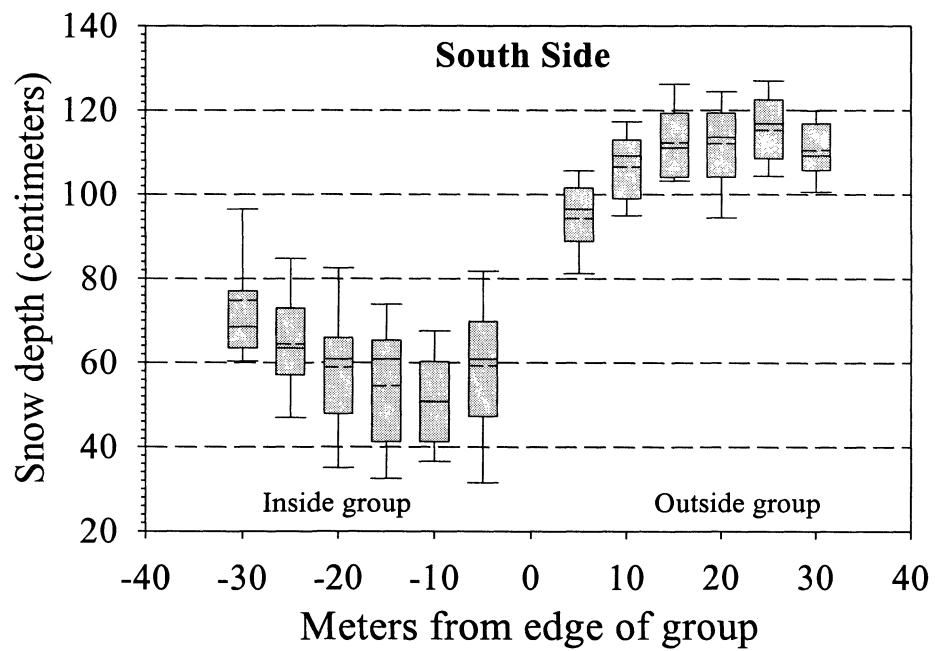
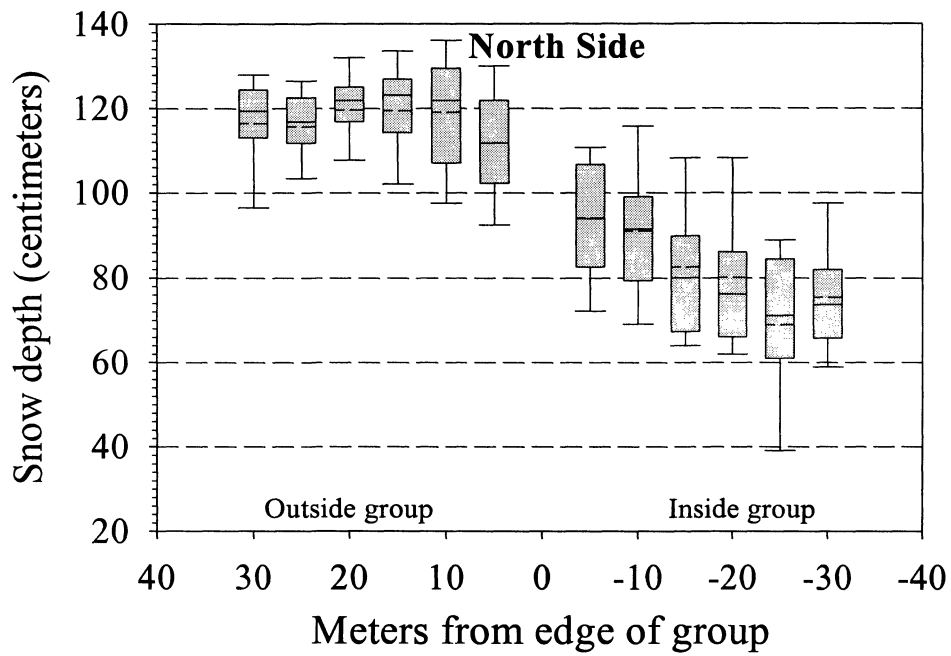


Figure 6. Snow depth relative to the edge of groups.

seriously affected by clogging and freezing in 2005, so that only the 2004 data were used for assessing the effectiveness of the various melt models.

Snowmelt at most of the lysimeter sites started on April 9th and ended on June 10th 2004 (Table 2). Both the beginning and end of snowmelt at all of the lysimeter sites was later than at the nearby Onion Park SNOTEL site, where snowmelt started on March 19th and ended on June 4th. Surprisingly, there was no difference in the timing of melt between sites in the open and in the retention groups in the SG treatment or in the control. The lysimeter at site 152 stopped recording melt on May 8th but this was likely because of an equipment failure rather than the actual end of melt as the other lysimeter in the control continued recording melt for almost another month.

The overall pattern of melt in the lysimeters was consistent with the observed temperature fluctuations during the melt period (Figure 7). For example from April 30th to May 8th the average daily temperatures was 8°C and melt was more rapid. On May 10th the temperature dipped to near 0°C and the melt rate declined substantially. The average daily melt rates in the group treatment (0.76 cm day⁻¹) and the control (0.78 cm day⁻¹) were very similar. However the maximum daily melt rate at lysimeter 80 in the group retention treatment (4.4 cm day⁻¹) was almost double that recorded in the control (2.6 cm day⁻¹). The total melt recorded in the SG-I sites was within 3% of that measured in the control. However the total melt at the SG-O sites was 16 to 37% higher than at either the SG-I or the control, reflecting the higher peak snow accumulation (Figure 7).

Melt rates at sites within the control were within 14% of each other throughout the melt period. In contrast, one of the lysimeter pairs in the SG

Table 2. Timing of beginning and end of snowmelt at Onion Park (OP) and the snowmelt lysimeters in 2004. SG-I and SG-O indicate sites inside and outside of the retention groups in the SG treatment, respectively. SE indicates the even thinning treatment.

<i>Site #</i>	<i>Start of Melt</i>	<i>End of Melt</i>	<i>Aspect</i>	<i>Elevation (m)</i>	<i>% Open</i>	<i>SWE</i>	<i>Location</i>
OP	19-Mar	04-Jun			100		Open
132	22-Apr	11-Jun	SW	2262	0.37	25.4	SG-I
148	09-Apr	7-Jun	SW	2256	1.00	23.3	SG-O
65	09-Apr	11-Jun	NW	2243	0.32	35.6	SG-I
80	09-Apr	11-Jun	W	2243	0.99	33.8	SG-O
108	05-May	11-Jun	W	2208	0.96	35.6	SG-O
152	09-Apr	08-May	Flat	2274	0.36	26.7	Control
52	24-Apr	11-Jun	NW	2246	0.26	30.5	Control
239	07-May	11-Jun	NW	2196	0.93	34.8	SE

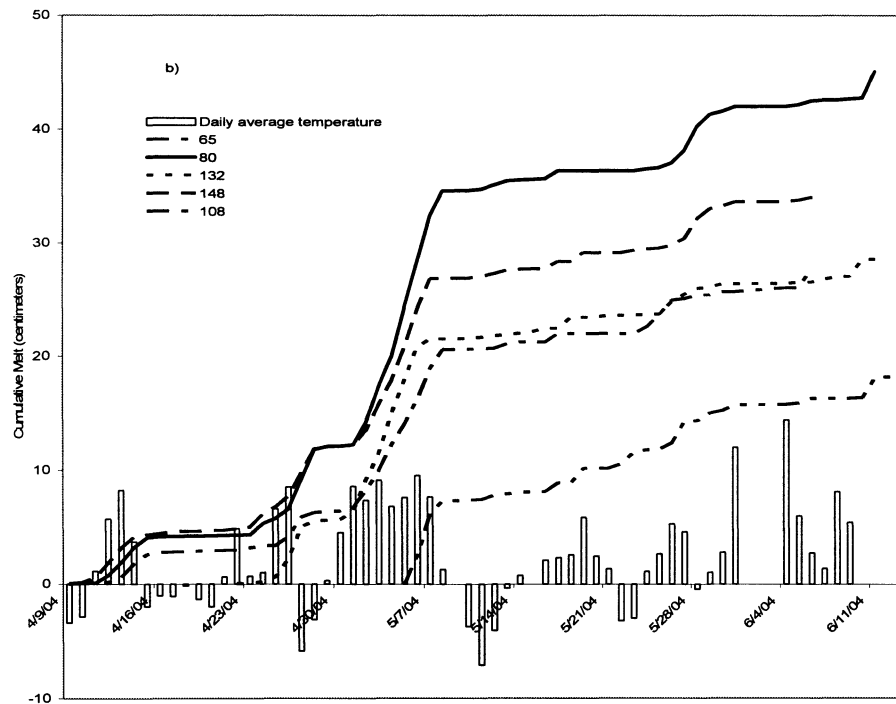
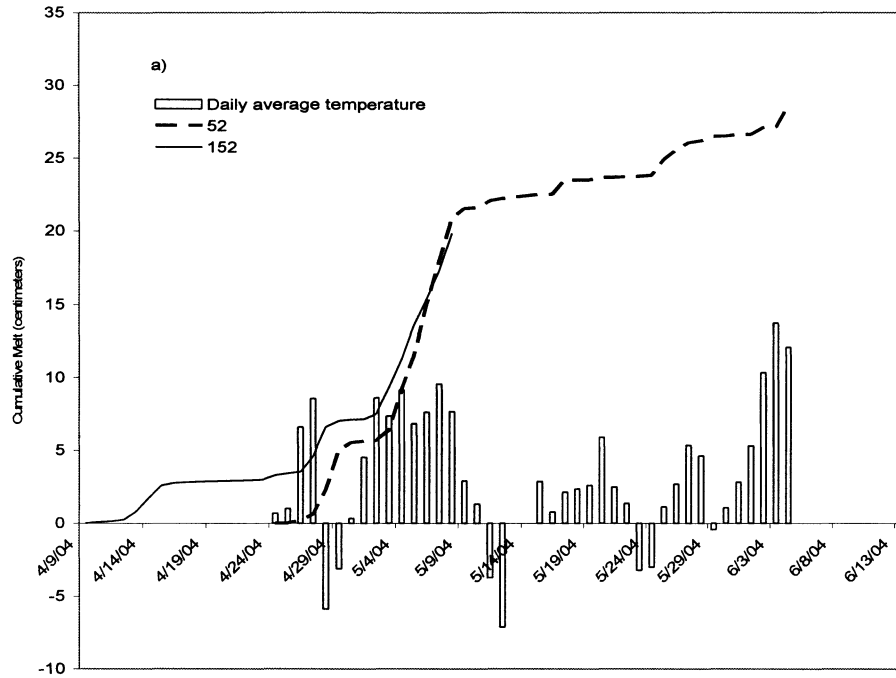


Figure 7. Cumulative melt rates in snowmelt lysimeters 2004 a) in the group retention unit and b) control sites 80, 148 and 108 are open sites, while sites 65 and 132 are group sites. Site 108 experienced technical problems during the melt season.

treatment indicated a consistently higher daily melt rate for the site in the opening (lysimeter 80) than for the site in the interior of a retention group (lysimeter 65) (Figure 8). For example on May 4th lysimeter 80 recorded 4.4 cm of melt while lysimeter 65 recorded just 2.3 cm. This contrast in melt rates was not observed in the other set of paired lysimeters, 148 and 132 (Figure 8). This is likely due to the fact that the “interior” lysimeter in this pair, lysimeter 132 lies within 5 m of the south edge of the group where it presumably receives more solar radiation.

There was not enough data from the SE treatment to allow a comparison to be made with the SG treatment or the control. From the limited data that was collected from lysimeter 239 in the thinned unit, melt the peak rate was higher than in the control and more comparable to the group unit lysimeters.

Snowmelt modeling at Onion Park

Temperature index model

The melt coefficients calculated from the historical data from Onion Park were 0.165, 0.179, and 0.285 cm day⁻¹°C⁻¹ for April, May and June, respectively. Rather than using different melt coefficients for each month, the coefficient corresponding to the month in which the majority of melt occurred was used. In 2004, most of the melt occurred between late April and late May, so the May coefficient of melt was used in the temperature index model. In 2005, most of the melt occurred between late May and early June, so the June coefficient of melt was used to predict melt rates.

In 2004, the temperature index (TI) model provided a reasonably good fit to the observed melt at the Onion Park SNOTEL site. Although, the model

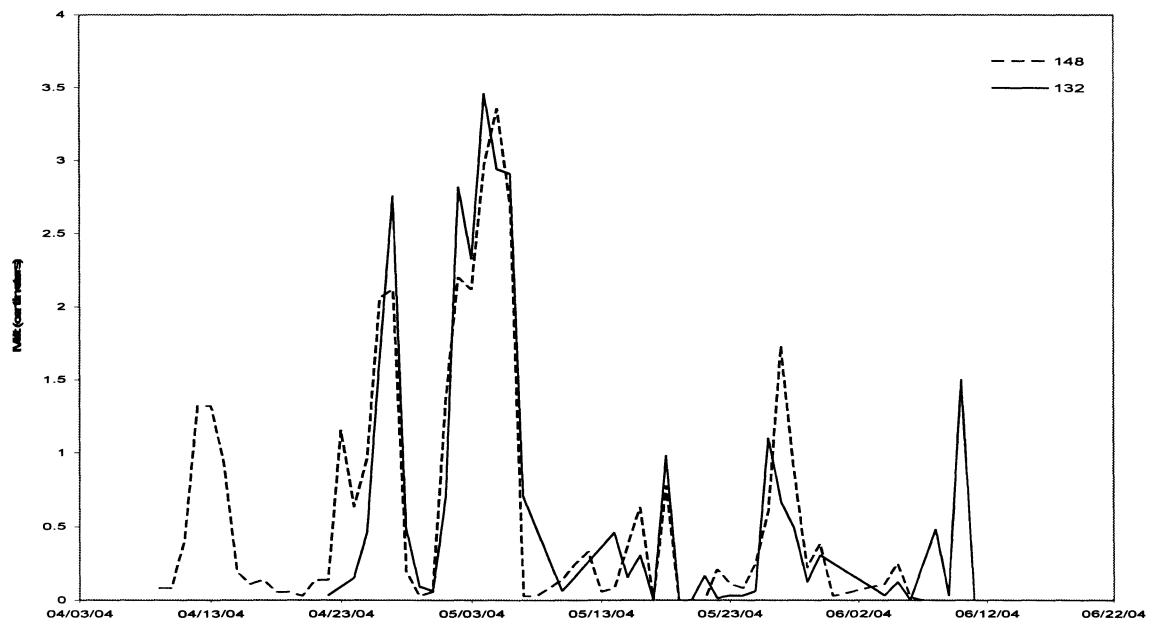
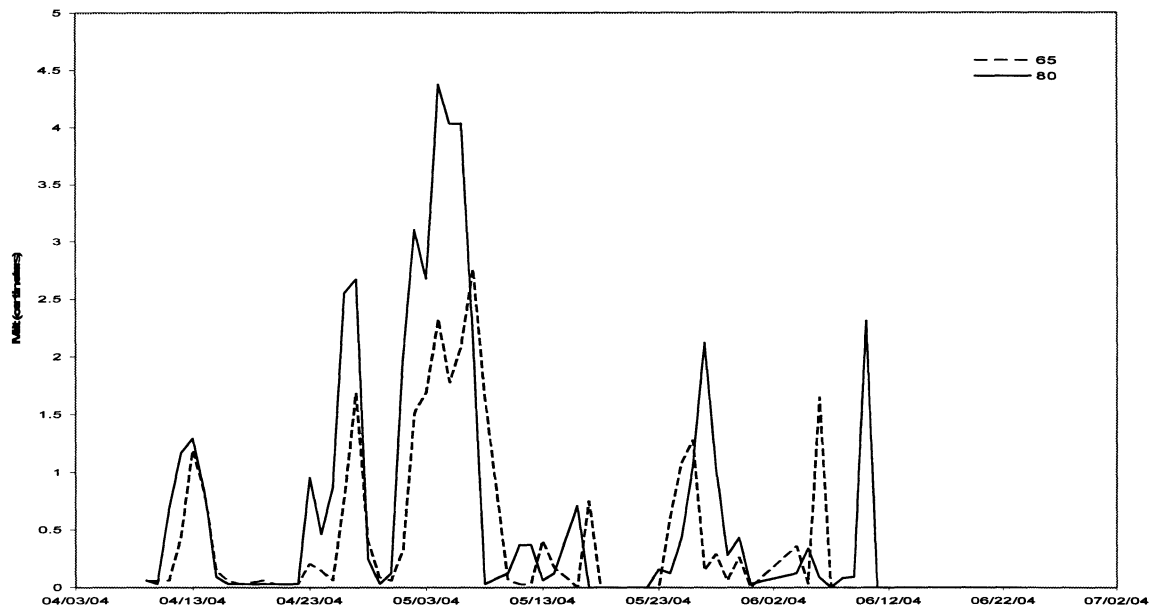


Figure 8. A comparison of daily melt for paired lysimeters 2004. Lysimeter 80 and 148 are open sites while 65 and 132 are located inside the retention groups.

consistently over estimated the daily melt rate towards the end of the melt period, the Nash Sutcliffe R^2 was still fairly high at 0.67 (Table 3 and Figure 9). The model did not perform as well in 2005 when it consistently over estimated daily melt throughout the melt period and the Nash Sutcliffe R^2 was just 0.43 (Figure 9). The model performed better when predicting the cumulative melt during the melt period than it did for individual daily values. The cumulative melt totals predicted by the *TI* were within 17 and 6% of the melt recorded during the snowmelt period at the Onion Park SNOTEL site in 2004 and 2005 respectively (Figure 10).

Hybrid temperature index method

The hybrid temperature index model was used with both seasonal and daily values for the coefficient of melt. The published values for the coefficient of melt ranged from 0.20 to 0.25 $\text{cm } ^\circ\text{C}^{-1} \text{ day}^{-1}$ (Martinec, 1989), however Brubaker et. al. (1996), found that values could be lower if wind and humidity are low. Both hybrid models were poor predictors of daily melt, and performed more poorly than the simple temperature index model (Figure 11). In 2004 the hybrid temperature index model ($HTIM_{sv}$) obtained from using the coefficient of melt from within the range of calculated values had a R_{NS}^2 value of 0.10. When the daily calculated coefficient of melt values ($HTIM_{dv}$) were used the Nash Sutcliffe R_{NS}^2 increased to 0.25 (Table 3). The results were similar for the 2005 data; the R_{NS}^2 values for the $HTIM_{sv}$ and $HTIM_{dv}$ models were just 0.23 and 0.29, respectively (Table 3).

In 2004, the hybrid model performed better when used to predict the cumulative melt. Although, the models over estimated the cumulative melt after the

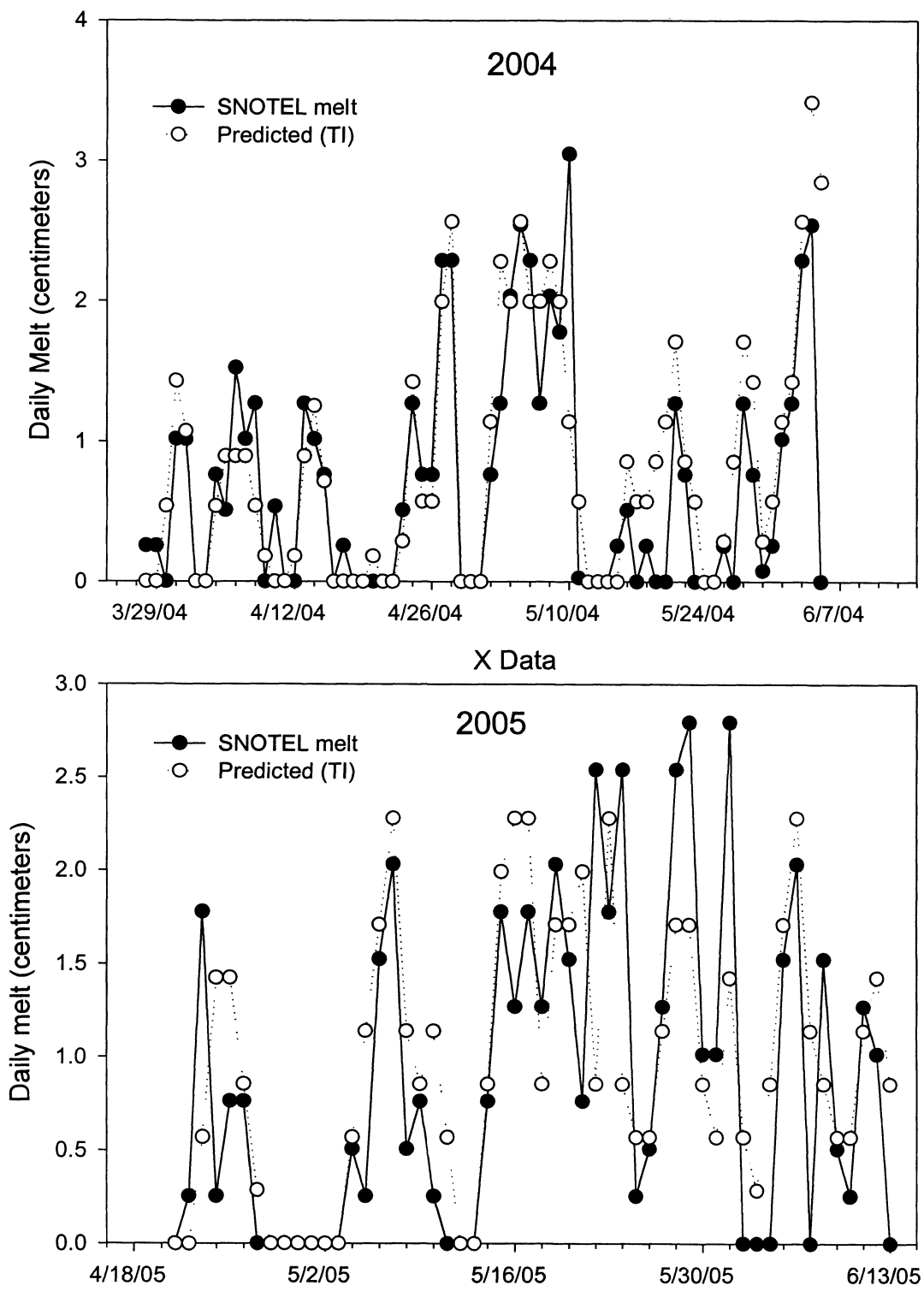


Figure 9. Daily melt for Onion Park and the daily melt predicted by the temperature index model 2004-2005.

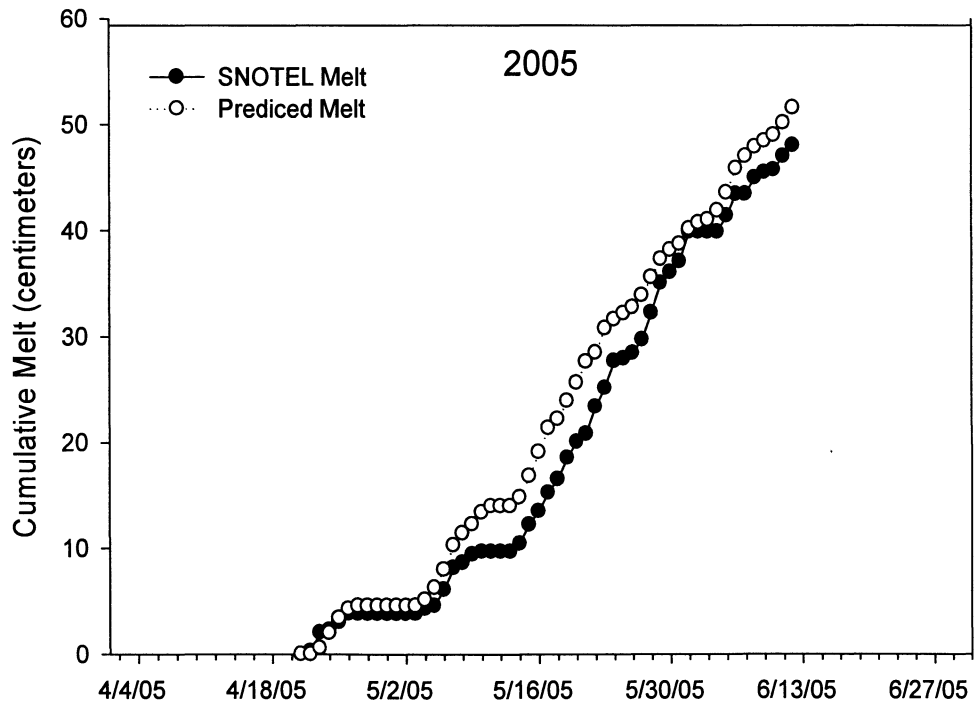
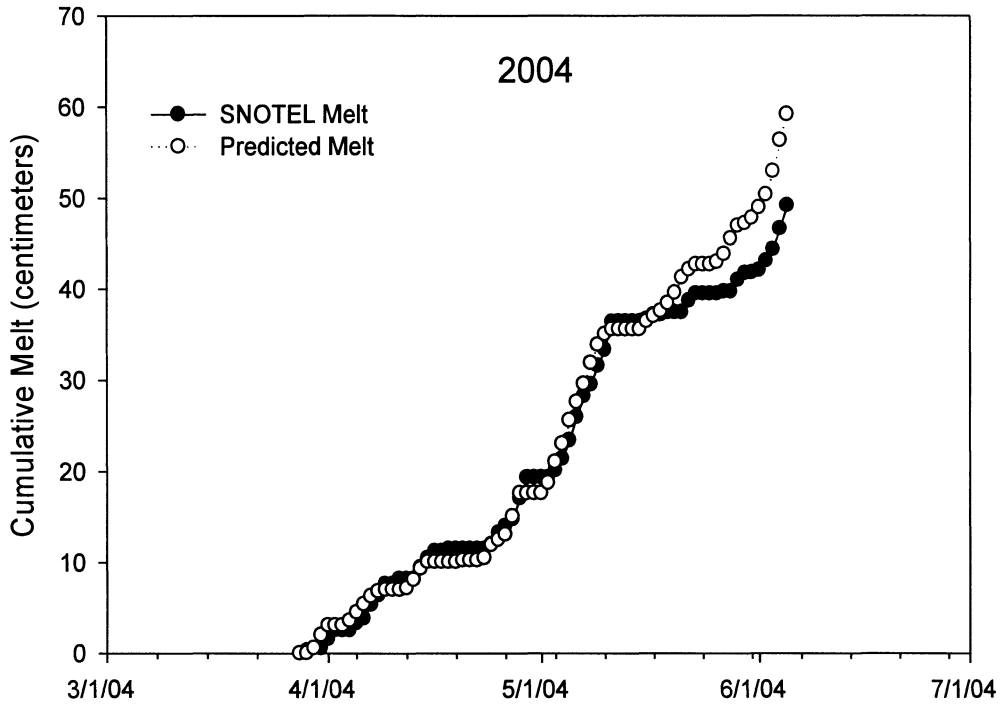


Figure 10. Cumulative melt for Onion Park in 2004 and 2005 compared to the melt predicted by the temperature index model.

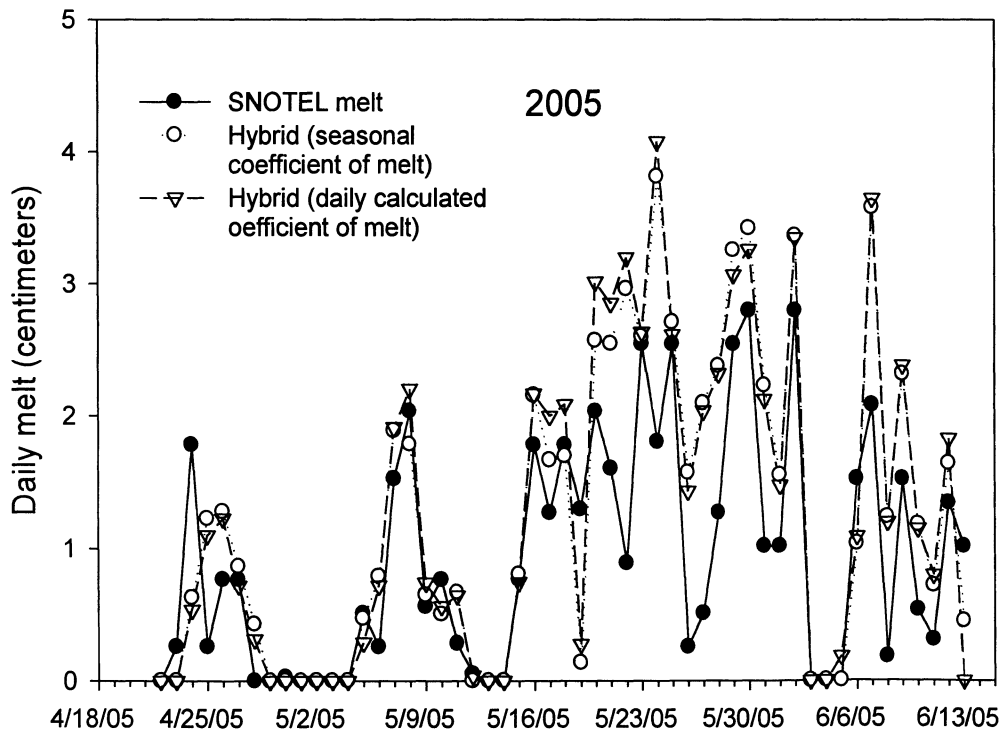
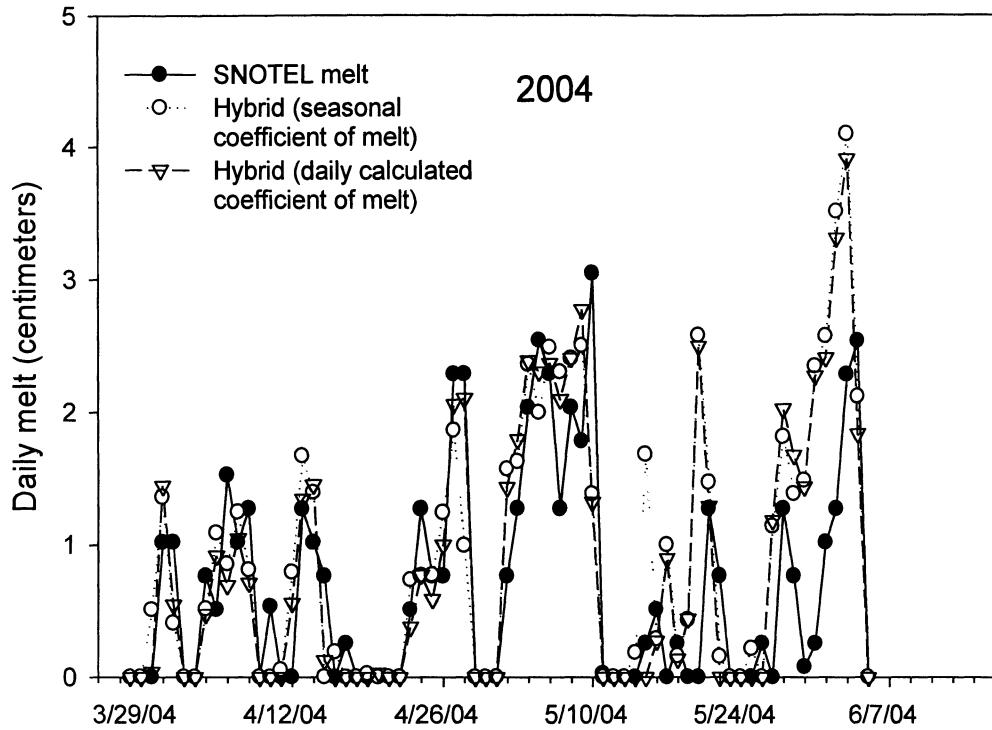


Figure 11. Observed daily melt at Onion Park compared to melt predicted with the hybrid temperature index models. Hollow circles show melt with the seasonal value for the coefficient of melt and hollow triangles are the results of the model with the daily calculated values for the coefficient of melt.

second week in May, the $HTIM_{sv}$ and $HTIM_{dv}$ models over estimated the observed cumulative melt by 22% and 18% respectively at the end of the 2004 melt season. In 2005, the models substantially over predicted melt after mid-May so that by the end of the melt period the $HTIM_{sv}$ over predicted cumulative melt by 27% and the $HTIM_{dv}$ over predicted melt by 29% (Figure 12).

Energy Balance Model

The energy balance (EB) modeling results were similar to those obtained using the hybrid model with a daily coefficient of melt (Figure 13). In 2004 the EB model fit resulted in a R_{NS}^2 of 0.10 for daily melt values, and in 2005 the R_{NS}^2 was 0.25 (Table 3). Similarly to the hybrid model, the EB model over predicted melt by 19% by the end of melt in 2004 (Figure 14). In 2005 the EB model over predicted melt by 29% (Figure 14).

Modeling snowmelt in the treatments

Modeling of snowmelt at the lysimeters was conducted using the hybrid model with a seasonal value for the coefficient of melt. When the model was used to predict snowmelt in the two lysimeters in the open (148 and 80), the results were similar to those obtained at the Onion Park SNOTEL site. A coefficient of melt of 0.15 provided the best fit to the observed values, and resulted in R_{NS}^2 values of 0.29 and 0.43 for lysimeters 148 and 80, respectively (Table 4). The best fit between the observed and predicted values was obtained in the early part of the melt season

Table 3. Nash Sutcliffe coefficient of efficiency (R_{NS}^2) for temperature index (TI), hybrid and energy balance (EB) snowmelt models when used to predict snowmelt at Onion Park SNOTEL station in 2004 and 2005.

<i>Model</i>	<i>2004</i>	<i>2005</i>
<i>TI</i>	0.67	0.43
<i>Hybrid Calculated</i>	0.25	0.23
<i>Hybrid Published</i>	0.10	0.29
<i>EB</i>	0.10	0.25

Table 4. Nash Sutcliffe coefficient of efficiency R_{NS}^2 for hybrid and canopy adjusted hybrid snowmelt models when used to predict melt at six lysimeter sites in 2004. Lysimeters 148 and 80 are in open areas, so the hybrid model and the hybrid canopy model used the same parameter sets.

	<i>Hybrid</i>	<i>Hybrid Canopy</i>
<i>52</i>	-1.91	0.34
<i>152</i>	0.29	0.71
<i>65</i>	-2.61	0.40
<i>132</i>	-1.46	0.22
<i>148</i>	0.29	NA
<i>80</i>	0.43	NA

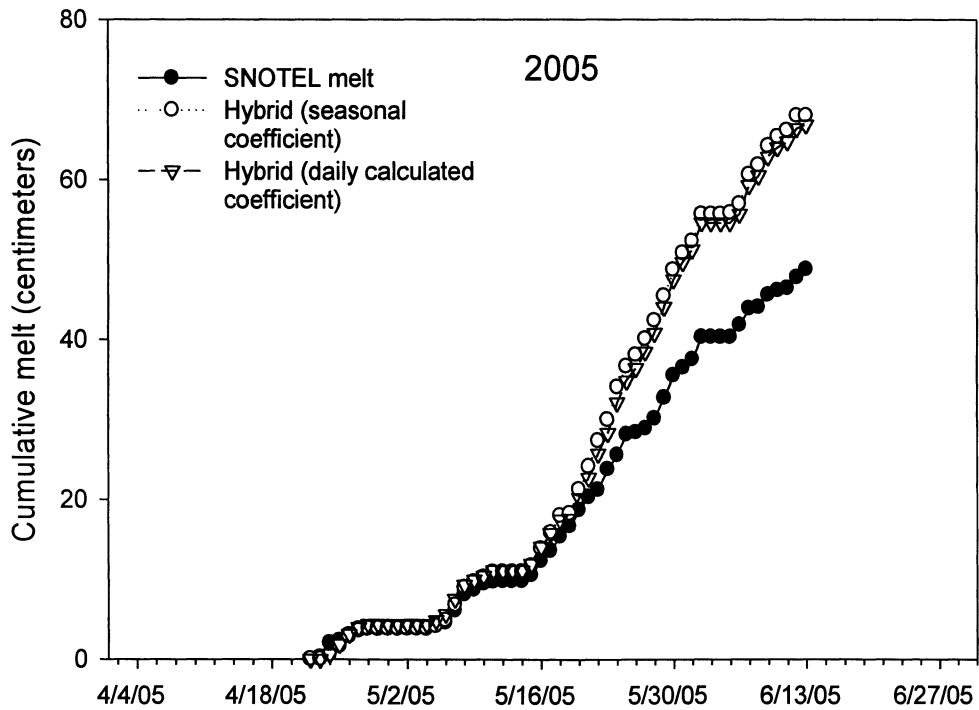
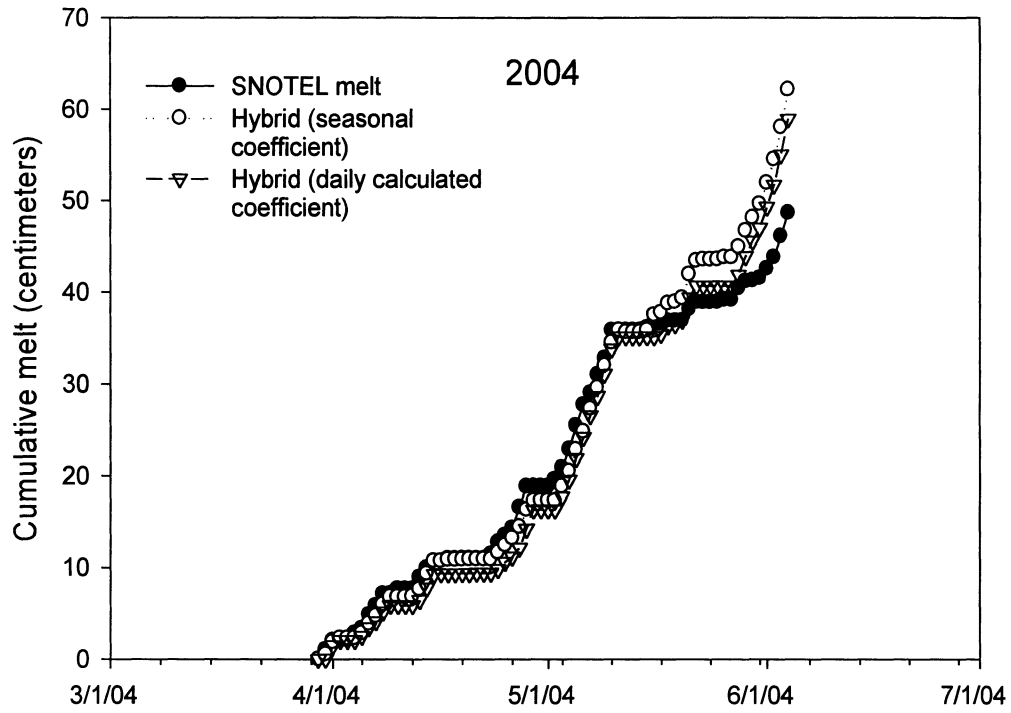


Figure 12. The hybrid model with seasonal values for the coefficient of melt and the hybrid with daily calculated values for the coefficient of melt compared to the melt observed at Onion Park SNOTEL.

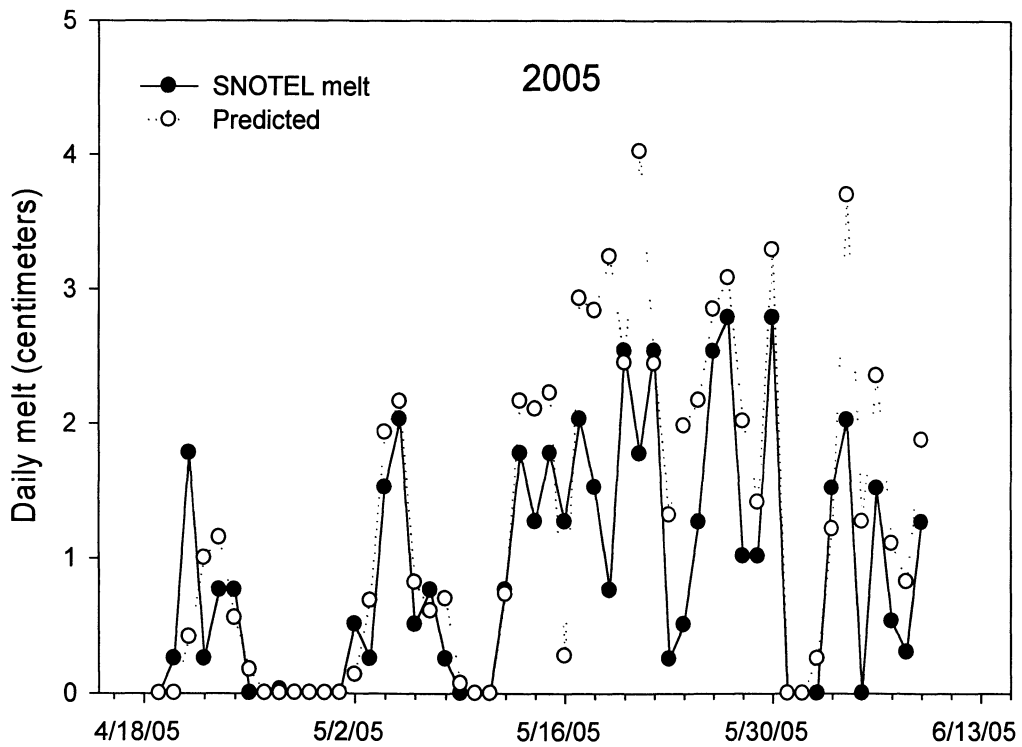
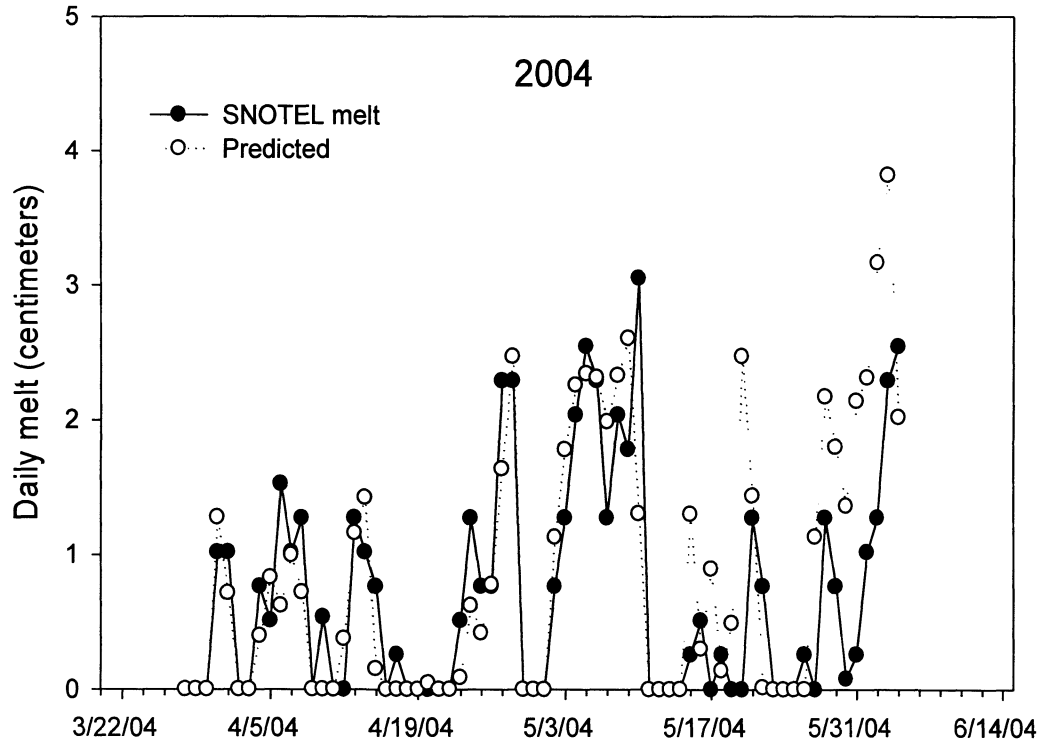


Figure 13. Daily melt for onion park compared to the daily melt predicted by the energy balance model in 2004 and 2005.

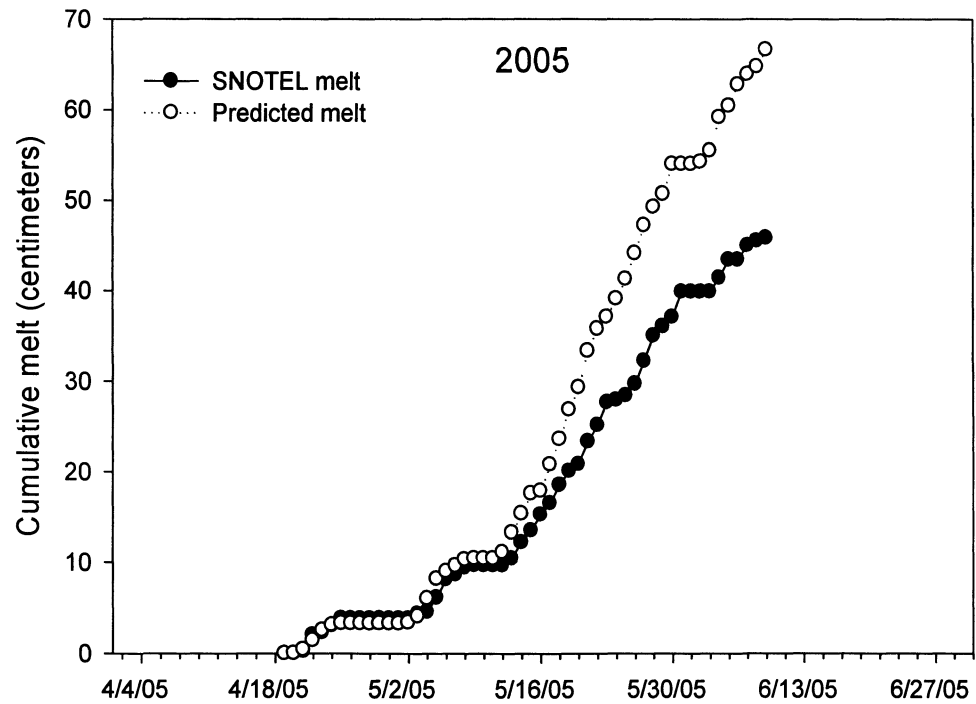
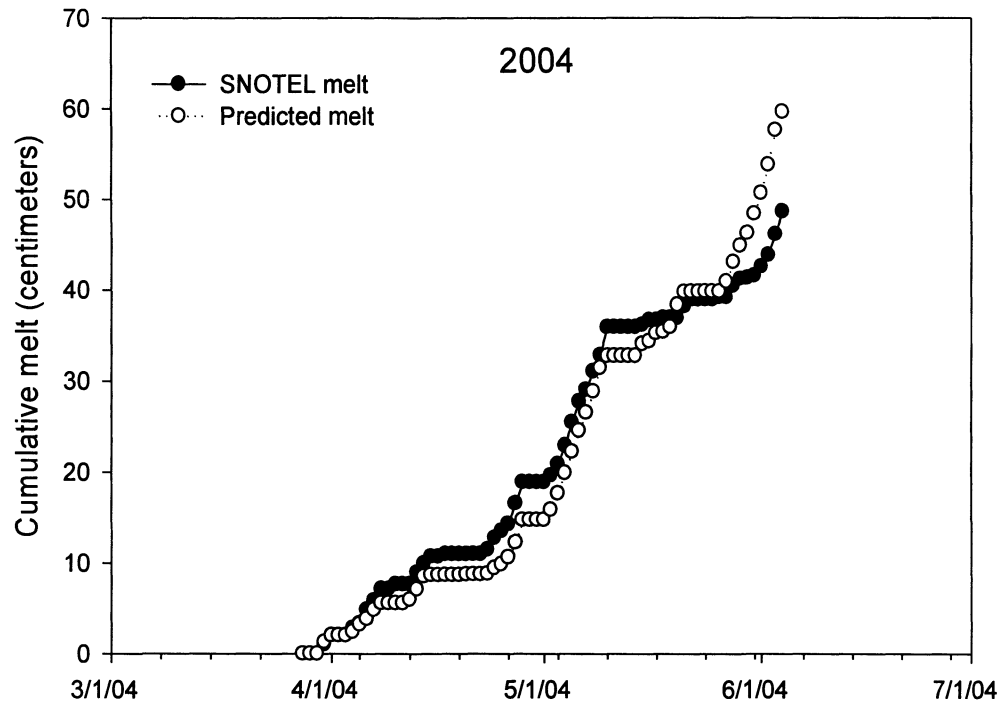


Figure 14. Cumulative melt predicted by the energy balance model compared to the melt observed at Onion Park for in 2004 and 2005.

(Figure 15). By the end of the melt season cumulative melt was over predicted by 21 and 31% at lysimeters 148 and 80 respectively (Figure 16).

The unadjusted hybrid model over predicted daily melt at sites under the canopy at all locations regardless of canopy coverage (Figure 17). Canopy measurements indicated that sites 65 and 132 in the retention groups had canopy coverage values of 0.68 and 0.63 respectively. The canopy cover values at sites 52 and 152 in the control were 0.74 and 0.64 respectively. Adjusting the hybrid model for the presence of forest canopy substantially improved the model fit in all but one of these lysimeters by reducing the net radiation available for melt, so reducing the overall melt rate. The exception was lysimeter 132, where the best model fit was obtained by assuming zero canopy cover (Figure 17). Lysimeter 132 is located 15 m from the edge of the group with a southwest facing aspect. It is likely that this lysimeter receives larger inputs of energy than would occur if the canopy was continuous throughout the stand.

The adjusted hybrid model was a good predictor of cumulative melt at all of the lysimeter sites beneath the canopy except 132. The total cumulative melt recorded at lysimeter 65 was over predicted by 61% with the unadjusted model but by only 7% over prediction with the adjusted model. The unadjusted model under predicted cumulative melt by 2% at lysimeter 52 while the adjusted model provided a near-perfect fit to the observed data. Cumulative melt was over predicted by 42% at lysimeter 152 with the unadjusted model and by 24% with the adjusted model. At site 132, the adjusted hybrid model over predicted the cumulative melt by 50%, whereas the unadjusted model under predicted by 22% (Figure 18).

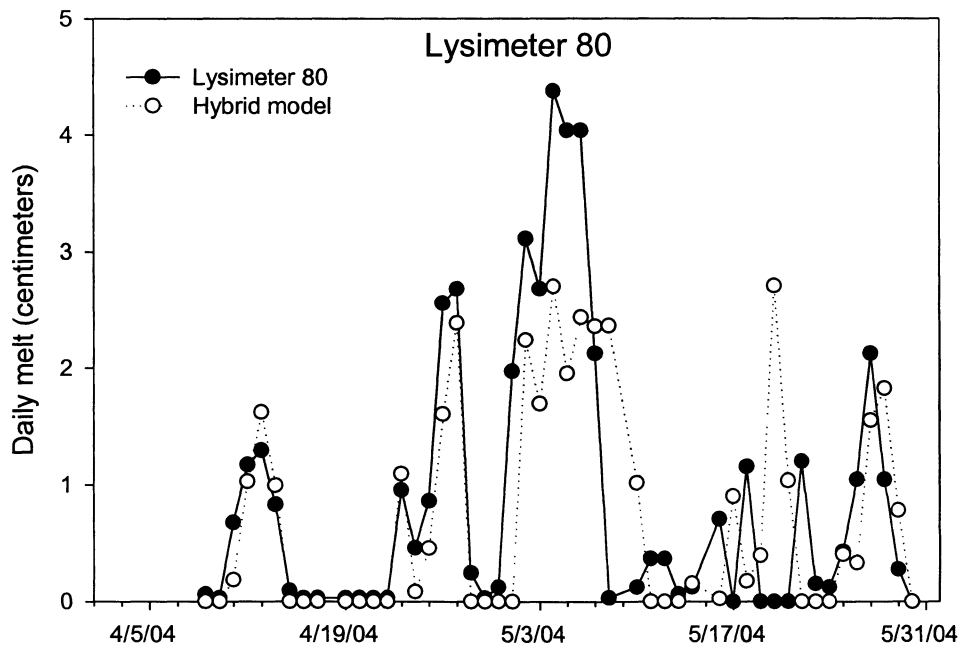
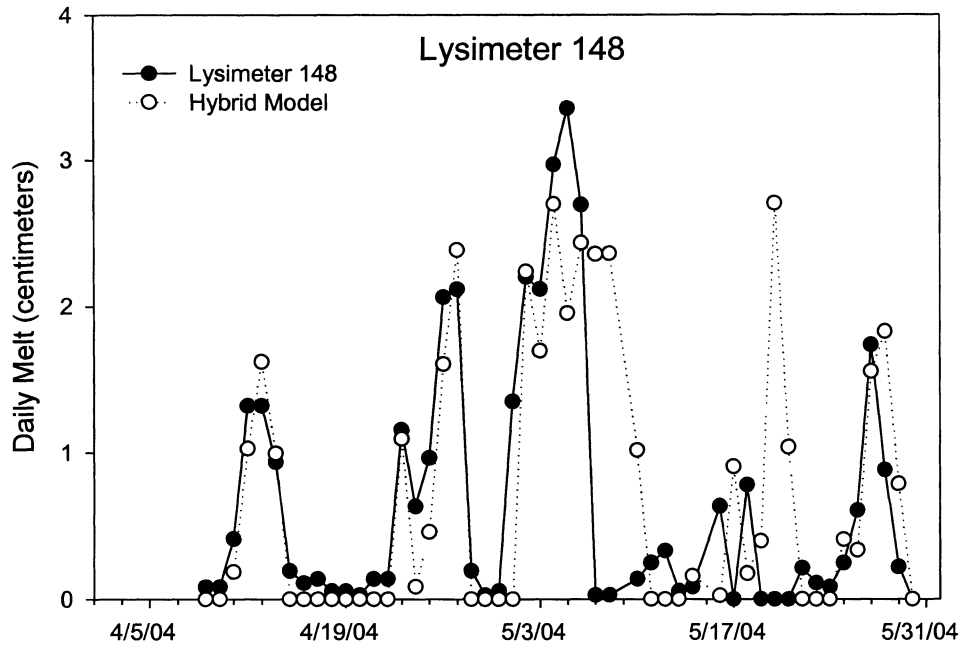


Figure 15. 2004 daily melt for the open site lysimeters compared to the melt predicted by the hybrid temperature index model.

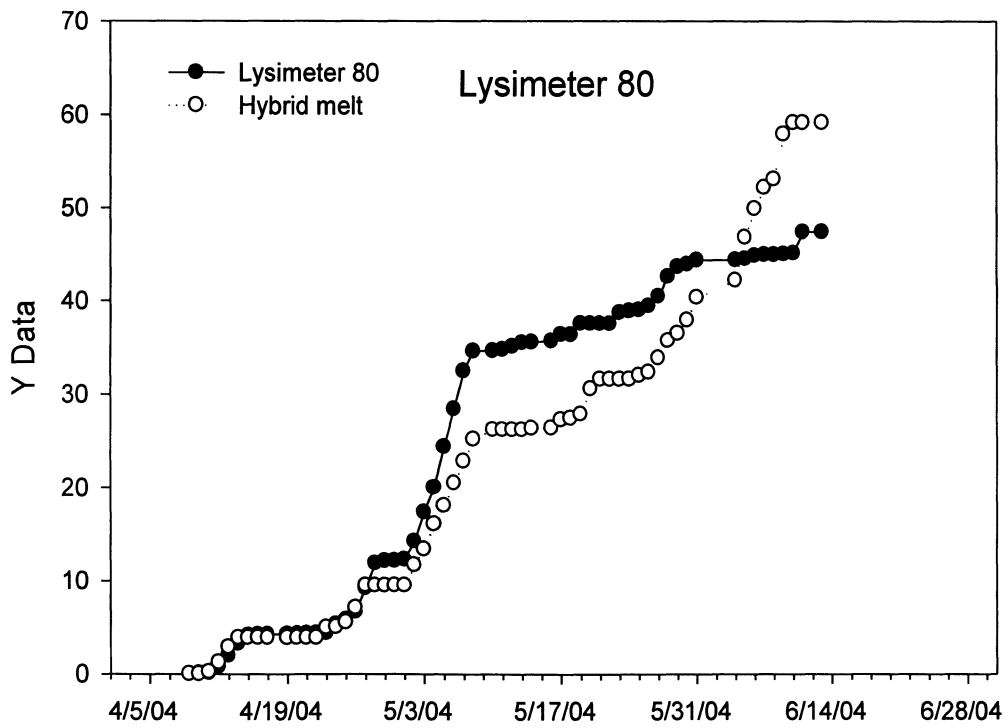
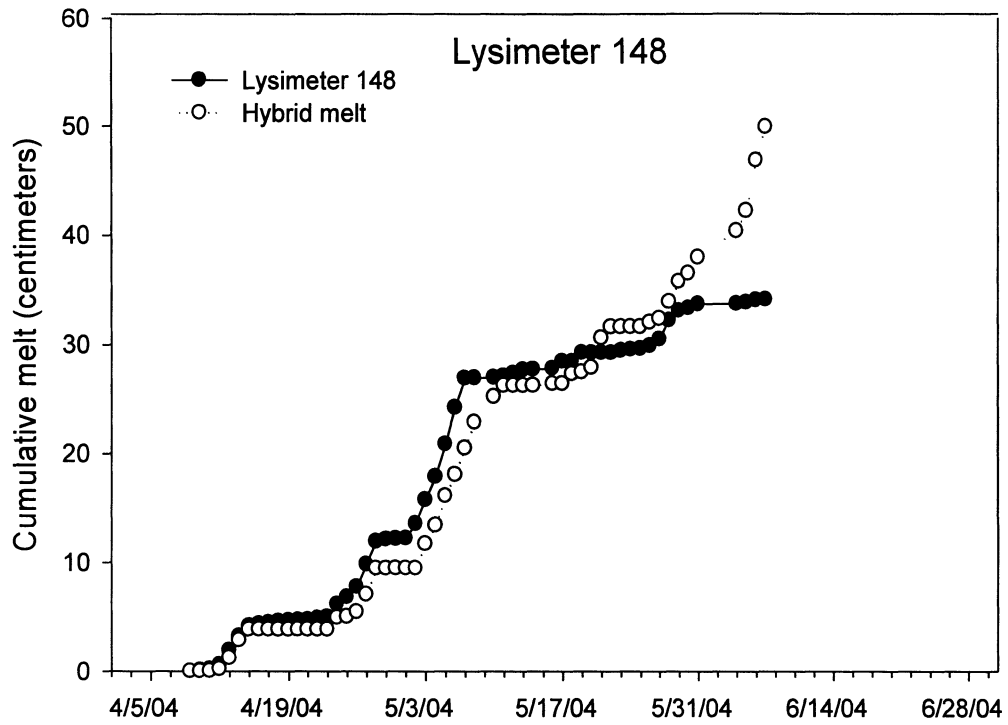


Figure 16. Cumulative melt recorded at the open lysimeters compared the cumulative melt predicted by the hybrid model.

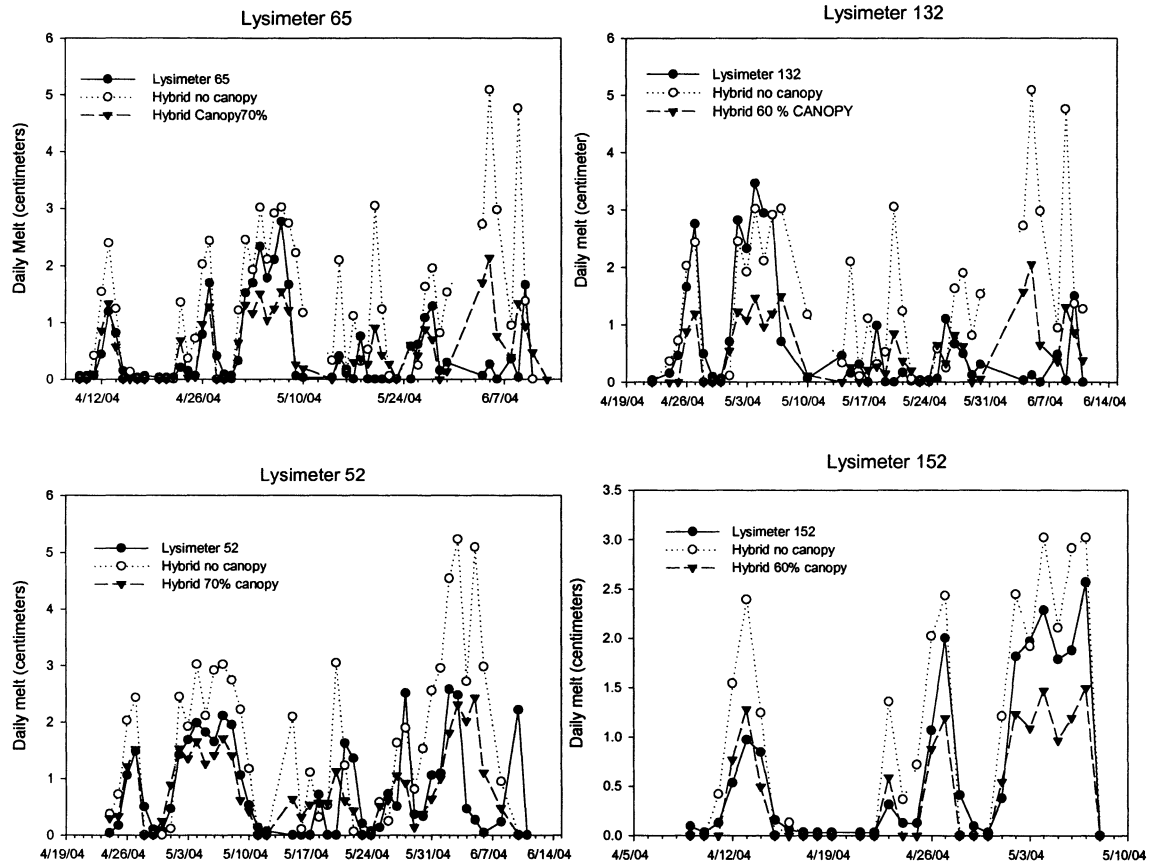


Figure 17 Daily melt at the lysimeters located under the canopy. Lysimeters 65 and 132 are located within groups of trees in the treatment unit and lysimeters 52 and 152 are located in the control unit. Each lysimeter is compared to hybrid models with no adjustment for canopy and one that is adjusted for canopy.

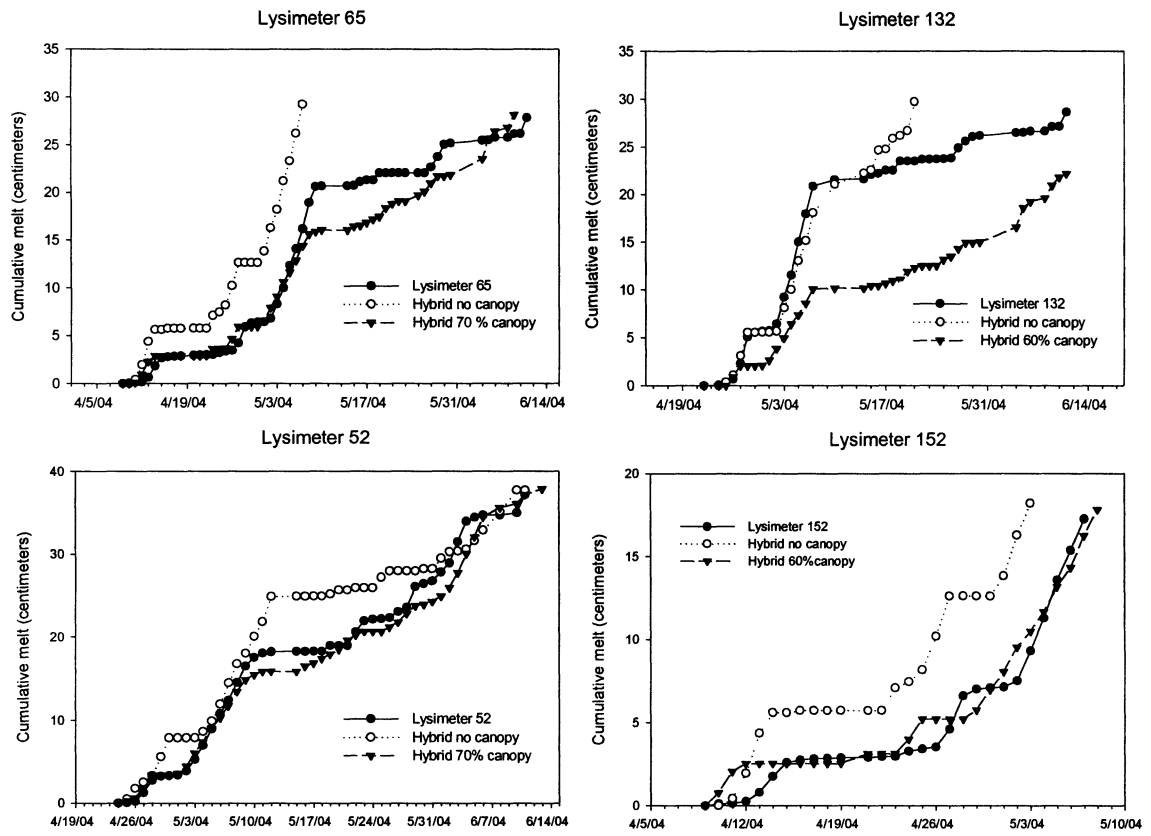


Figure 18. Cumulative melt from each lysimeter compared the cumulative melt predicted by the hybrid models with and without adjustment for canopy. Lysimeters 65 and 132 are in the group treatment units and 52 and 152 are located in the control unit.

Discussion

Snow accumulation

Previous research has shown that the effects of clearcutting on snow accumulation depends on the spatial arrangement of the harvesting and particularly the size of the individual clearcuts (Golding and Swanson, 1978; Troendle and Leaf, 1980; Troendle and King, 1985). The results of this study illustrate that the effects of alternative silvicultural treatments also depend on the spatial arrangement of the residual trees. Both thinning treatments in this study removed approximately 50% of the stand basal area. The difference between the treatments was the spatial arrangement of the residual trees. In the even thinning treatment the residual trees were uniformly spaced across the treatment, while in the group retention unit they were left in 0.2 to 0.8 ha groups. As a result of the treatments the evenly thinned unit had up to a 20% increase in SWE relative to the control, while the group retention treatment resulted in no significant increase in SWE when measured at the treatment scale. We attribute the difference in treatment effect to the way that the spatial arrangement and the size of the groups affected canopy interception, sublimation and wind scour.

Canopy interception is the primary control on snow accumulation in forested watersheds. Snow water equivalent is inversely related to canopy density (Gary and Troendle, 1982; Moore and McCaughey, 1997). Consequently, thinning of the forest canopy results in greater snow accumulation (Golding and Swanson, 1978; Troendle and King, 1985). The 20% (72 mm) increase in SWE in 2004 is similar to results reported from Wyoming where thinning of a dense stand of lodgepole pine resulted in a 53 mm increase in SWE (Gary and Watkins, 1985). The results are also

comparable to a 41 ha shelterwood cut in Colorado that removed 40% of the basal area and resulted in a 48 mm increase in SWE (Troendle and King, 1987).

The largest difference between the even thinning and the control was in 2004, which had a relatively large winter snowpack and the smallest difference was in 2005 when the snow accumulation was 73% of the 2004 value. This is consistent with other studies that have found that the greatest differences in SWE between open and forested sites is in high snowfall years (Harestad and Bunnell, 1981). In this respect the evenly thinned site behaves like an open site due to the reduced canopy.

In the group retention treatment, increased sublimation from the canopy due to greater exposure to solar radiation and additional wind scour in the openings offset gains resulting from decreased canopy interception in the openings. Evidence for this comes from the fact that the retention groups had a lower mean SWE than sites located inside the control, despite having similar canopy densities. In addition the snow depth in the retention groups decreased from the north to the south side of the groups.

Wind scour may have further reduced the total snow accumulation inside the groups. Wind effects can reach up to 240 m into the edge of a forest whereas the retention groups have a maximum radius of 80 m (Chen et al., 1995). To reduce the effect of wind scour within the groups they would have to be much larger in size.

Redistribution of snow by wind from the adjacent forest canopy can supplement gains in SWE in adjacent clearings (Schmidt and Troendle, 1989). In the group retention treatments at TCEF, there is evidence that snow blown out of the groups and into the openings was subject to further redistribution by wind. In 2004, the mean SWE in the openings was less than in the evenly thinned units, while in

2005 the mean SWE was slightly greater in the openings than in the evenly thinned unit. This suggests that most of the wind scour takes place in the late season in TCEF and that the minimal canopy cover in the even thinning unit reduces the effect of wind scour. Further evidence for the effect of wind scour comes from the fact that bare spots were observed on the windward side of snow crests and ripples formed by wind were observed in the openings between groups. These features were not found in the control. The size and shape of some of the openings may have increased wind scour in some areas; many of the openings are corridor like and may funnel wind at increased velocities.

The differences in accumulation between the groups and the openings in the group retention treatment along with the increased wind scour and sublimation losses inside the groups resulted in higher variability in SWE in the group retention unit compared to the thinned treatment and the control. In the evenly thinned unit the reduced variability in canopy density resulted in less spatial variability in SWE than in the control. However, this study was conducted east of the continental divide in Montana, where winds are often high. Areas with lower wind speeds may have different results.

The difference in the amount and distribution of snow accumulation in the two treatments suggests that they could have different effects on stream flows if applied over an entire watershed. The group retention cut could produce a slower and longer release of snowmelt, resulting in lower peaks and possibly higher base flow. In contrast, the evenly thinned unit could melt at a faster rate, resulting in higher peak flows. More research needs to be done to quantify the effect of the treatment on streamflows. In the northern Rockies at least 15% of the total basal

area needs to be removed from a fully forested watershed before there are detectable differences in streamflow (Stednick, 1996). This may vary depending on species and density composition. Since the treatments implemented at TCEF removed only 50% of the basal area on a stand basis, at least 30% of the total forested area of a watershed would have to be treated to affect streamflow. The magnitude of the effect would likely vary depending on the position of the treated areas relative to the streams, as a proportion of the additional runoff may be taken up by the remaining trees.

Effect of canopy cover on snowmelt

The forest canopy exerts a strong control over the energy available to melt snow (Gary and Troendle, 1982). In this study, canopy cover was important in controlling the maximum daily melt rates in the treatments. The SG treatment included areas with a full canopy within the retention groups and areas with no canopy cover in the surrounding openings. The daily maximum melt rates were up to 40% higher in the openings compared to the control. These accelerated melt rates may be due to the larger inputs of solar radiation because of a lack of attenuation by the forest cover or warm winds that are common to the forests east of the continental divide in central Montana. In contrast, the maximum melt rates inside the retention groups were not statistically different with the exception of lysimeter 132. Lysimeter 132 is located within 5 meters of the edge of a group, so it may have been exposed to radiation levels more comparable to the SG-O sites. A second possible source of additional radiation is from longwave radiation emitted from tree warmed by the sun due to the proximity to the edge of the group.

The results show that SG treatment increased the variability in the maximum daily melt rate compared to an uncut control. From the limited data available, it appears that the daily maximum melt rates in the evenly thinned unit were similar to the maximum melt rates in the open in the SG treatment. This makes sense because the percent open canopy at site 239 was 0.93, which is similar to the values measured at the SG-O sites (Table 2).

Surprisingly, the presence of canopy cover had little to no effect on the timing and duration of snowmelt (Table 2). This may be due to the limitations associated with measuring snowmelt using small lysimeters (Kattelmann, 2000). In some cases, the lysimeter drains collected debris, creating a place for ice to form and clog the drains. This clogging probably led to false recording of the timing of melt particularly early in the melt season. In some cases, the rapid outflow of melt water following the unclogging of the drain may have led to artificially high maximum daily melt rates.

Snowmelt modeling at Onion Park

Energy budget and hybrid models that include a radiation component are generally more accurate at predicting melt on a daily basis than temperature index (TI) models. However, at the Onion Park site, the temperature index model performed better than either the hybrid model or the energy balance model. The location of the Onion Park SNOTEL makes it well suited for modeling using a TI methodology for two reasons. First, the Onion Park station lies in a small clearing, where the majority of the radiation warming the snow pack is direct solar radiation rather than long wave radiation. Second, wind effects are minimal inside the small

clearing where the Onion Park SNOTEL station is located, so that turbulent transfers of energy to the snowpack are much reduced. Under these circumstances, where solar radiation is the most important energy source, the air temperature is a good measure of the amount of energy available for melt and the TI approach works well. The model would not perform as well in a more cloudy or foggy environment, and would have little value for predicting melt under a forest canopy due to the dominance of long wave radiation sources.

The fact that the hybrid and energy balance model performed similarly suggests that the poor performance was due to limitations in the radiation data used to calculate snowmelt. In both 2004 and 2005, the hybrid and energy balance models consistently over-predicted melt towards the end of the melt season. This suggests that the radiation flux values used to calculate the melt rate were too high. Radiation data for the models was obtained from sensors at a climate station located within the SE treatment in a relatively open area with a slight north aspect. In contrast, the Onion Park site lies in a small flat clearing where trees cast a shadow across the snow surface for much of the day. The over-prediction of melt in the latter half of the melt season could be because the climate station, located in an open area, received more solar radiation on a daily basis than the Onion Park snow pillow. The implication is that small variations in the radiation flux due to the presence of shadows at the edges of stands and in clearings can significantly affect the ability of energy based models to predict snowmelt at a point. Since treated stands have unusually high number of “edges”, snowmelt modeling is even more difficult than in untreated stands with a more continuous canopy.

Use of the hybrid model requires the selection of an appropriate value for the melt coefficient (a_r), which can be calculated from site specific temperature, relative humidity and windspeed data on a daily basis, or the model can be calibrated to a single value that falls within the range of calculated values and represents the entire melt period. Surprisingly, the daily calculated melt coefficient provided little improvement over the seasonal value when used to predict daily melt. In fact in 2004, the seasonal melt coefficient provided a better model fit than the daily value. Since the hybrid model with a seasonal coefficient of melt performed as well or better than either the hybrid model with a daily melt coefficient or the energy budget model, it made sense to use the hybrid model with a seasonal melt coefficient when modeling snowmelt at the lysimeters. This approach also met one of the primary goals of the research, which was to find a simple model to predict melt under varying canopies using the least possible amount of site specific data.

Snowmelt modeling at the lysimeters

The hybrid model with the seasonal melt coefficient provided a reasonable fit to the observed daily melt at lysimeter 148, which is located in an opening between groups in the SG treatment. However the model consistently underpredicted melt at lysimeter 80, also located in an opening, where daily peak melt rates were often 30 to 50% higher than at lysimeter 148. The model performed better at the beginning of the melt season and towards the end of the snowmelt period. The underprediction of melt at lysimeter 80 in the middle of the season could be because the lysimeter was receiving additional melt from lateral flow, a problem common to many snowmelt lysimeters (Kattelmann, 2000). Presumably, in the early part of the melt season few

ice layers were present in the snowpack, but as the melt season continued and many cycles of freeze and thaw took place more lateral paths formed, so increasing the contribution area of the lysimeter (Kattelmann, 2000). The problem disappeared later in the season because enough of the snowpack would have melted to eliminate the lateral flow paths.

Adjusting the radiation component of the hybrid model to account for the presence of the forest canopy considerably improved the model performance for lysimeter 65, which lies in one of the groups in the SG treatment and lysimeters 52 and 152 in the control. Forest canopies alter radiation by decreasing the shortwave radiation flux and increasing the longwave radiation flux with increasing canopy density. For low canopy densities solar radiation is at a maximum, while the longwave radiation flux is at a minimum. The opposite is true for high canopy densities. The lowest net radiation under the canopy, and hence the least amount of energy available for melt, occurs at intermediate canopy densities (Dunne and Leopold, 1979). At lysimeters 65, 52, and 152 the unadjusted model overpredicted melt because the radiation flux was too high. Within the range of canopy densities measured at these sites (60-70%) the net radiation under the canopy is lower than in the open, and the adjusted model did a good job of accounting for this effect on the radiation budget.

Although the adjusted hybrid model improved the fit between the observed and predicted values at lysimeters 65, 52 and 152, the Nash-Sutcliffe coefficients were still quite low. This could be due to several different factors. First, temporary freezing of the drain hole or blockage of the drain hole by debris may have caused a lag between occurrence of melt and the time when it was recorded by the tipping

bucket. Since the Nash-Sutcliffe coefficient is based on the fit between daily values, this would sharply reduce the strength of the correlation. Secondly, rainfall was subtracted from the total melt rates on a daily basis, but the rainfall totals were not adjusted for the effect of canopy interception. Rain gages at each lysimeter site would be needed to be able to correctly account for rainfall in the melt totals. Third, the melt predictions were based on daily average temperatures rather than on daily maximum temperatures so that melt rates on days with a high maximum temperature may have been underpredicted by the model. Finally, the equation used to calculate the net radiation under the canopy (equation 6) may not be a good predictor of the available energy in very dense lodgepole stands like those found at Tenderfoot. High stem densities in these stands may lead to a higher longwave flux than equation 6 predicts, so that the model underpredicts melt. Measurements of the radiation budget under the canopy and in different densities would be required to determine whether this is the case.

In contrast with lysimeters 65, 52 and 152, the best model fit at lysimeter 132 was obtained using a zero value for the canopy density. Lysimeter 132 is located within 5 m of the edge of the group, and is positioned on a southwest aspect. This location probably allows for additional energy input through the edge of the group, so increasing the melt rate. The fact that the model performed better towards the end of the melt season is consistent with this conclusion; as the season progressed the sun moved higher in the sky, so that the edge effect became less important. Once again, this highlights the difficulties inherent in modeling snowmelt in spatially complex stand structures with a lot of edges. In addition to the problems caused by shadows from adjacent trees in open areas, snowmelt rates for sites under the canopy

but near the edge of stands may be higher than predicted because of the additional radiation flux.

Conclusion

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 some forested areas. The results of this study demonstrate that manipulating tree spacing can have substantially different effects on snow accumulation and snowmelt depending on the spatial arrangement of the treatments. For central Montana, if forest harvest is to be conducted with the intent of increasing the water yield then the even thinning treatment may be the most appropriate because of the significant increase in snow accumulation. However, the effect of group selection harvesting may vary depending on the orientation and size of openings.

Although the lysimeter data provided somewhat conflicting results the thinning treatments may affect the rate of snowmelt. This could significantly change the hydrographs of the streams the watershed drains into. If a slow release with a steep climbing limb and steady consistent recession limb were desired the appropriate treatment would be the group retention unit. The open sites in the group unit may yield larger amounts on a daily basis, but the retention groups would give a slower consistent melt on a daily basis thus prolonging melt. Alternatively, the evenly thinned unit could result in a faster flashier hydrograph due the sparse canopy and

high accumulations. Further research on a watershed scale would be needed to determine if this is the case.

Modeling the melt under various degrees of forest canopy coverage is best accomplished using a hybrid temperature index model with the radiation component adjusted for canopy. However, the ability of such models to predict melt in thinned stands is limited by high spatial variability in the radiation flux, due to shading in clearings and additional radiation inputs near forest edges.

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