From the Tree to the Forest: The Influence of a Sparse Canopy on Stand Scale Snow Water Equivalent

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ABSTRACT

The canopy of an individual tree has a negative effect on the accumulation of snow around tree boles, resulting in a decrease in snow depth inward from the edge of the canopy to the tree trunk. This influence of trees on snow distribution affects the total volume of water stored in the snowpack, especially for a sparse forest stand. However, snow measurements, in particular depth, are typically made between trees, and this neglects the decreased accumulation around trees. As well, little is known about changes in snowpack density under the canopy compared to between trees. Sparse individual trees have their own microclimate (energy balance, wind profiles, etc.) that could produce directional variations in snowpack properties. To establish how the decreased snow depth and possibly change in snowpack density under the canopy can affect estimates of stand scale SWE, depth and density measurements were taken in the four cardinal directions around three *Picea engelmanii* and two *Abies lasiocarpa* during the winters of 2005 and 2007 near Cameron Pass, northern Colorado. These near tree measurements were assessed against existing snow depth models and superimposed on a 50-m transect of depth measurements taken at 0.5-m intervals. Three scenarios of a sparse forest were considered: one tree with a 1-m canopy radius, one tree with a 2-m canopy radius, and three trees each with a 2-m canopy radius. Directionality was observed in the snow depth increasing away from each tree. An increasing trend in snowpack density was observed outward from each tree. The estimated average transect snow water equivalent decreased by 12.8% with the addition of three trees with 2-m canopy radii.

Keywords: forest canopy, snow depth, snow density, snow water equivalent, *Picea engelmannii*, *Abies lasiocarpa*

INTRODUCTION

Snow is an important storage component of the hydrological cycle, especially in mountainous regions, where high-elevation seasonal snowpacks contribute a large percentage of total annual downstream water supply. For about a third of the Earth's land area, ice fields and snow fields function as fresh-water reservoirs by storing precipitation and delaying runoff (Perlman, 2005). In Colorado, up to 85% of the annual runoff and groundwater recharge in the Colorado River basin originates as snowmelt (Snow, 2005). Understanding the extent and causes of changes and variability in the snowpack is essential for accurate prediction of the timing, rate, and magnitude of snowmelt runoff.

There are three measurable interrelated properties that describe the snowpack: depth, snow water equivalent (SWE), and density. Depth is the most easily measured variable and together with density yields SWE, the equivalent depth of water contained in the snowpack in millimetres. Density varies spatially less than depth and SWE (Elder *et al.*, 1991). However, density can vary

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temporally by an order of magnitude from freshly fallen snow ranging from 50 to 150 kg/m3 (e.g., Fassnacht and Soulis, 2002) to a peak at the onset of melt of 400 kg/m3 or higher (Doesken and Judson, 1997), all due to factors such as gravitational settling, melting and recrystallization, and wind compaction.

Variability of snow accumulation in a forest stand is a function of the effects of vegetation structure on interception, and associated losses to redistribution, evaporation, and sublimation. While the evaporation of intercepted snow may result in minimal water loss from the watershed, losses to sublimation may be significant. Montesi *et al.* (2004) found that sublimation rates were greater at lower elevations (2920 m); however, more water was lost to sublimation at higher elevations (3260 m) due to increased snowfall and accompanying increased interception. Studies have shown that the wind redistribution of intercepted snow out of the watershed may also result in considerable water loss (Golding and Swanson, 1986; Stegman, 1996). However, disruptions in wind velocity gradients created by canopy openings may cause snow to be redistributed locally, resulting in enhanced snow accumulation in these clearings relative to areas under the canopy (Troendle and Leaf, 1980, Golding and Swanson, 1986). In addition to these losses, snow accumulation around the individual tree is further reduced by increased thermal radiation due to the canopy (Link and Marks, 1999; Sicart *et al.*, 2004). Small-scale (< 1 m) variability in snow depth may also be attributed to factors such as variability in ground roughness and small-scale slope and aspect (Fassnacht *et al.*, 2006). The effects of redistribution, decreased loss from interception, and radiative transfer on the accumulation of snow in a forest stand have important implications for timber and watershed management (Troendle and King, 1985; Golding and Swanson, 1986).

The inverse relationship between canopy density and snow accumulation at the surface has been documented by many (e.g., Troendle and Leaf, 1980; Golding and Swanson, 1986; Woo and Steer, 1986; Sturm, 1992; Hardy and Albert, 1996). Although this reduction in snow accumulation for the individual tree may be relatively small, when extrapolating to a larger scale (i.e., the tree stand, forest, or watershed) the loss of snow water storage is considerable. Estimates of snow water storage for a forest with a sparse canopy are commonly derived from measurements limited to areas between trees. The purpose of this paper is to determine the influence of considering near tree measurements on the estimation of stand scale snow water equivalent versus using measurements collected only in forest openings.

BACKGROUND

The relationship between the forest canopy and snow distribution has been investigated since the innovative work starting in 1909 at the Wagon Wheel Gap Experiment Station in Colorado, that examined the effects of forest cover removal on streamflow at the headwaters of the Rio Grande (Bates and Henry, 1928). Experimental forests were subsequently established across various plant communities to provide research on examining the effects of timber harvest on water yield, and these studies have consistently reported greater snow accumulation in forest clearings than under the canopy (e.g., Troendle and Leaf, 1980, Troendle and King, 1985; Golding and Swanson, 1986; Schmidt and Troendle, 1989). For instance, at the Marmot Creek experimental watershed in Alberta, Golding and Swanson (1986) reported greater snow in clearings than in the surrounding forest, whether the clearings were large 8 to 13-ha blocks, or small circular clearings from 1/4 to 6 times the height (H) of the surrounding trees. Troendle and Leaf (1980) found that for a coniferous forest, maximum accumulation occurred in clearings of 2 to 5 H. They reported that accumulation decreased below values for the surrounding forest when the clearing along the mean wind direction exceeded 13 H (Troendle and Leaf, 1980). Wind speed at the snow surface in large clearings was relatively unaffected by the surrounding forest, and accumulation was less for clearings larger than 20 H width than in the forest (Golding and Swanson, 1986).

Studies have investigated the negative effects of the canopy on snow accumulation around individual trees (e.g., Golding and Swanson, 1986; Talbot *et al.*, 2006), with researchers modelling the increase of snow depth outward from the tree bole to the edge of the canopy (e.g., Woo and Steer, 1986; Sturm, 1992; Hardy and Albert, 1995). Woo and Steer (1986) established a relationship between snow depth (*h(r)*) and distance from the trunk (*r*) for spruce trees in northern Ontario using a third order polynomial relationship:

$$h(r) = \sum_{i=0}^{3} b_i r^i \quad (1)$$

where b_i is a coefficient related to tree diameter and cardinal direction from the tree. For spruce trees in the Alaskan taiga, Sturm (1992) found that snow depth at the trunk was 20% of the total undisturbed snow away from the tree. Snow depth was modelled as a function of distance from the tree trunk, identifying a smooth increase in snow depth around the tree from minimum observed depth (h_{min}) to the maximum observed depth (h_{max}). Sturm fit his data to the equation:

$$h(r) = h_{\max} + (h_{\min} - h_{\max}) \exp\left[-\left(\frac{r}{k} \right)^2 \right] \quad (2)$$

where *k* is a fitting parameter related to the canopy radius or tree trunk diameter. Hardy and Albert (1995) measured snow depth around a large white spruce in northern Vermont, and found that snow depth below the canopy was on average 34% of snow depth accumulated in the open. However, they did not confirm a smooth increase in depth with distance as was seen by Sturm (1992); they observed a transitional zone (zone 3) beginning where snow depth increased sharply and ending where the depth became level. Taking this zone into account, they proposed a new equation for snow depth profiles around conifers as:

$$h(r) = \frac{h_{\max} - h_{\min}}{\pi} \arctan(\alpha r + \beta) + \frac{h_{\max} + h_{\min}}{2} \quad (3)$$

where α and β are adjustable constants related to the geometry of the tree well. The coefficient α is related to slope of the snow depth profile in zone 3, and β is equal to - α r_o, where r_o is the location of greatest increase in snow depth. It was determined that increased branch and needle density resulted in a higher interception efficiency, and thus the models of Woo and Steer (1986) and Sturm (1992) poorly predicted the snow accumulation profile around the tree sampled by Hardy and Albert (1995).

In their examination of directional data collected around seven conifer trees over five years in Colorado, Fassnacht *et al.* (2006) found that snow depth increased with distance away from the tree trunk and they stated that both equations (1) and (2) were applicable to the snow depth increase away from their trees. Density tended to increase away from the tree, and some directionality was observed in snow depth and density when comparing different transects (Fassnacht *et al.*, 2006). However, it was determined that for the small number of density samples collected, a power function explained only 48% of the variance in the density data for the north direction, and this relationship had decreasing significance in the east, west, and south directions (Fassnacht *et al.*, 2006).

Musselman *et al.* (*in submission*) found deeper snow depth and greater SWE in the north direction versus the south direction for two conifers in the Valles Caldera of New Mexico. They used a binary regression tree to estimate discrete snow depth from *r*, distance to the canopy edge, and an index of solar radiation. The solar radiation accounted for the directionality in snow depth.

While the spatial distribution of snow has been well characterized for numerous forest stands and clearings, the decreased snow depth below the canopy has been modelled by few (e.g., Woo and Steer, 1986; Sturm, 1992; Hardy and Albert, 1995; Musselman *et al.*, *in submission*). To date, only Fassnacht *et al.* (2006) and Musselman *et al.* (*in submission*) examined the directional variation of snowpack properties around individual trees. Stand scale snow sampling in a forested area is typically limited to areas between trees (Fassnacht *et al.*, 2006). The objectives of this study are i) to examine the directionality of snow depth around individual trees in a spruce-fir community in Northern Colorado, ii) to determine if there are changes in snowpack density under the canopy compared to between trees, and iii) to determine the influence of these measurements on estimated stand scale snow water equivalent relative to measurements collected only between trees.

STUDY AREA

The data for this study were collected during the 2004-2005 and 2006-2007 snow seasons, hereinafter the winters of 2005 and 2007. Sampling occurred off Colorado Highway 14, near Cameron Pass in Northern Colorado (Figure 1). The study area is located along Joe Wright Creek, a tributary of the Cache la Poudre River in the South Platte River basin. Located nearby is the Natural Resources Conservation Service (NRCS) Joe Wright snow telemetry (SNOTEL) site (05J37S). Continuous snowcover for this area usually begins in mid-October and persists until mid-June with peak SWE occurring May 1st (NRCS, 2007). From the 27 years of historical SNOTEL data (1980 - 2006), the average annual precipitation is 1130 mm with 717 mm typically falling as snow between October 15 and May 1 (considered winter), and the average peak snow water equivalent is 680 mm (NRCS, 2007). From the temperature record of 1990 through 2006, the average annual temperature is 0 degrees Celsius with a winter average temperature of -5.5 degrees Celsius.

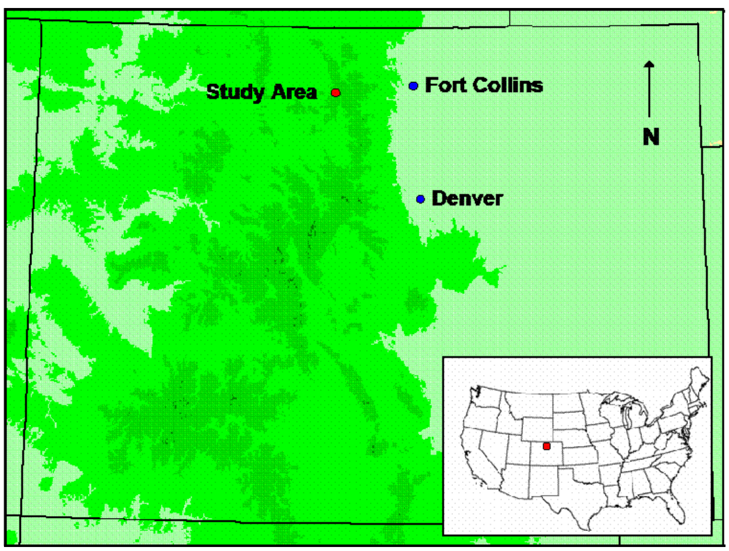

Figure 1. Location of study area

The winters of 2005 and 2007 were quite typical in comparison to the historical record: the winter precipitation was 630 and 650 mm, respectively, the peak SWE was 607 mm and the mean winter temperature was -3.7 degrees Celsius for both years. Snow accumulation began on September 22 for the 2005 winter, peaked on May 14, and was completely melted by June 20. For the 2007 winter, accumulation began on October 18, peaked on April 29, and was completely melted by June 19. Both years were average in terms of snow (Figure 2).

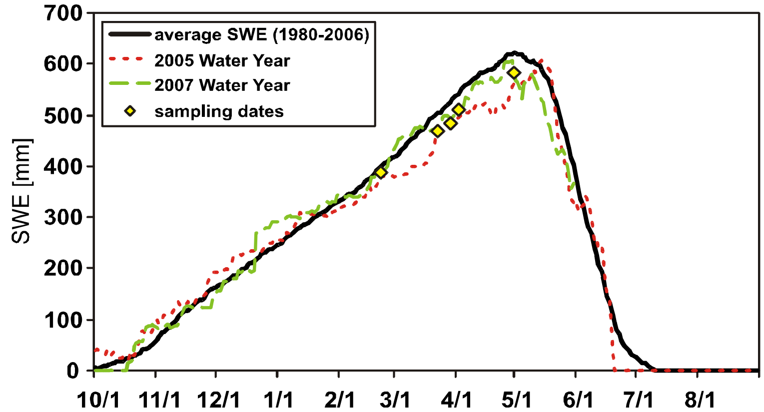

Figure 2. Average SWE for the 2005 and 2007 water years compared to the 27-year average (1980-2006).

The sample stand is located in the subalpine Spruce-Fir community and is dominated by Engelmann spruce (*Picea engelmanii*) and sub-alpine fir (*Abies lasiocarpa*), with the occasional Colorado blue spruce (*Picea pungens*), Douglas fir (*Pseudotsuga menziesii*), and lodgepole pine (*Pinus contorta*). Five trees were selected for this study – three *Picea engelmanii* and two *Abies lasiocarpa* (Table 1). The height of the trees ranged from 7 to 18 m, and diameter at breast height (DBH) ranged from 8.5 to 18.7 cm (Table 1). The distance to canopy edge varied from 0.9 to 2.5 m (Table 1), with the mean distance to canopy edge in the north, east, south and west directions being 1.5 m, 1.4 m, 1.6 m, and 1.4 m, respectively.

Table 1. Summary of ancillary data, types of snow measurements, and sampling dates for selected trees.

Tree	Tree species	Height [m]	DBH [cm]	Edge of canopy [m]				Date	Data collected	
				N	E	S	W		Depth	Density
A	*Picea engelmannii*	7	8.5	0.9	0.9	1.2	1.1	Feb 16, 2007	X	X
B	*Picea engelmannii*	18	18.7	2.5	1.9	1.8	2.0	Feb 22, 2007	X	
								Mar 23, 2007	X	
								Apr 6, 2007	X	
								Apr 30, 2007	X	
C	*Abies lasiocarpa*	9	8.7	1.4	1.6	1.5	1.3	Mar 23, 2007	X	X
D	*Picea engelmannii*	14	10.1	1.2	1.1	2.0	1.3	Apr 6, 2007	X	X
E	*Abies lasiocarpa*	6.7	19	1.9	1.7	1.8	1.7	Mar 29, 2005	X	
								Mar 23, 2007	X	
								Apr 6, 2007	X	
								Apr 30, 2007	X	

METHODS

Snow depth data were collected using depth probes between 2 trees at 0.5 m intervals along a 50-m north-south transect, and radially around the five trees (Table 1) every 0.1 m along 2 to 4 m transects for the four cardinal directions. Snow water equivalent data were collected with a Federal snow sampler at approximately 0.1 m intervals around three trees (A, C, and D). Density was computed as a ratio of the measured SWE to snow depth. Average density for the clearing were collected in snowpits adjacent to the transect using a technique developed by R. Perla of Environment Canada in which a wedge-shaped sampler 20 cm long, 10 cm wide, and 10 cm high is used to obtain a 1000-ml volume (Elder *et al.*, 1991).

Depth ($h(r)$) and density (ρ_s) were plotted for each of the four directions as a function of distance from the tree trunk (r). These data were standardized by dividing snow depth or density at any distance from the tree by the corresponding value for that parameter at the canopy edge. Equations 1 through 3 as well as a power function in the form:

$$y = ax^b \tag{4}$$

were fitted to the standardized depth and density data.

Two statistical measures were used to evaluate the appropriateness of the model predictions: the coefficient of determination (r^2) and the Nash-Sutcliffe efficiency coefficient (E). The coefficient of determination assesses the fit of the models to the directional data as:

$$r^2 = \frac{\sum\left(h_{obs} - \overline{h_{obs}}\right)\left(h_{\text{mod}} - \overline{h_{\text{mod}}}\right))}{\sqrt{\left(h_{obs} - \overline{h_{obs}}\right)^2}\sqrt{\left(h_{\text{mod}} - \overline{h_{\text{mod}}}\right)^2}} \tag{5}$$

where h_{obs} is the observed snow depth, $\overline{h_{obs}}$ is the average observed snow depth, and h_{mod} is the modelled snow depth, h_{mod} is the average modelled snow depth. For the density data, ρ_s is used for the different h values. The r^2 coefficient can vary from 0 to 1 with a value of 1 meaning that all variability in the data is explained by the model. The Nash-Sutcliffe coefficient is a metric typically used to evaluate the simulation of streamflow data (Nash and Sutcliffe, 1970), and is given as:

$$E = 1 - \frac{\sum\left(h_{obs} - h_{\text{mod}}\right)^2}{\sum\left(h_{obs} - \overline{h_{obs}}\right)^2} \tag{6}$$

An E value of 1 indicates a perfect fit between observed and modelled data, while a coefficient equal to or less than 0 indicates that the average of the observed data is a better predictor than the model. The Nash-Sutcliffe coefficient is an indicator of goodness-of-fit for these models that is recommended by the American Society of Civil Engineers (ASCE, 1993).

To determine the influence of individual trees on stand scale snow water equivalent, trees with various canopy sizes were superimposed on the March 23, 2007 set of transect depth data. Three scenarios were chosen for analysis and compared to the north-south transect consisting of no trees: i) a transect with one tree with a 1 m canopy radius, ii) a transect with one tree with a canopy radius of 2 m, and iii) a transect with three trees, each with a canopy radius of 2 m. The influences of these trees were examined assuming snowpacks of both constant and variable density. Density adjustments were calculated using March 23 density data for tree C's north and south directions. For each scenario, the mean transect SWE was calculated from model-simulated snow depth, and changes in SWE (%) were compared for the three scenarios assuming both a power law and Sturm (1992) depth adjustments for canopy effects.

RESULTS

Snow Depth

The snowpack around all trees exhibited a trend of continuous increasing depth with distance from the tree trunk (Figures 3 and 4), similar to the smooth transition observed by Sturm (1992), and there was directional variation with this increase. Individual trees showed different degrees of snow depth increase away from the tree trunk.

While tree A (Figure 3a) showed a limited increase with depth, there was an approximate 15-cm snow depth at the bole and a subtle increase thereafter. Data for this tree were collected along transects of 1 m length, which is about 0.1 m past the edge of canopy for the north and east directions (0.9 m), and 0.3 m less than the canopy edge for the south direction (1.2 m) (Table 1), and the south transect was the only transect to exhibit a continual increase in snow depth with distance, while the north transect had the deepest snow. Every direction around tree C except for the south demonstrated a continual increase in snow depth from the tree to the end of the transect (Figure 3b), and the west transect had the deepest snow at distances close to the tree bole (from 0.1 to 1.3 m away). Beyond 1.4 m, the snow depth was similar for the four directional transects. Snow depth data were collected for the east and south transects for tree D and illustrated a deeper snow depth for the east transect than for the south (Figure 3c).

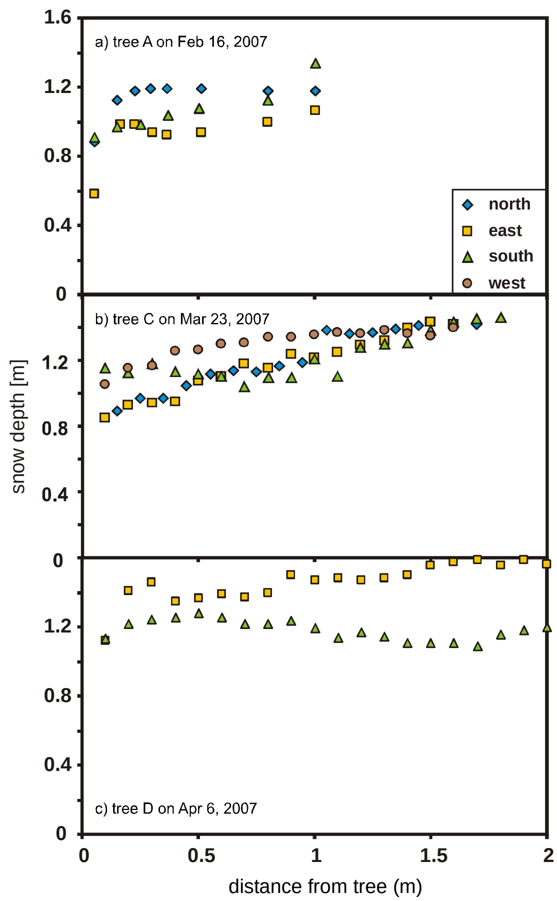

Figure 3. Snow depth as a function of distance from a) tree A on February 16, 2007, b) tree C on March 23, 2007, and c) tree D on April 6, 2007 for the four cardinal directions (north, east, south, west).

The four transects for tree B exhibited more of an asymptotic-type increase in snow depth over distance than tree E (Figure 4a and 4b). For the four sampling dates of tree E, the snow depth was deepest in the south transect compared to the north, east and west transects. Variation was observed for different dates and the two trees; for tree B (Figure 4a), the west transect was deepest for all dates and the south transect was next deepest, and for tree E (Figure 4b), the south transect was the deepest and the east transect tended to be next deepest. The north transects of trees B and E were shallowest, especially at greater distances (Figure 4aiii, 4biii, 4biv). On March 29, 2005 the south transect of tree E was the deepest from 0.6 to 3.5 m (Figure 4bi), but no directionality was displayed among the other three transects, while the west transect had the most snow for distances close to the tree bole (0.1 to 0.3 m).

The north transect of snow depth data for tree B on April 6, 2007 is representative of other measured data, showing a continuous increase in depth over distance, and was used to compare the four snow depth models (equations 1-4) (Figure 5). The power function and the relationship proposed by Sturm (1992) fit the data best based on the Nash-Sutcliffe coefficient. The Woo and

Steer (1986) (Equation 1) was the poorest fit, and while the Hardy and Albert (1995) (Equation 3) relationship had a large E value of 0.88, it did not represent the distribution in snow depth as well as the Sturm and power functions.

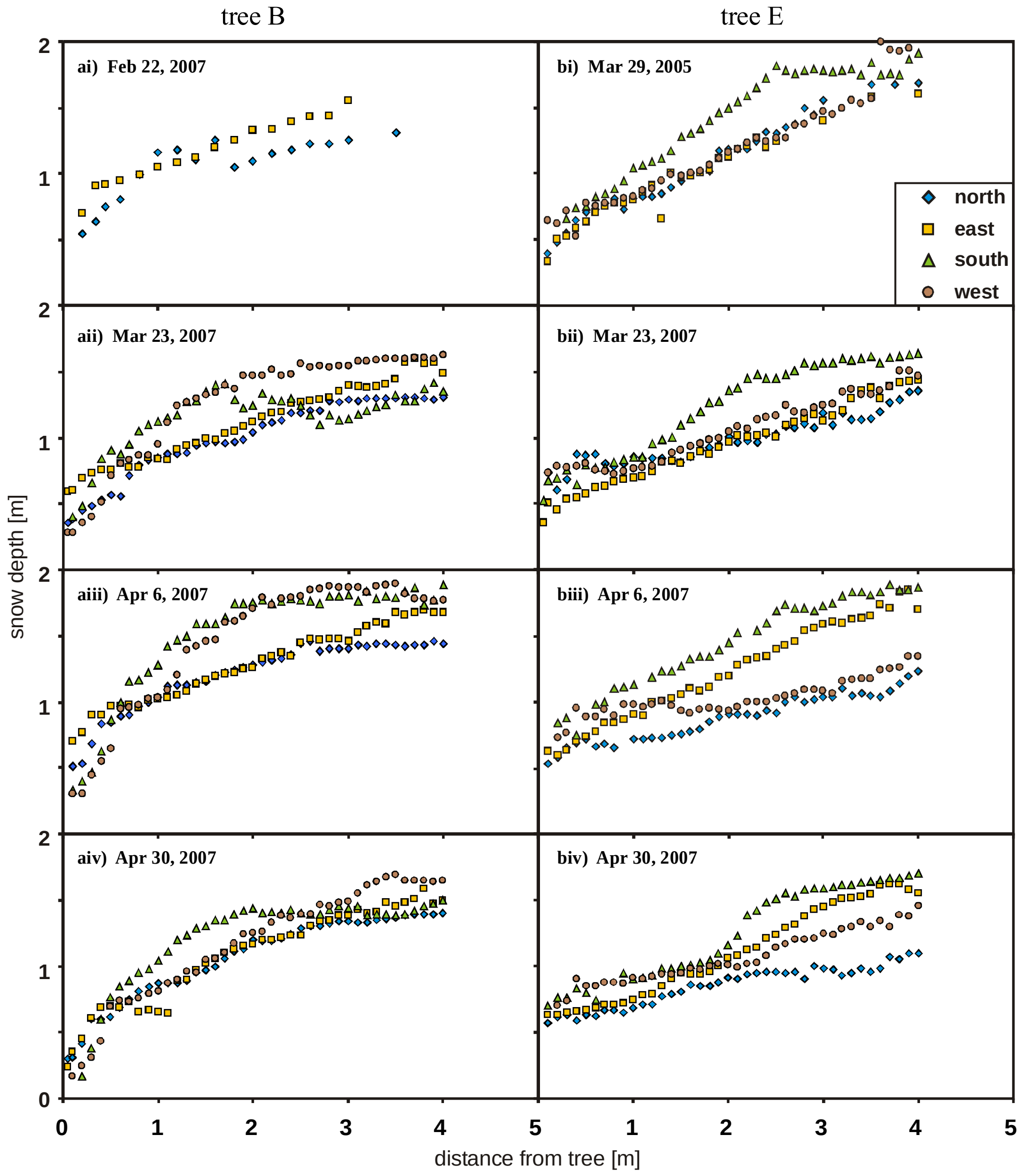

Figure 4. Snow depth as a function of distance from a) tree B and b) tree E on four dates for the four cardinal directions (north, east, south, west).

A power function was a better fit for the standardized directional data compared to the Sturm (1992) function (Figure 6 and Table 2). A power law explained 68% of the relationship (r^2) between snow depth and distance from the tree for the east direction, 62% for the north direction, 46% for the west direction, and only 34% for the south (Table 2). The Sturm (1992) model (equation 2) only explained the east and south transects better than using the mean snow depth (Table 2).

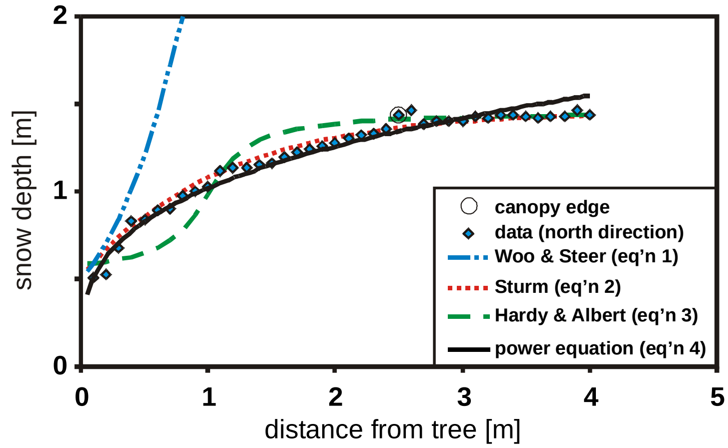

Figure 5. April 6 2007 north transect snow depth profile data for Tree B compared with the power function and empirical models of Woo and Steer (1985), Sturm (1992), and Hardy and Albert (1995). Coefficients used in Equation (1) were $b_0 = 0.5$, $b_1 = 0.8$, $b_2 = 1$, and $b_3 = 0.4$. A fitting parameter (k) of 2.2 was used in Equation (2). Parameters used in Equation (3) were $\alpha = 4.0$ and $\beta = -4.0$.

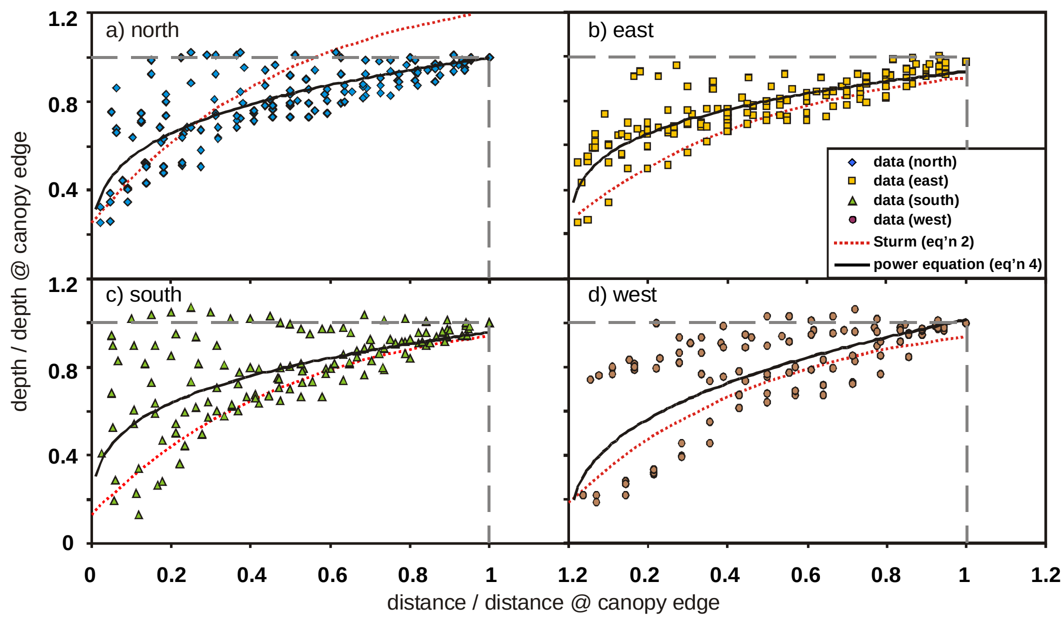

Figure 6. Directional snow depth data standardized to canopy edge values for all dates compared with the power function and Sturm's (1992) empirical relationship.

Table 2. Nash-Sutcliffe coefficients and coefficients of determination for the Sturm equation and power functions fit to each standardized directional depth transect.

Direction	Sturm (1992)	Power function
north	–0.30	0.62
east	0.27	0.68
south	0.46	0.34
west	–5.40	0.46

Snow Density

While increasing snow density with distance was not as obvious as the increase in snow depth, overall there was an increase in density with distance from the tree (Figure 7a-c). Density measurements from the snowpits in the clearing (collected with the 1000 mL wedge cutter) and estimated from the SNOTEL site were generally greater than those collected under the canopy with the Federal sampler. Sampling locations with the greatest density generally corresponded with those points of deepest snow. Directionality was also less evident, but variability between transects did occur over small distances. Trends of increasing density were more evident for tree A (Figure 7a), than tree C (Figure 7b) or tree D (Figure 7c). For trees A and C, the greatest increase in density occurred close to the trees (Figure 7a and 7b). However, directional differences was more obvious for trees C and D than tree A. The east transect tended to be least dense, while the north transects was more dense, especially closest to the trees. The west transect was most dense from 0.5 to 1 m away from tree C (Figure 7b), but this was the only tree for which the west transect density was measured.

The standardized depth integrated snow density data for the three trees exhibited an increasing pattern similar to tree A (Figure 7a), but exhibited more of an increasing trend (Figure 8a-8d) than the individual measurements for trees C and D (Figure 7b and 7c). Although the number of samples was small (13), a power function accounted for 86% of the relationship between standardized density and distance in the west direction (Table 3). A power law applied to south transect data (39 samples) accounted for 38% of the variance, while power functions fit to north (23 samples) and east (31 samples) transect data explained only 26% and 17% of the variance, respectively (Table 3).

Stand Scale Snow Water Equivalent

For the March 23, 2007 50-m north-south transect, the average SWE was 464 mm, and average snowpack densities for the north and south directions of tree C (Figure 7b) were 335 kg/m^3 and 344 kg/m^3, respectively. Using the Sturm depth equation with one 1-m canopy tree and a constant density across the transect, the estimated SWE was 2.5% less than without the tree (Table 4). Increasing the tree size to a 2-m canopy resulted in 3.7% less, and 9.0 % less for three 2-m trees (Table 4). Using the power function (equation 4) depth adjustments resulted in lower estimates of mean snow water equivalent than depth adjustments using Sturm (equation 2), yielding a further 0.1, 0.7, and 2.5% less estimated SWE for the three tree configurations (Table 4).

The difference in estimated average transect SWE between the two depth adjustment methods was only 0.1% with the addition of one tree with 1-m canopy radius to the transect, with Sturm yielding a decrease in estimated SWE of 2.5%. For the larger tree using a constant density, the SWE estimate was 3.7% lower for Sturm and a further 0.7% less for the power function. However, the addition of three 2-m canopy trees produced differences in estimated mean SWE of 2.3% for the constant density, and 3.6% difference for the variable density.

When assuming changes in snowpack density due to canopy effects, the addition of the different tree configurations caused a 2.8, 4.2, and 10.8% reduction in estimated transect SWE using the Sturm equation (Table 4). For the power function, these estimates were 2.9, 4.9, and 12.8% less. In the extreme case, that is with a decreasing density approaching each tree, the addition of three trees with canopy radii of 2 m yielded a reduction in estimated SWE of 50 mm using the Sturm equation, and 67 mm using the power function. Within the context of estimating stand scale SWE, the presence of only a few trees of various canopy radii can significantly reduce mean transect snow water equivalent (Table 4).

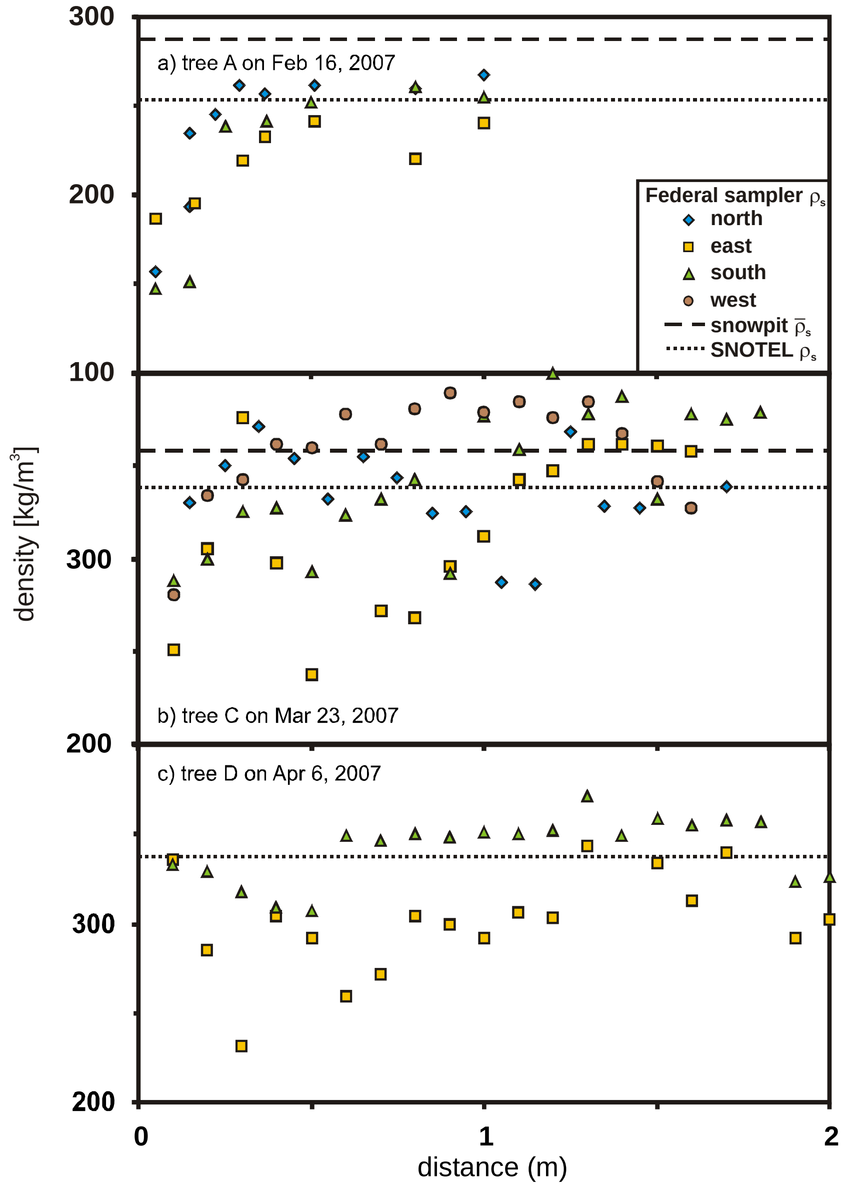

Figure 7. Depth integrated snow density as a function of distance from a) tree A on February 16, 2007, b) tree C on March 23, 2007, and c) tree D on April 6, 2007 for the four cardinal directions (north, east, south, west). The dashed line represents the average snowpit density measured using the 1000-mL wedge sampler and was 289 and 358 kg/m^3 for February 16 and March 23, respectively. The dotted line represents the daily mean density computed from the SNOTEL SWE and depth measurement and was 257, 340, and 335 kg/m^3 for the three days.

Table 3. Coefficients of determination for power laws fit to each standardized directional density transect.

Direction	r^2 value
north	0.26
east	0.17
south	0.38
west	0.86

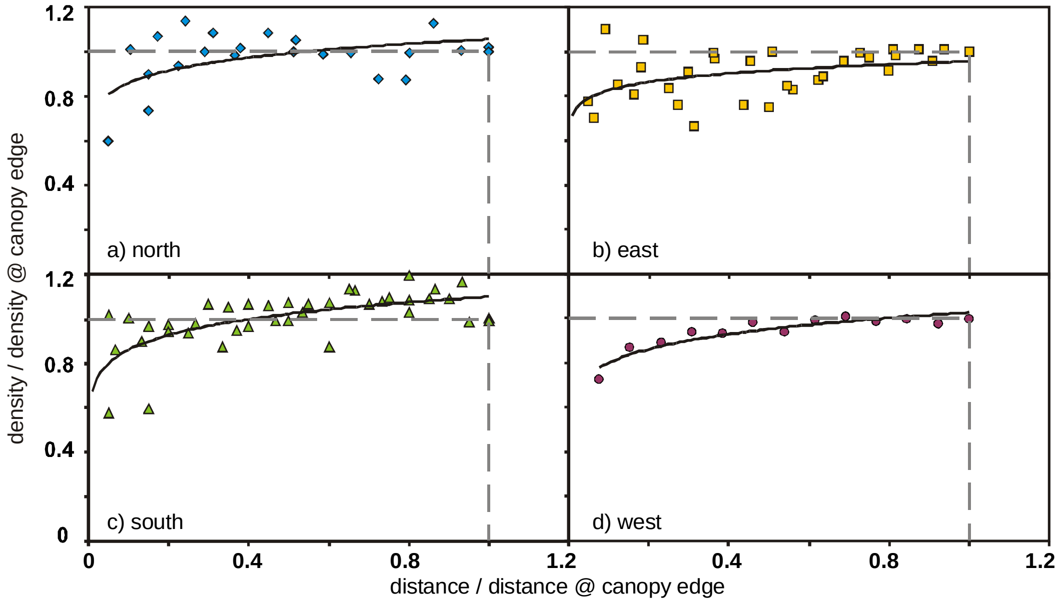

Figure 8. Directional depth integrated snow density data standardized to canopy edge values for all dates with the best-fit power function.

Table 4. Changes in estimated mean SWE (%) for three scenarios applied to March 23, 2007 depth transect, assuming both constant and variable snowpack density.

	Constant density		Variable density	
	Power	Sturm	Power	Sturm
no trees	464 mm	464 mm	464 mm	464 mm
one - 1m	−2.6%	−2.5%	−2.9%	−2.8%
one - 2m	−4.4%	−3.7%	−4.9%	−4.2%
three - 2m	−11.3%	−9.0%	−12.8%	−10.8%

DISCUSSION

The distribution of snow away from the trunks of individual conifers sampled in this study resemble accumulation patterns represented in earlier studies (e.g., Woo and Steer, 1986; Sturm, 1992; Hardy and Albert, 1995, Fassnacht *et al.*, 2006). The snowpack around trees also displayed directional variation in snow depth and density similar to those seen in previous works (Fassnacht *et al.*, 2006, Musselman *et al.*, *in submission*). Other studies have relied on coarser resolution measurements for the collection of snow depth and density data; Hardy and Albert collected depth measurements at approximately 0.5-m intervals, while Musselman *et al.* (*in submission*) collected snow depth data at 0.2, 0.5, 1, 2, 4, and-6 m from the tree, and density data at 0.5, 1, 2, 3, and 4-m distances from the tree. The time series data of snowpack data presented in this study were collected at a finer resolution (0.1 m), enabling a detailed comparison of snowpack properties between directions over multiple sampling dates.

Smooth asymptotic increases in snow depth were most similar to observations made by Sturm (1992) for medium-sized spruce trees (0.6 to 2.2 m canopy radius) in the Alaskan taiga (Figure 6). While the model by Hardy and Albert (1995) predicted directional depth data reasonably well, the lack-of-fit was likely due to the presence of a transition zone around their large white spruce (3.5 m crown radius) that was not observed for our trees (0.9 to 2.5 m mean canopy radius) (Figure 6). Hardy and Albert (1996) determined that differences in accumulation patterns between their tree and those observed by Sturm (1992) were primarily due to the increased interception efficiency of their tree, and this is likely the reason why their model did not predict snow accumulation around our trees.

Directional variation in snow depth seemed to be spatially and temporally consistent. For three of the five trees sampled, the south direction had the greatest snow depth from the tree to the canopy edge (Figures 3 and 5). For trees B and E, this trend was maintained throughout the 2007 winter (Figure 5). Directionality may be the result of variations in solar exposure and thermal radiation around the tree due to variable canopy size, as documented by Link and Marks (1999), Sicart *et al.* (2004), and Musselman *et al.* (*in submission*). While wind redistribution may also affect accumulation patterns around trees, the only effects of redistribution were observed for tree A on Feb 16, 2007. The north side of this tree, which faced a small clearing, displayed visibly greater amounts of snow accumulation, and data show that this direction has the greatest snow depth for most of the transect (from 0.05 to 0.8 m away from the tree) (Figure 4).

Snow accumulation patterns for these conifers may also have been affected by such factors as microtopography (ground roughness) and small scale slope and aspect. This was especially true for trees A, C, and D; a 30 cm high root wad was present for every direction but the north around tree A which, coupled with the effects of redistributed snow, resulted in greater snow amounts for this direction, and root wads were also present around the entire boles of trees C and D.

Trends of increasing snow density with distance and directionality were most evident for tree A (Figure 7), and less obvious for trees C and D that were sampled later in the winter of 2007. This may have occurred due to destructive metamorphism of snow crystals resulting in more homogeneous snowpack layers. Sampling of trees C and D occurred after periods of melt-freeze; these cycles often result in ice layers within the snowpack that have been known to creating problems for measurements with the Federal sampler. While the Federal Sampler allowed for the collection of depth integrated density samples at a finer horizontal resolution (0.1 m) than was possible with the 1000 mL sampler, collection of samples with the 1000 ml would have provided a vertical profile. However, such sampling destroys a larger area than the Federal sampler. The extent of disturbance induced by sample extraction is unknown, but it can be assumed that within the vertical profile less of the snowpack is altered due to use of the Federal Sampler than the 1000 mL sampler.

The increasing trend in snow depth has been observed, yet directionality must be considered. A similar trend is less obvious for snow density, especially later in the season and in the context of directionality. More data, including layer characteristics, as per Musselman *et al.* (*in submission*), are required to understand density variations under the canopy over the snow season. As well, snow depth is a function of the characteristics of the ground and snow surface, so such small variations should be measured or considered.

Snowpack interpolation at the small watershed scale (~ 1 km^2) has been performed for alpine basins without trees (e.g., Elder *et al.*, 1991) or without definite under the canopy measurements. Future snowpack investigations in sparsely forested areas should consider the subtleties of depth, and to a less degree density, variation under the canopy.

CONCLUSIONS

Observations of snow depth around five trees of the spruce-fir community in Northern Colorado illustrated that the increase in snow depth moving away from a tree was not consistent in all directions. In the specific trees sampled in this study, overall the snow was the deepest for the transect south from the tree. However, this was not consistent for all trees and did not correspond with the sampling of Musselman *et al.* (*in submission*) in New Mexico. More snow depth data should be collected for individual trees over the snow season in different locations. The proximity of individual trees with respect to other trees should be considered.

There was a variation in snowpack density under the canopy. Earlier in the accumulation season it tended to increase with distance away from the tree, while it became more random as the snowpack became denser. It is difficult to measure the density of the snowpack over a small interval, yet these data have been shown to be important to estimate the stand scale SWE. Small horizontal scale measurements of density with the Federal Sampler should be combined with vertical profiles using the 1000 mL wedge sampler to improve the understanding of density variation.

The estimation of stand scale SWE is in part a function of the measurement data; if trees exist within the measurement area, sampling under the canopy can influence interpolation of SWE. Scale is important, and this necessitates the resolution of sampling and interpolation. While trees were only superimposed on a depth transect of data, the estimated decrease in SWE became significant when more trees were introduced. In a sparse canopy setting, finer resolution data, e.g., 0.1-m, could be used over larger scales e.g., 100-m or larger, to assess the impact of decreased SW from less depth and lower density near trees.

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