HYDROLOGICAL PROCESSES
Hydrol. Process. **26**, 2524–2534 (2012)
Published online 18 July 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.9450

Forest influences on snow accumulation and snowmelt at the Hubbard Brook Experimental Forest, New Hampshire, USA

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Abstract:

Many factors influence snow depth, water content and duration in forest ecosystems. The effects of forest cover and canopy gap geometry on snow accumulation has been well documented in coniferous forests of western North America and other regions; however, few studies have evaluated these effects on snowpack dynamics in mixed deciduous forests of the northeastern USA. We measured snow depth and water equivalent near the time of peak snowpack accumulation and, again, during snowmelt to better understand the effect of forests on snowpack properties in the northeastern USA. Surveys occurred in openings and under the forest canopy at plots with different characteristics (e.g. aspect, elevation, forest composition) within the Hubbard Brook Experimental Forest in New Hampshire, USA. Snow water equivalent (SWE) was significantly greater in openings ($p = 0.021$) than in forests on north-facing plots but not on south-facing plots ($p = 0.318$) in early March 2009. One month later, SWE was more variable but remained greater in openings on north-facing plots ($p = 0.067$), whereas SWE was greater ($p = 0.071$) under forests than in clearings on south-facing plots, where snowmelt had sufficiently progressed. During peak accumulation, SWE decreased with increasing conifer cover on north-facing plots. During the snowmelt period, SWE on south-facing plots decreased with increasing basal area, sky view factor and diameter at breast height of trees on the plots. These results have implications for spring streamflow and soil moisture in the face of changing climate conditions and land use pressures in the forests of northern New England. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS snow distribution; snow water equivalent (SWE); snowmelt; forests; sky view factor

Received 24 August 2011; Accepted 1 June 2012

INTRODUCTION

Forests can have substantial influences on snow accumulation and melt through the interception of snow on foliage and branches and alterations to various components of the snowpack energy balance (Dewalle and Rango, 2008). Previous studies of forest–snow interactions and comparisons of snowpack properties to nearby forest clearings have shown that gap size strongly influences both radiation dynamics and turbulence, such that differences in snow depth or water equivalent between nearby forested and cleared areas depends on gap size (Varhola *et al*., 2010b). Golding and Swanson (1986), working in Alberta, Canada, showed that snow accumulation was greatest in clearings of between two and three tree heights in diameter, with larger openings experiencing wind scour and snow depletion relative to surrounding forests and smaller openings influenced by interception of the surrounding forests. Maximum snow accumulation occurred in clearings of five tree heights in diameter in a Colorado study (Troendle and Leaf, 1980) and four tree heights in a Sierra Nevada, California study (Anderson and West, 1965), but other studies have shown little influence of gap size in settings where local (i.e. small scale) wind dynamics and aspect appear to exert more dominant controls on snow accumulation and melt (Berndt, 1965; Pomeroy *et al*., 1997). A recent study by Lawler and Link (2011) elucidates the important spatial and temporal controls on all-wave radiation and melt dynamics across a range of forest gap sizes in a high latitude setting, pointing to the complex interactions between canopy shading and gap size across the snow melt season. Recent studies have also shown considerable promise in relating snowpack variability to forest properties that can be derived from ground-based instruments, such as hemispherical photography (Essery *et al*., 2008; Lopez-Moreno and Latron, 2008) and airborne laser scanning (LIDAR) (Varhola *et al*., 2010a).

Numerous studies in evergreen coniferous forests demonstrate important differences in snow accumulation and melt between forested and open areas (Berris and Harr, 1987; Gary, 1974; Golding and Swanson, 1986; Haupt, 1951; Marks *et al*., 1998; Stegman, 1996; Winkler *et al*., 2005) and show that the removal of forests can alter streamflow during snowmelt or rain-on-snow events (Harr, 1986; Troendle and King, 1985). Importantly, studies in evergreen forests highlight the influence of canopy characteristics, including leaf area index, canopy density and tree canopy structure (Musselman *et al*., 2008; Pomeroy *et al*., 2002; Veatch *et al*., 2009), and canopy gap size

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(Golding and Swanson, 1986) on snow dynamics. A recent meta-analysis of 33 snow studies drawn from 65 sites, primarily within evergreen forests of western North American and Europe shows a clear reduction in both snow accumulation and snow melt with increasing forest cover, with fully (i.e. 100%) forested areas experiencing 50% less snow accumulation, on average, than open areas (Varhola *et al.*, 2010b).

Fewer studies have examined the role of the mixed deciduous, evergreen forests of eastern North America on snowpack dynamics. Notable exceptions include early work in northern New England documenting differences in snow depth and water equivalent between forested areas and clearings. Sartz and Trimble (1956), working at the Bartlett Experimental Forest in northern New Hampshire, found that snow depth was greater in cleared areas than in adjacent forested areas, but snow density was greater under forested stands, resulting in little difference in snow water equivalent between stands of hardwood forests and clearings. A study in northwestern New Hampshire found approximately 20% lower snow water content under red and white pine stands than in hardwood stands or cleared areas (Hart, 1963). Working in northern Michigan, Urie (1966) showed that plots within dense (crown densities exceeding 80%) pine forests contained 30% less water equivalent in the snowpack than plots within deciduous forests over two measured winters. Hendrick *et al.* (1971) showed that conifer forests at the Sleepers River watershed in northeastern Vermont held 30% more water in the snowpack on a south-facing site and more than 50% more snow water on a north-facing site, and snow depletion rates for open sites exceeded conifer forests sites by days to more than a week. More recently, a study in the Turkey Lakes Watershed in southeastern Canada documented lower snow water equivalents in mature hardwood forests than in adjacent cleared areas, but these differences were only statistically significant for one of 2 years studied and only on some slope positions, findings the authors attributed to a mid-season melt during their first year of study and the likely redistribution of snow by wind on north-facing slopes (Murray and Buttle, 2003). Collectively, these studies suggest than the less-studied forests of northeastern North America can have detectable impacts on snow cover, particularly within the mixed deciduous, evergreen stands that occur at higher elevations and on north-facing slopes across this region. Authors of these studies also point to the importance of forest–snow interactions on runoff processes, with references to the implications for mitigating soil frost and associated rapid runoff (Hart, 1963), sustaining ground water recharge (Urie, 1966) and water supplies (Sartz and Trimble, 1956), and regulating biogeochemical fluxes (Murray and Buttle, 2003).

Our interest in studying forest influences on snowpack properties stems from a desire to understand and predict the effects of changing forest cover in the mixed forests of the northeastern USA on hydrological processes and the maintenance of high-quality water supplies. Several recent reports point to rapid rates of change in forests of the northeastern USA, where dense populations in proximity to forests and increasing pressures in the form of housing development and biofuel production have the potential to alter forest structure and influence stream flow and water quality (BERC, 2007; Foster *et al.*, 2010; NRC, 2008; Stein *et al.*, 2005). In this context, we initiated a study to examine forest influences on snowpack properties in the mixed deciduous, evergreen forests of New Hampshire. Our objective was to determine whether measureable differences exist in snowpack properties between forested and cleared areas across an elevation and aspect gradient. We aimed to place our results within a broader geographic context by comparing them to previous studies, adding to the data comparison published by Lundberg *et al.* (2004).

METHODS

Study area

The study was conducted at the Hubbard Brook Experimental Forest, a 3160-hectare forest reserve located within the White Mountain National Forest of New Hampshire, managed by the US Department of Agriculture Forest Service and part of the National Science Foundation-supported Long-term Ecological Research (LTER) network. The Hubbard Brook valley is oriented approximately east–west, ranging in elevation from 250 m in the east to 1015 m at the summit of Mt. Kineo on the western end of the valley (Bailey *et al.*, 2003). Average annual precipitation, measured over the period 1955–2000 at stations across the valley, ranges from 1225 mm at 250 m to 1500 mm at 800 m (Bailey *et al.*, 2003). Weekly snow courses conducted at sites across the Hubbard Brook valley since 1965 indicate that a seasonal snowpack typically develops by early December and lasts on south-facing slopes until April and on north-facing slopes until May. Peak snow-water equivalent (SWE) typically occurs in March with an average annual magnitude of 145 mm on the south-facing slopes and 220 mm on the north-facing slopes (Campbell *et al.*, 2010; Bailey *et al.*, 2003).

For this study, we selected two forested and two open plots at low, mid- and high elevations on the south-facing slopes of watersheds 5 and 6 and the north-facing slopes of watershed 7 (Figure 1). A third forested plot was selected at high elevation on each aspect to increase the representation of evergreen conifers in sampled sites. The open plots were situated in rain gauge clearings, maintained by the Hubbard Brook Experimental Forest to provide a 45° canopy clearing to the rain gauge located at the plot centroid. These clearings are roughly circular with diameters ranging from 30–43 m or approximately one to three times the canopy height of the surrounding forest (Table I). Vegetation on the forested plots was dominated by deciduous hardwoods, including sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), American beech (*Fagus grandifolia*), yellow birch (*Betula alleghaniensis*) and paper birch (*Betula papyrifera*) at low and mid

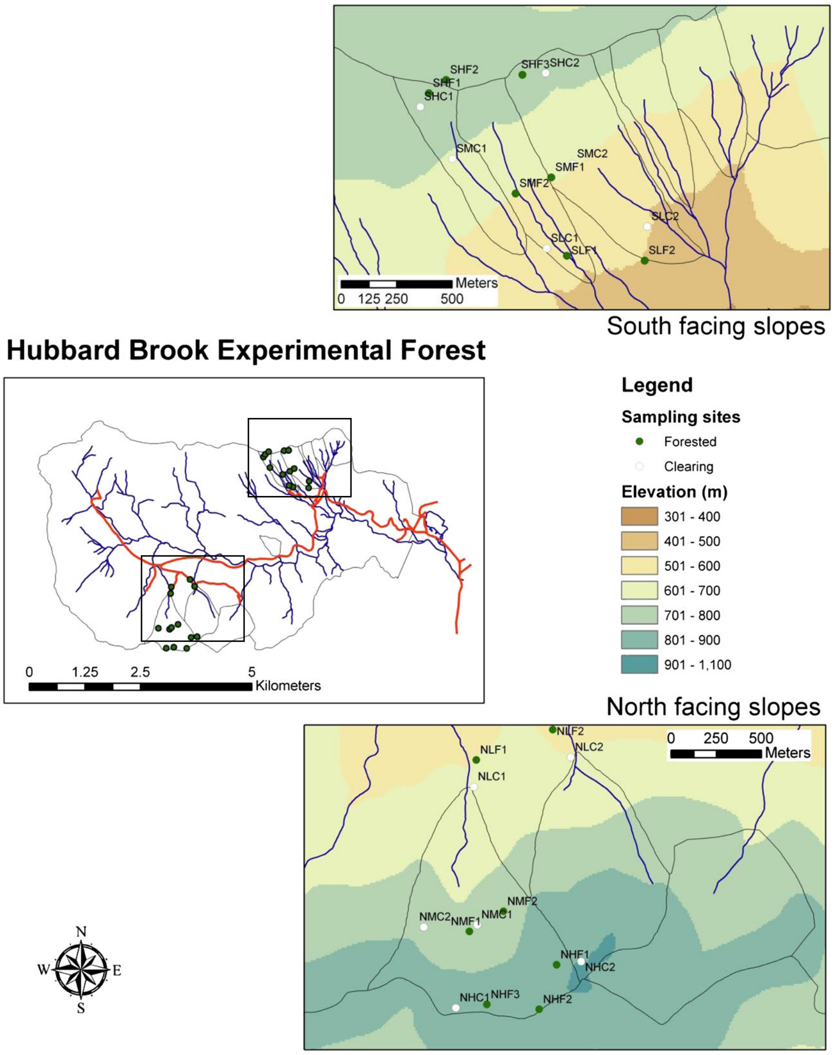

Figure 1. Study area: the Hubbard Brook Experimental Forest in northern New Hampshire and location of snow plot measurements for this study

elevations, particularly on the south-facing plots. Evergreen conifer species (hereafter referred to as conifers), including red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*), have greater dominance on north-facing plots and at higher elevations. As noted in Table I, these conifer species were absent in all but one plot on the south-facing slopes but comprised between 30 and 100% of the trees on all but one (NLF2) of the forested plots on the north-facing slopes.

Field measurements

To determine a spatial measurement interval for our study, we conducted preliminary measurements on 20 February 2009 on one forested (NLF2) and one open (SLC1) plot (Figure 1). We measured snow depth on each plot and snow mass on the forested plot along a north–south oriented transect and an east–west oriented transect at approximately 1-m intervals over a distance of 20 m. We used semivariograms to examine the spatial structure of snowpack properties at these plots (Figure 2). These pilot measurements showed no spatial structure to snow depth on the south-facing cleared plot and little spatial autocorrelation at sample spacings greater than 5 m on the north-facing forested plot (Penn, 2009). We therefore set a 5-m sampling interval for this study based on these findings.

Snow properties were measured on all 26 plots on 4 March and 1 April 2009 with the objective of capturing peak snowpack accumulation on the first sampling date and conditions indicative of the snowmelt period during the second sampling date. At each plot, we recorded the coordinates of the plot center using a Trimble GeoExplorer global positioning system and established two 30-m transects: one oriented north–south across the plot and the other oriented east–west across the plot, intersecting at the plot center. Based on the results of our pilot measurements described previously, we measured snow depth and mass using Adirondack and Federal style snow sampling tubes at 5-m intervals along each transect for a total of 13 measurements per plot (only one measurement at the plot center).

Forest metrics were measured at the plots on 20 February, 4 March, 18 March and 1 April 2009. A single prism plot measurement, taken from the plot center, was used to estimate forest basal area (BA, m^2/ha) of the plot. Average tree diameter at breast height (DBH, cm) and percent coniferous composition were measured

Table I. Summary values for 26 forested and cleared plots measured at the Hubbard Brook Experimental Forest. Plot locations given in Figure 1

Site [a]	Elevation (m)	DBH (cm)	Basal area (m^b/ha)	Sky view factor	Percent coniferous	Mean tree height or canopy opening size [b] (m)	4 March snow depth[c] (cm)	4 March SWE [c] (cm)	1 April snow depth [c] (cm)	1 April SWE [c] (cm)	Change in depth (cm)	Change in SWE (cm)
NLC1	615	0	0	1.00	0	31	92.0	20.0	57.8	18.6	−34.2	−1.4
NLC2	600	0	0	1.00	0	40	104.0	26.1	75.9	22.5	−28.1	−3.6
NLF1	601	29	30	0.44	31	26	76.6	17.7	38.6	12.7	−38.0	−5.0
NLF2	583	33	25	0.52	0	28	87.4	20.3	51.0	13.4	−36.4	−6.9
NMC1	734	0	0	1.00	0	38	113.8	25.9	87.1	29.2	−26.6	3.3
NMC2	772	0	0	1.00	0	37	111.2	29.0	81.7	30.9	−29.5	1.9
NMF1	737	28	28	0.43	25	n/a	106.8	25.2	78.6	26.4	−28.2	1.2
NMF2	750	27	34	0.32	33	26	99.5	23.4	73.6	23.7	−25.9	0.3
NHC1	858	0	0	1.00	0	43	116.0	29.3	79.1	25.3	−36.9	−4.0
NHC2	901	0	0	1.00	0	29	106.8	24.9	84.3	25.1	−22.5	0.2
NHF1	875	27	41	0.31	50	17	90.3	21.4	68.9	19.5	−21.3	−1.9
NHF2	881	20	46	0.23	100	15	78.8	17.2	69.9	18.2	−8.9	1.0
NHF3	852	28	34	0.25	73	16	99.8	22.8	85.2	24.0	−14.6	1.2
SLC1	503	0	0	1.00	0	42	75.5	23.7	18.3	6.0	−57.2	−17.7
SLC2	498	0	0	1.00	0	30	70.5	18.6	18.7	5.6	−51.8	−13.0
SLF1	523	28	21	0.59	0	7	74.7	19.0	30.3	10.1	−44.3	−8.9
SLF2	538	31	41	0.49	0	30	67.9	18.1	25.6	8.8	−42.2	−9.3
SMC1	690	0	0	1.00	0	41	86.7	22.7	23.6	8.2	−63.1	−14.5
SMC2	598	0	0	1.00	0	30	79.0	18.8	23.9	8.1	−55.1	−10.7
SMF1	606	28	30	0.52	0	19	78.6	22.9	14.4	3.9	−64.3	−19.0
SMF2	608	29	14	0.57	0	8	64.0	16.5	28.3	8.8	−35.8	−7.7
SHC1	768	0	0	1.00	0	33	76.7	16.9	27.1	9.0	−49.6	−7.9
SHC2	774	0	0	1.00	0	35	77.7	22.8	21.1	6.6	−56.7	−16.2
SHF1	768	25	23	0.53	0	11	84.1	19.0	48.6	14.5	−35.5	−4.5
SHF2	739	22	21	0.33	78	13	83.1	18.2	56.4	16.9	−26.7	−1.3
SHF3	725	10	21	0.49	0	n/a	90.5	20.6	54.6	19.1	−36.0	−1.5

[a] Site name coding is used to indicate aspect (S = south, N = north), elevation (L = low, M = mid, H = high) and cover type (C = clearing, F = forest).
[b] Values for tree height estimated by Whitehurst *et al*. (2011) with values listed as n/a not available from LiDAR returns. Values for opening size taken as mean of two measurements taken along orthogonal transects from forest edge to forest edge.
[c] Values represent mean of 13 measurements taken 5 m apart along two orthogonal transects.

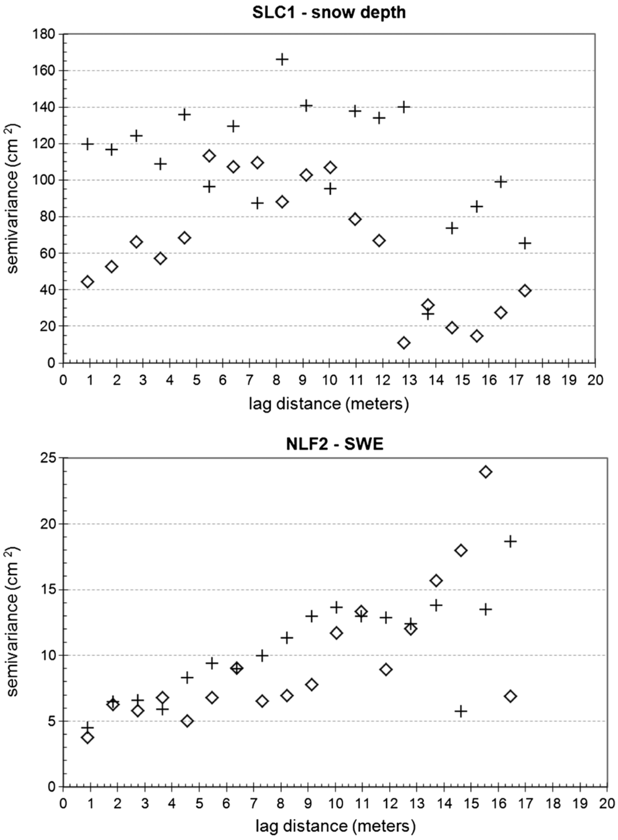

Figure 2. Semivariograms for pilot snow depth measurements made on plot SLC1 (top) and SWE measurements made on plot NLF2 (bottom) on 20 February 2009. Crosses are measurements along an east–west (E-W) transect across the plot; diamonds are measurements along a north–south (N-S) transect across the plot. Snow depth measurements made at SLC1 show strong spatial autocorrelation at sample spacings of < 5m in the N-S direction but no spatial autocorrelation at any scale in the E-W direction. SWE measurements at NLF2 show spatial autocorrelation at sample spacing in the range of 5–10 m. Additional details are given in Penn (2009)

for each tree identified in the prism plot. Hemispherical digital photos of the forest canopy were taken using a Nikon Coolpix 5400 digital camera equipped with a FC-E9 fish-eye lens. At each plot, three hemispherical photos were taken within a 5-m radius of the plot center and analyzed with Gap Light Analyzer software (Frazer *et al.*, 1999) to estimate the sky view factor (SVF) or the percentage area of the sky hemisphere above the effective horizon (Hellström, 2000; Lopez-Moreno and Latron, 2008; Lundberg *et al.*, 2004). Measures of SVF were averaged from the three photos to obtain one value per site.

Analyses

Statistical analyses were conducted using SPSS Statistical Software (SPSS v. 15.1, SPSS Inc., 2006). The 13 snow depth and SWE measurements taken at each plot were averaged for a plot-average estimate of SWE and snow depth for each sampling date. Plot average snow depth and SWE, along with all forest metrics (BA, DBH, SVF and percent conifer), were assessed for normality using the Kolmogorov–Smirnov (K-S) Normality Test. Regression analysis was used to evaluate trends in snow depth and SWE with elevation for all plots and with forest metrics for the forested plots. *T*-tests were used to assess differences in SWE between forested and cleared plots.

To place our study within a broader temporal context, we used long-term data from the Hubbard Brook Experimental Forest snow monitoring program. These data are collected weekly by Hubbard Brook forest staff beneath the forest canopy nearby the long-term rain gauge stations using a sampling protocol described in Bailey *et al.* (2003). Weekly snow survey data for the 2008–2009 winter were plotted for four sites to evaluate the timing of our sampling within the seasonal trajectory of snow accumulation and melt. We also used the long-term snow survey data to track changes in the date of peak snow accumulation for two sites with more than 40 years of continuous records. These time series date were evaluated using the nonparametric Mann–Kendall test for trend.

To compare our results with those of previous studies, we calculated the ratio of SWE in each forested plot on the north-facing slopes to the nearest similar-elevation cleared plot for the 4 March 2009 sample date to approximate the fraction of SWE falling in clearings that could be estimated as intercepted or sublimated from the forest canopy, termed the interception-sublimation fraction (F) by (Lundberg *et al.*, 2004). We selected only the plots on north-facing slopes for our earlier sampling date for this analysis to minimize the possibility that differences were because of snowmelt, rather than forest canopy effects on snow accumulation.

RESULTS

Our sampled plots were composed mostly of deciduous tree species with a minimal conifer component, except for the three plots at the highest elevation on the north-facing slope and one high-elevation plot on the south-facing slope (Figure 3). On average, trees on the north-facing plots were larger, ranging in size from 20–35 cm DBH, compared with 5–35 cm DBH on south-facing slopes, with basal areas ranging from 25–50 m^2/ha, compared with 10–45 m^2/ha on south-facing slopes. Canopy sky-view factor varied little among plots on south-facing slopes but covered a wider range of values on north-facing slopes because of the larger presence of evergreen conifers on some of these plots (Table I, Figure 4). Canopy sky view factor decreased non-linearly as the percentage of conifers on the plots increased, such that for a plot with 50% conifers, approximately 33% of the sky is visible from the forest floor (Figure 5).

During the year of our study, snow accumulation on south-facing slopes peaked in late February, reaching 19.3 cm of water equivalent at the high-elevation station and 15.5 cm SWE at the low-elevation station (Figure 6). Accumulation progressed another 2.5 weeks on north-facing slopes, reaching a peak of 30.7 cm SWE at the high-elevation monitoring station and 25.7 cm SWE at the low-elevation monitoring station on 16 March 2009. Between the first (4 March) and second (1 April) sampling date, the weekly

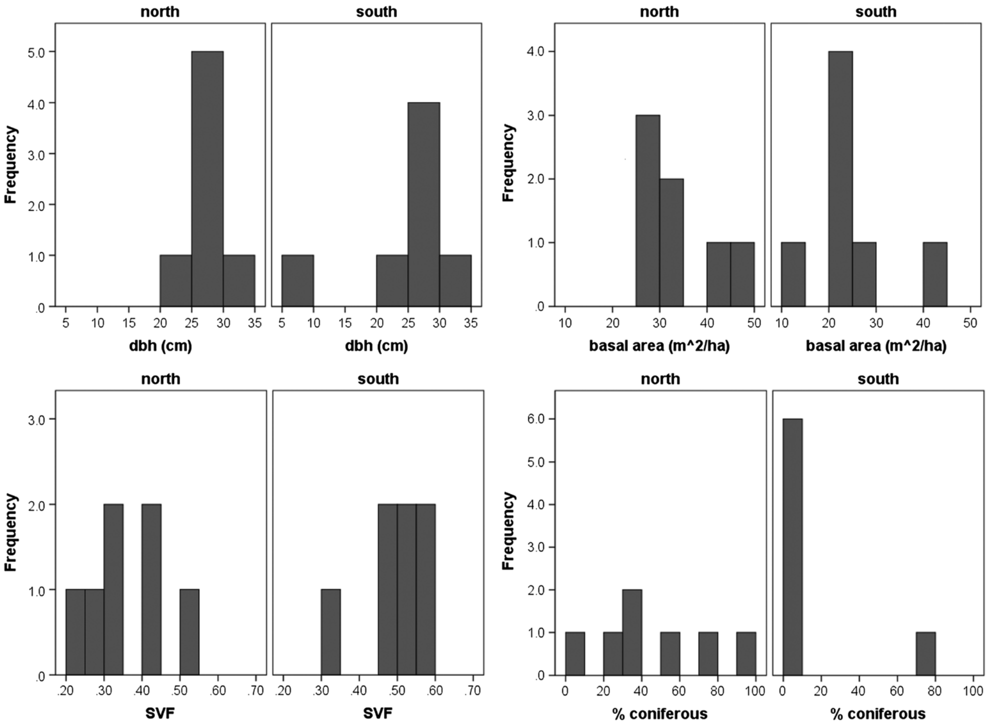

Figure 3. Histograms of forest metrics for each of the 14 forested plots displayed by plot aspect

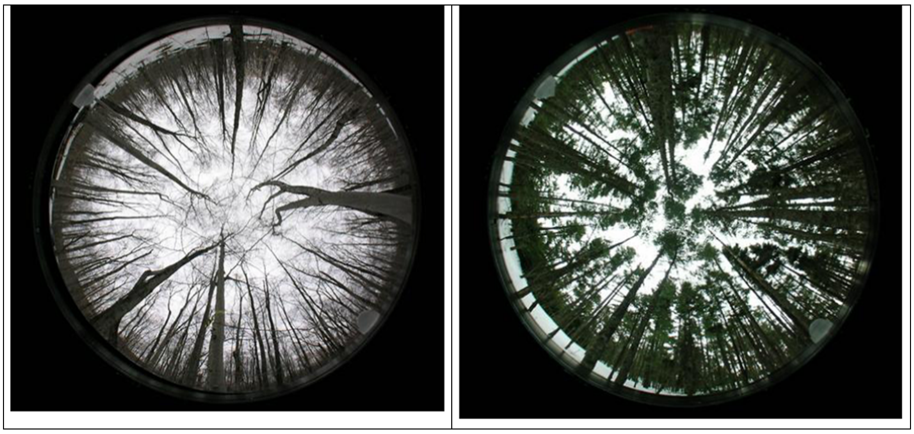

Figure 4. Photographs taken with a hemispherical (fish-eye) lens on forested plots SLF2 (left) and NHF2 (right)

snow monitoring data show that nearly 40% of the snow at the south-facing high elevation station and nearly 50% of the snow at the south-facing low elevation station had depleted, but only 30% and 23% of the snow had depleted on north-facing high and low elevation stations, respectively, by 1 April 2009. Snow melt was complete at the south-facing low elevation station by 6 April and 13 April at the south-facing high elevation station, but on the north-facing slopes, not until 27 April at the low elevation station and 11 May 2009 at the high elevation station (Figure 6). On average, long-term data from Hubbard Brook show that snowmelt tends to occur on average of roughly 3 weeks earlier on south-facing slopes than on north-facing slopes. Analyses of long-term trends indicate that the timing of peak snow water equivalent has changed over the period of record (Figure 7). At Station 2 on the south-facing slope, the day of snowmelt onset has advanced by 0.25 days per year for 1956–2011 ($p = 0.063$), and at Station 17 on the north-facing slope, it has advanced by 0.29 days per year for 1966–2011 ($p = 0.097$).

Average plot SWE measured on 4 March 2009 across the 26 plots of our study ranged from a minimum of 16.5 cm to a maximum of 29.3 cm, and that on 1 April 2009 ranged from a minimum of 3.9 cm to a maximum of 30.9 cm (Table I). Although we intended to capture conditions at peak accumulation and during melt, we accomplished this objective only for plots on the south-facing slopes. Additional snowfall and subsequent melt on north-facing slopes caused some plots to increase and others to decrease in depth and water equivalent between the 4 March and 1 April sampling dates. The greatest overall change in SWE was a mean loss of 19 cm on a mid-elevation, south-facing forested plot, followed closely by losses of 16.2 and 17.7 cm on south-facing cleared plots. Although snow tended to be deeper with greater water equivalent at higher elevation, none of the aspect-date combinations showed a

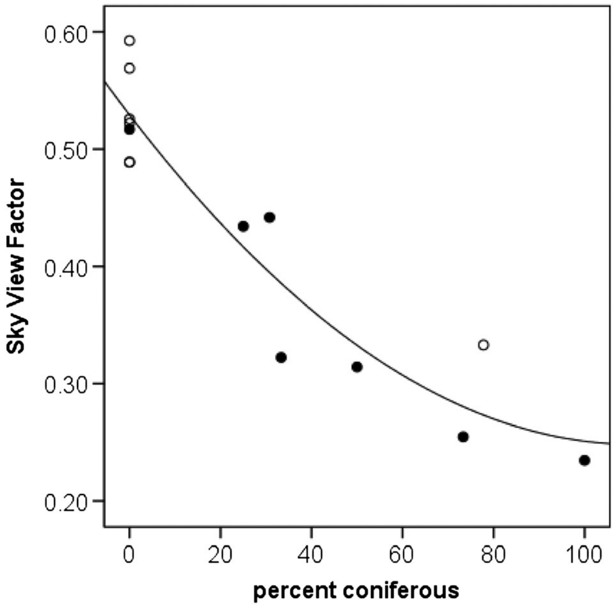

Figure 5. Plot of canopy sky view factor *versus* percentage of trees on each plot as conifers for 14 forested plots measured in this study. Closed circles are plots on north-facing slopes; open circles are plots on south facing slopes. Regression model for the fit is $Y = 2.295e^{-5}X^2 - 0.005X + 0.529$ ($p < 0.0005$, $R^2 = 0.887$)

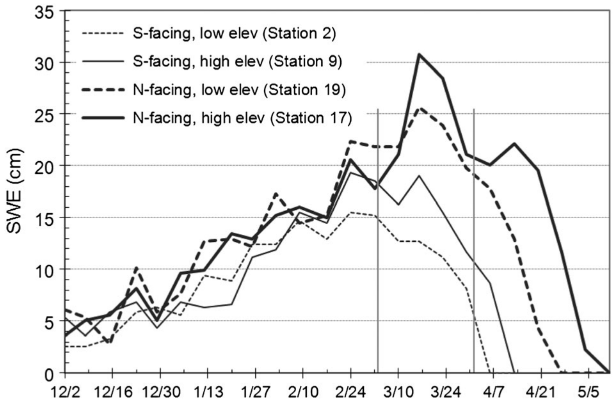

Figure 6. Bi-weekly snow monitoring measurements made by staff of the Hubbard Brook Experimental Forest. Vertical lines indicate dates of sampling for this study

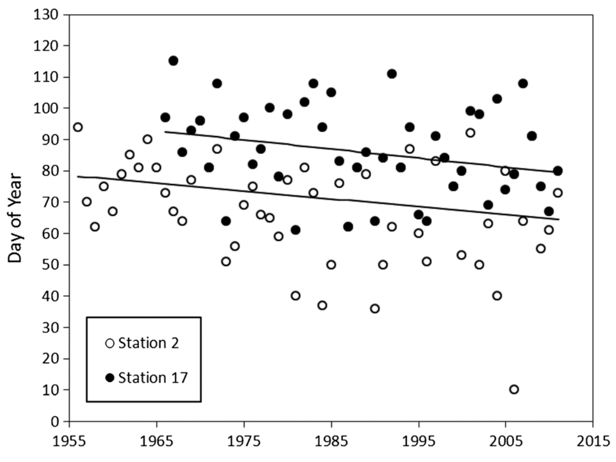

Figure 7. Plot of the day of peak snow accumulation by year for long-term monitoring stations, including Station 2 on the south-facing slopes and Station 17 on the north-facing slopes, of the Hubbard Brook Experimental Forest

statistically significant trend in SWE with elevation over the relatively narrow elevation gradient (523–881 m) of our plots (Figure 8).

Our results show that SWE was significantly greater ($p = 0.021$) in openings (mean difference = 4.7 cm, SE = 1.8 cm) than in forests on north-facing plots during the accumulation period measured on 4 March 2009 but not (mean difference 1.41 cm, SE = 1.4 cm, $p = 0.318$) on the south-facing plots (Figure 9). On the second sampling date, differences in SWE were significant on both north-facing (mean difference = 5.6 cm, SE = 2.8 cm, $p = 0.067$) and south-facing plots (mean difference 4.5 cm, SE = 2.3 cm, $p = 0.071$). The direction of difference between forested and cleared plots shifted over the two sample dates, with SWE in clearings exceeding SWE in forests on 4 March and SWE in the forest exceeding SWE in clearings by 1 April on south-facing slopes, which were farther along the snowmelt trajectory (Figure 6).

Snow cover on the 4 March sampling date (i.e. near peak accumulation) declined with increasing conifer cover on north-facing plots, where forests appear to exert some influence on snow accumulation (Figure 9), but this relationship was weak and explained only 10% of the variability in SWE among these plots (Figure 10). Low elevation plots fell below the trend line on this non-significant relationship, indicating that elevation also contributed to some of the measured variability in SWE among the plots. Among the south-facing forested plots, where sampling on 1 April captured snowmelt conditions, SWE declined with increasing basal area of trees within the plots and sky view factor, but these relationships were not statistically significant and explained only 14% and 26%, respectively, of the variability in SWE among the plots. Size of trees, as measured by the mean DBH of trees in the plot, was most strongly related to SWE on south-facing plots on 1 April, explaining 64% of the variability in SWE among these plots (Figure 10).

DISCUSSION

Our results demonstrate that the water content of the snowpack was measurably different in forested stands relative to clearings at our field site in New Hampshire. A number of factors undoubtedly influenced the magnitude of differences we could detect and trends associated with forest canopy characteristics. First, snowfall during the winter of 2008–2009 ranked at or below average, with peak accumulation at the long-term monitoring station 2 on the south-facing slopes falling 18.5% below average and peak accumulation at station 17 on the north-facing slopes falling 9.8% above average (Figure 6, Campbell *et al*., 2010). Murray and Buttle (2003) only found statistically significant differences in SWE between forested and cleared plots during a year with more prodigious snowfall. Second, our small sample sizes also undoubtedly contributed to relatively weak correlations with forest metrics. Previous examinations of snowpack variability indicate that sample size strongly influences the ability

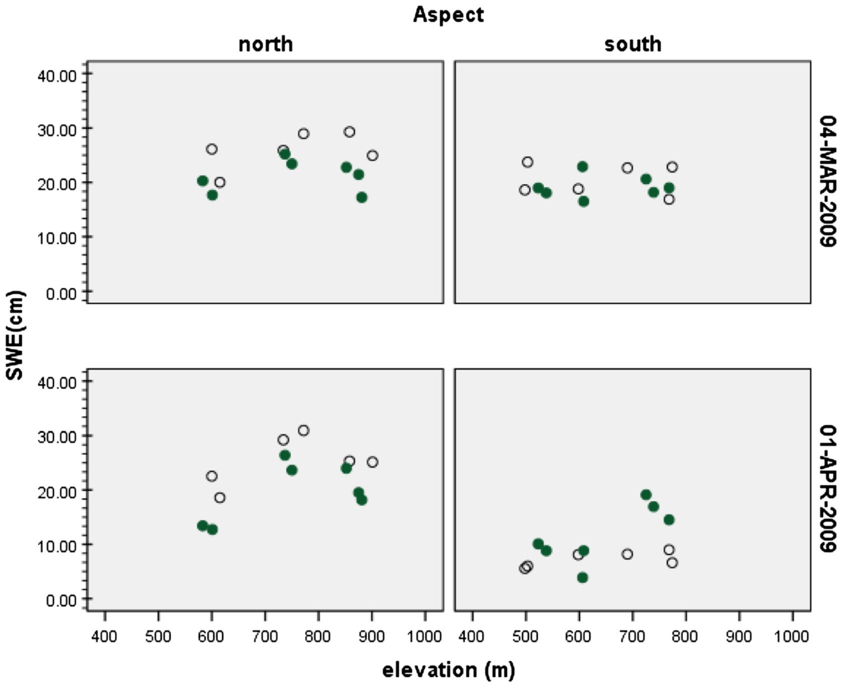

Figure 8. Plots of SWE *versus* elevation by sampling date and plot aspect. Closed symbols are forested plots; open symbols are clearings

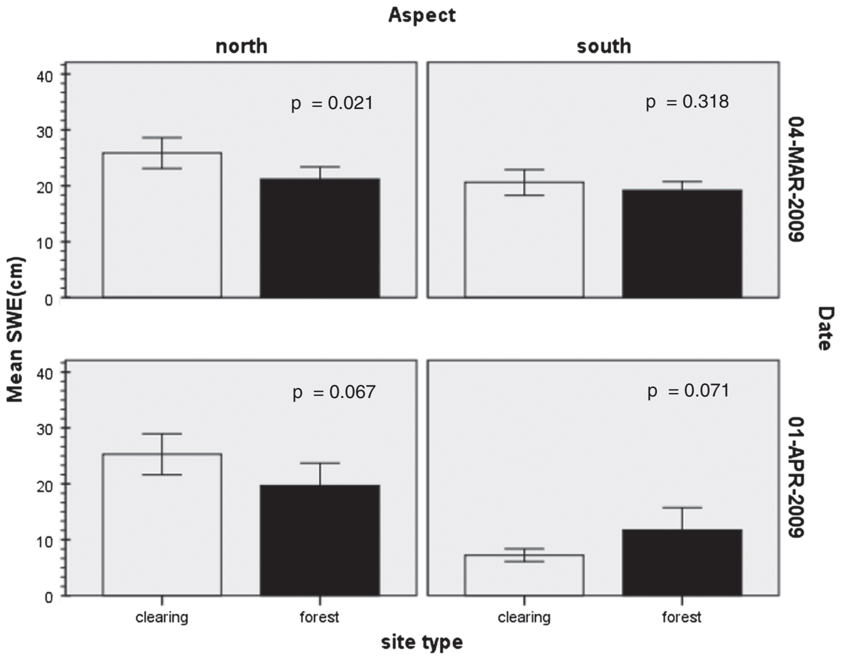

Figure 9. Bar graphs mean SWE across all forested ($n = 14$) and cleared ($n = 12$) plots by sampling date and plot aspect

to detect statistically significant effects of forest canopy characteristics on snow properties (Winkler, 2001; Winkler and Spittlehouse, 1995). Finally, as evidenced in Figure 6, only plots on the south-facing slopes had proceeded substantially through the snowmelt season by the time of our second sampling on 1 April, making snowmelt-induced differences between forested and open plots impossible to detect, given the timing of our surveys on north-facing sites.

Although forests in this landscape exert a modest but detectable effect on the snowpack during both the accumulation and melt season, the forest variables we measured provided only limited insight into controls on snow properties. Mean plot SWE decreased on the north-facing plots with increasing percent conifer on our 4 March sampling date, but lower snow cover on the low elevation plots weakened the statistical power of this relationship, given the relatively small size of our sample. The absence of a forest-clearing difference on south-facing plots, where conifers were absent from all but one plot, leads us to infer that canopy interception of snow controls differences in snow accumulation between forests and clearings at this

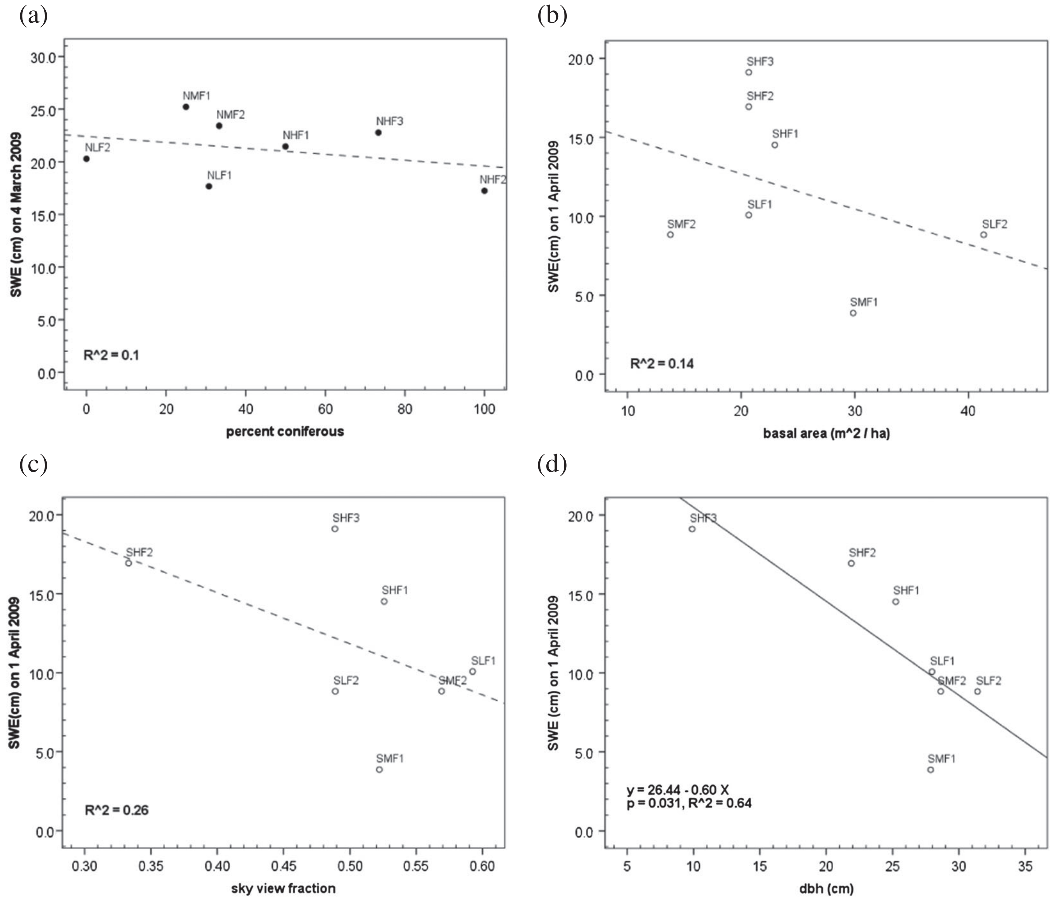

Figure 10. Plots of plot-average SWE *versus* percent coniferous trees on north-facing sites on 4 March 2009 (a), and plot average SWE *versus* basal area (b), sky view factor (c), and mean tree diameter at breast height (d) for south-facing sites on 1 April 2009

site, a conclusion that is consistent with other studies in eastern North America (Hart, 1963; Sartz and Trimble, 1956; Talbot *et al*., 2006; Urie, 1966). The trends we detected in decreasing SWE with increasing basal area, sky view factor and DBH during the snowmelt period on south-facing plots are consistent with relationships identified in other studies (Lopez-Moreno and Latron, 2008; Talbot *et al*., 2006), suggesting that shading by branches and stems likely attenuates snowmelt in forested sites. Although there has been important progress in identifying key forest metrics that explain variability in snowpack properties (Lawler and Link, 2011; Lopez-Moreno and Latron, 2008; Talbot *et al*., 2006), other studies have also identified difficulties in discriminating strong statistical relationships between site scale forest characteristics and snow depth or water equivalent (Murray and Buttle, 2003; Winkler and Moore, 2006).

These findings corroborate a limited number of studies conducted in deciduous and mixed deciduous, evergreen forests of the eastern USA and Canada, which have received considerably less attention to the influence of forests on snow cover, relative to forests of western North America and the boreal region. Previous studies in eastern forests, including northern Michigan (Urie, 1966), central Ontario (Murray and Buttle, 2003) and in the vicinity of our field site in New Hampshire (Hart, 1963; Sartz and Trimble, 1956) show that the mixed deciduous-conifer forests of eastern North America accumulate less snow than nearby openings and attenuate snowmelt and runoff. A comparison of our findings to those of other studies where hemispherical photography has been used to quantify canopy closure, as shown in Figure 11, indicates

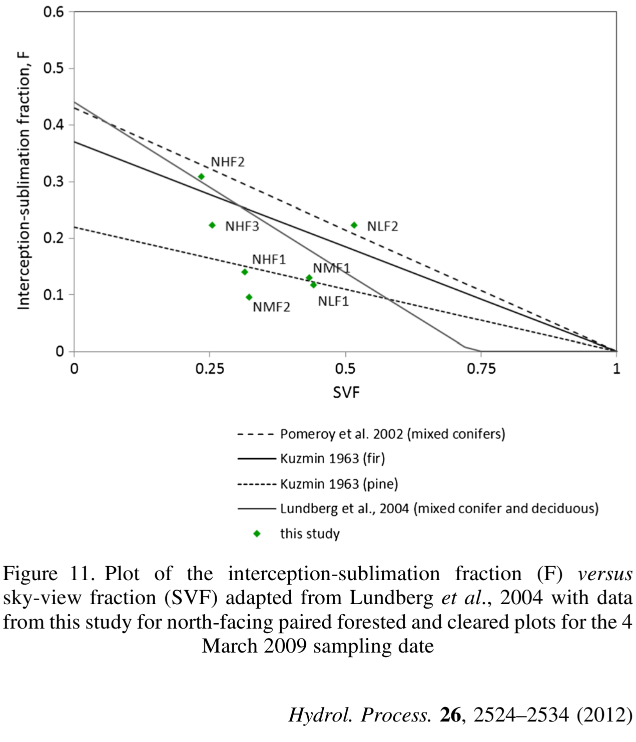

Figure 11. Plot of the interception-sublimation fraction (F) *versus* sky-view fraction (SVF) adapted from Lundberg *et al*., 2004 with data from this study for north-facing paired forested and cleared plots for the 4 March 2009 sampling date

that the high-elevation mixed deciduous-evergreen forests at Hubbard Brook intercept snow at levels equivalent to those documented by Pomeroy *et al.* (2002) in boreal forests of central and western Canada (Figure 11). Similarly, the forested plots at mid- and low-elevation north-facing sites at Hubbard Brook have snow interception levels that are bracketed by those documented by Lundberg *et al.* (2004) for forests in Japan and by Kuzmin (1963) for forests in Russia.

The role of forests in intercepting snow and mediating snowmelt shown here have important implications for the maintenance of soil moisture and spring flows in this region, where recent trends show a gradual but substantial reduction in forest cover associated with development and biomass harvesting (Foster *et al.*, 2010; Stein *et al.*, 2005). The relatively large differences in SWE between forested (mean SWE = 11.7 cm) and cleared (mean SWE = 7.2 cm) plots on south-facing slopes during the snowmelt period suggests that reductions in forest cover may result in larger spring snowmelt flooding and reduced summer soil moisture, as winter snow packs melt more rapidly in forest openings on sun-exposed slopes; effects that have been documented in watershed studies at Hubbard Brook (Hornbeck, 1973) and other experimental forest sites (Jones and Perkins, 2010; Verry *et al.*, 1983). These effects may be of particular concern as the longevity of the snowpack is compromised and the timing of snowmelt shifts because of changes in climate that have been observed in the past and are projected to continue into the future (Campbell *et al.*, 2010; Huntington *et al.*, 2003). Forest management schemes should consider these altered patterns of snow accumulation and melt and might be useful for maintaining adequate soil moisture and water supply under changing future conditions.

ACKNOWLEDGEMENTS

This work was supported by grants from the National Sciences Foundation through a Research Experience for Undergraduates supplement (ANT-0338008) to T. Neumann and B. Wemple and from the Vermont NASA EPSCoR program through a grant to J. Frolik, C. Skalka and B. Wemple. University of Vermont students M. Casari, S. Donovan, E. Furtak-Cole, T. Lanagan, E. Matys, H. Peterson, C. Robinson, N. Rustigian and P. Tobin assisted with field surveys. A. del Peral assisted with canopy photo analysis. USFS personnel Ian Halm, Tammy Wooster, and Derek Eaton assisted with transportation to field sites. W. Keeton provided the use of the camera. A. Whitehurst provided LiDAR-derived tree heights for the forested plots. A. McIntosh, G. Hawley, M. Pelto and two anonymous reviewers provided valuable comments of earlier versions of this manuscript. This manuscript is a contribution of the Hubbard Brook Ecosystem Study. Hubbard Brook is part of the LTER network, which is supported by the National Science Foundation. The Hubbard Brook Experimental Forest is operated and maintained by the USDA Forest Service, Northern Research Station, Newtown Square, PA.

REFERENCES

Anderson HW, West AJ. 1965. Snow accumulation and melt in relation to terrain in wet and dry years. In *33rd Western Snow Conference*. Colorado Springs, CO.; 73–82.

Bailey AS, Hornbeck JW, Campbell JL, Eager C. 2003. Hydrometeorological database for Hubbard Brook Experimental Forest. In *U.S.D.A. Forest Service, General Technical Report NE-305*. Newtown Square, PA.

BERC. 2007. Northern Forest Biomass Energy Action Plan. Biomass Energy Resource Center; 16 pp.

Berndt H. 1965. Snow accumulation and disappearance in lodgepole pine clearcut blocks in Wyoming. *Journal of Forestry* **63**: 88–91.

Berris SN, Harr RD. 1987. Comparative Snow Accumulation and Melt During Rainfall in Forested and Clear-Cut Plots in the Western Cascades of Oregon. *Water Resources Research* **23**: 135–142.

Campbell JL, Ollinger SV, Flerchinger GN, Wicklein H, Hayhoe K, Bailey AS. 2010. Past and projected future changes in snowpack and soil frost at the Hubbard Brook Experimental Forest, New Hampshire, USA. *Hydrological Processes* **24**: 2465–2480.

Dewalle DR, Rango A. 2008. *Principles of Snow Hydrology*. Cambridge University Press: Cambridge, New York.

Essery R, Pomeroy J, Ellis C, Link T. 2008. Modelling longwave radiation to snow beneath forest canopies using hemispherical photography or linear regression. *Hydrological Processes* **22**: 2788–2800.

Foster D, Kittredge D, Donahue B, Motzkin G, Orwig D, Ellison A, Hall B, Colburn B, D'Amato A. 2010. *Wildlands and Woodlands: A Vision for the New England Landscape*. Harvard University Press: Petersham, Massachusetts; 36.

Frazer GW, Canham CD, Lertzman KP. 1999. *Gap Light Analyzer (GLA), Version 2.0: Imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs, users manual and program documentation*. Simon Fraser University, Burnaby, British Columbia and the Institute for Ecosystem Studies: Millbrook, New York.

Gary HL. 1974. Snow accumulation and melt as influenced by a small clearing in a lodgepole pine forest. *Water Resources Research* **10**: 348–353.

Golding D, Swanson RH. 1986. Snow distribution patterns in clearings and adjacent forest. *Water Resources Research* **22**: 1931–1940.

Harr RD. 1986. Effects of Clearcutting on Rain-on-Snow Runoff in Western Oregon: A New Look at Old Studies. *Water Resources Research* **22**: 1095–1100.

Hart G. 1963. Snow and frost conditions in New Hampshire, under hardwoods and pines and in the open. *Journal of Forestry* **61**: 287–289.

Haupt HF. 1951. Snow accumulation and retention on ponderosa pine lands in Idaho. *Journal of Forestry* **49**: 859–871.

Hellström RÅ. 2000. Forest cover algorithms for estimating meteorological forcing in a numerical snow model. *Hydrological Processes* **14**: 3239–3256.

Hendrick R, Filgate B, Adams W. 1971. Application of environmental analysis to watershed snowmelt. *Journal of Applied Meteorology* **10**: 418–429.

Hornbeck JW. 1973. Storm flow from hardwood-forested and cleared watersheds in New Hampshire. *Water Resources Research* **9**: 346–354.

Huntington TG, Hodgkins GA, Keim BD, Dudley RW. 2003. Changes in the Proportion of Precipitation Occurring as Snow in New England (1949–2000). *Journal of Climate* **17**: 2626–2636.

Jones JA, Perkins RM. 2010. Extreme flood sensitivity to snow and forest harvest, western Cascades, Oregon, United States. *Water Resources Research* **46**(W12512): 21. DOI:10.1029/2009WR008632

Kuzmin PP. 1963. Formirovanie Snezhnogo Pokrova i Metody Opredeleniya Snegozapasov (Snow cover and snow reserves). English translation by Israel Program for Scientific Translation, Jerusalem); 139 pp.

Lawler RR, Link TE. 2011. Quantification of incoming all-wave radiation in discontinuous forest canopies with application to snowmelt prediction. *Hydrological Processes* **25**: 3322–3331.

Lopez-Moreno JI, Latron J. 2008. Influence of canopy density on snow distribution in a temperate mountain range. *Hydrologic Processes* **22**: 117–126.

Lundberg A, Nakai Y, Thunehed H, Halldin S. 2004. Snow accumulation in forests from ground and remote-sensing data. *Hydrological Processes* **18**: 1941–1955.

Marks D, Kimball J, Tingey D, Link T. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a case study of the 1996 Pacific Northwest flood. *Hydrological Processes* **12**: 1569–1587.

Murray CD, Buttle JM. 2003. Impacts of clearcut harvesting on snow accumulation and melt in a northern hardwood forest. *Journal of Hydrology* 197–212. http://dx.doi.org/10.1016/S0022-1694(02)000352-9
Musselman KN, Molotch NP, Brooks PD. 2008. Effects of vegetation on snow accumulation and ablation in a mid-latitude sub-alpine forest. *Hydrological Processes* **22**: 2767–2776.
NRC NRC. 2008. *Hydrologic Effects of a Changing Forested Landscape*. The National Academies Press: Washington, D.C.
Penn CA. 2009. Forest Influence on Peak Snow Accumulation and Snowmelt in the Hubbard Brook Experimental Forest, New Hampshire. In *Rubenstein School of Environment and Natural Resources*. University of Vermont: Burlington; Undergraduate Honors thesis, 34pp.
Pomeroy J, Granger RJ, Pietroniro A, Elliot J, Toth B, Hedstrom NR. 1997. Hydrological pathways inthe Prince Albert model forest. In *NHRI Contribution Series CS-97004*. Saskatoon, Saskatchewan; 154 p.
Pomeroy JW, Gray DM, Hedstrom NR, Janowicz JR. 2002. Prediction of seasonal snow accumulation in cold climate forests. *Hydrological Processes* **16**: 3453–3558.
Sartz R, Trimble JG. 1956. Snow storage and melt in a northern hardwoods forest. *Journal of Forestry* **54**: 499–502.
SPSS Inc. 2006. SPSS for Windows, Rel. 15.1. Chicago.
Stegman SV. 1996. Snowpack changes resulting from timber harvest interception, redistribution and evaporation. *Journal of the American Water Resources Association* **32**: 1353–1360.
Stein SM, McRoberts RE, Alig RJ, Nelson MD, Theobald DM, Eley M, Dechter M, Carr M. 2005. Forests on the edge: Housing developments on America's private forests. In *USDA Forest Service General Technical Report*.
Talbot J, Plamondon AP, Levesque D, Aube D, Prevos M, Chazalmartin F. 2006. Relating snow dynamics and balsam fir stand characteristics, Montmorency Forest, Quebec. *Hydrological Processes* **20**: 1187–1199.
Troendle C, King R. 1985. The effect of timber harvest on the Fool Creek watershed, 30 years later. *Water Resources Research* **21**: 1915–1922.
Troendle CA, Leaf CF. 1980. *Hydrology. An approach to water resources evaluation of non-point silviculture sources*. U.S. Environmental Protection Agency: Athens, GA; 173.
Urie DH. 1966. Influence of Forest Cover on Snowpack and Ground-Water Rechargea. *Ground Water* **4**: 5–9.
Varhola A, Coops NC, Bater CW, Teti P, Boon S, Weiler M. 2010a. The influence of ground- and lidar-derived forest structure metrics on snow accumulation and ablation in disturbed forests. *Canadian Journal of Forest Research* **40**: 812–821.
Varhola A, Coops NC, Weiler M, Moore RD. 2010b. Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology* **392**: 219–233.
Veatch W, Brooks PD, Gustafson JR, Molotch NP. 2009. Quantifying the effects of forest canopy cover on net snow accumulation at a continental, mid-latitude site. *Ecohydrology* **2**: 115–128.
Verry E, Lewis J, Brooks K. 1983. Aspen clearcutting increases snowmelt and storm flow peaks in north central Minnesota. *Water Resources Bulletin* **19**: 56–67.
Whitehurst AS, Dubayah R, Blair JB, Hofton M, Swatantran A. 2011. The characterization of canopy layering in forested ecosystems using full waveform lidar. *American Geophysical Union Fall Meeting Abstracts* **H13D-1237**.
Winkler R. 2001. The effects of forest structure on snow accumulation and melt in South-Central British Columbia. PhD thesis, Faculty of Forestry, University of British Columbia, Vancouver, Canada.
Winkler RD, Moore RD. 2006. Variability in snow accumulation patterns within forest stands on the interior plateau of British Columbia, Canada. *Hydrological Processes* **20**: 3683–3695.
Winkler RD, Spittlehouse DL. 1995. The importance of sample size in forest/clearcut snow accumulation comparisons. In *Mountain Hydrology Peaks and Valleys in Research and Applications*, Guy BT, Barnard J (eds). Cambridge: Ontario; 39–45.
Winkler R, Spittlehouse D, Golding D. 2005. Measured differences in snow accumulation and melt among clearcut, juvenile, and mature forests in southern British Columbia. *Hydrological Processes* **19**: 51–62.

