Snow–Shrub Interactions in Arctic Tundra: A Hypothesis with Climatic Implications

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ABSTRACT

In the Arctic, where wind transport of snow is common, the depth and insulative properties of the snow cover can be determined as much by the wind as by spatial variations in precipitation. Where shrubs are more abundant and larger, greater amounts of drifting snow are trapped and suffer less loss due to sublimation. The snow in shrub patches is both thicker and a better thermal insulator per unit thickness than the snow outside of shrub patches. As a consequence, winter soil surface temperatures are substantially higher, a condition that can promote greater winter decomposition and nutrient release, thereby providing a positive feedback that could enhance shrub growth. If the abundance, size, and coverage of arctic shrubs increases in response to climate warming, as is expected, snow–shrub interactions could cause a widespread increase (estimated 10%–25%) in the winter snow depth. This would increase spring runoff, winter soil temperatures, and probably winter CO_2 emissions. The balance between these winter effects and changes in the summer energy balance associated with the increase in shrubs probably depends on shrub density, with the threshold for winter snow trapping occurring at lower densities than the threshold for summer effects such as shading. It is suggested that snow–shrub interactions warrant further investigation as a possible factor contributing to the transition of the arctic land surface from moist graminoid tundra to shrub tundra in response to climatic warming.

1. Introduction

Air temperatures in Alaska and other parts of the Arctic have increased (Chapman and Walsh 1993), and climate simulations suggest that any continued warming will be greater in the Arctic than in lower latitudes (Kattenberg et al. 1996). One expected result of warming is an increase in plant productivity, which may be reflected in recent increases in the seasonal amplitude of high-latitude CO_2 (Keeling et al. 1996; Zimov et al. 1999) and in the seasonally integrated normalized difference vegetation index (an index of plant productivity) (Myneni et al. 1997), although other interpretations of these data are possible.

If the productivity of the tundra rises, an increase in the height and abundance of shrubs is likely to be one important outcome. Transects along climatic gradients show that shrub tundra replaces tussock tundra near the southern tundra limit where the climate is warmer (Aleksandrova 1980; Bliss and Matveyeva 1992). Similarly, Holocene warming was accompanied by expansion of *Betula* (birch) and other shrubs (Ager 1983; Payette et al. 1989; Anderson and Brubaker 1993; Brubaker et al. 1995; Jacoby and D'Arrigo 1995). Some manipulation experiments in which growing season temperatures were elevated have also resulted in an increase in shrubs (Hobbie and Chapin 1998), though other similar experiments have not shown the same temperature effect (e.g., Chapin et al. 1995).

An increase in shrub abundance would have important implications for regional climate in the Arctic. In summer, changes in energy partitioning between the shrub canopy and the ground could lead to changes in shading and active layer thickness. In winter, shrubs and snow would interact in several ways. Because the Arctic is windy and snow-covered 9 months of the year, snow drifted by the wind is trapped by shrubs. In this paper we show that an increase in shrubs could augment the depth of snow on the ground, both locally and generally, in part by diminishing winter water losses caused by wind-driven sublimation. We also show that when the snow depth in and around shrubs is increased, higher

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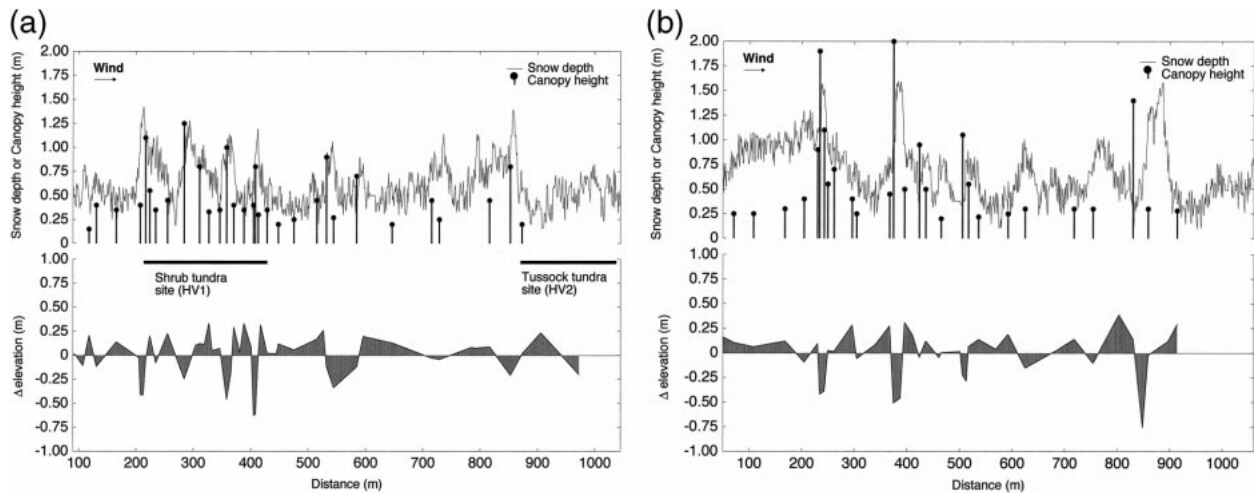E-mail: msturm@crrel.usace.army.mil.

FIG. 1. Spatial variations in snow depth, canopy height, and topographic relief along transects (a) from shrub to tussock tundra and (b) from shrubby tussock to tussock tundra. Note that near 700 m in the first transect there is an area of deeper snow and taller canopies not associated with a topographic depression. The Δ elevation was computed by subtracting a 50-m moving average of elevation from the measured elevation, producing a profile that highlights the local relief.

subnivian temperatures result. We suggest that at these higher temperatures, more winter decomposition and nutrient mineralization may occur, producing more favorable conditions for the growth of shrubs. In this paper we point out the existence and the potential importance of these winter biogeophysical linkages, and suggest that they play a role in the general response of the tundra to climate change.

2. Study design

We measured variations in snow properties and vegetation across a landscape in arctic Alaska (69°06′N, 149°00′W) covered by three types of vegetation: 1) tussock tundra, 2) shrubby tussock tundra, and 3) riparian shrub (McFadden et al. 1998). The site was near Happy Valley on the Dalton Highway, about half-way between Prudhoe Bay and the Brooks Range. Several shallow water tracks drained the gently sloping area. These were oriented perpendicular to the prevailing winter wind and filled with drifting snow. Outside of water tracks, a thin (average 0.6 m), wind-blown snow cover developed at the site (Benson and Sturm 1993). In April 1996, when the snow cover had reached maximum depth, we measured an extensive set of snow properties (depth, density, stratigraphy, thermal conductivity, and the temperature of the snow–ground interface) along intersecting traverse lines through the three vegetation types, each line being about 1 km long. In July we returned and recorded the topography, vegetation species, canopy height, stem thickness, and leaf area index (LAI) along the same lines. Canopy height was taken as the average height of the five tallest shrubs at each measurement station, and stem thickness was a similar average of the diameter of five randomly chosen stems, measured at the base of the plant using a caliper. LAI, leaf area per

unit ground area, was measured using an optical plant canopy analyzer (LI-COR, Inc., LAI-2000). Detailed snow and vegetation measurements (data every meter for 200 m) were measured at the intersections of the traverse lines in the three vegetation types. Both snow and vegetation measurements were extrapolated spatially using aerial photographs taken in May (partial snow cover) and August (no snow). Continuous snow–ground interface temperature records (±0.7°C) were collected nearby using mini-dataloggers (see http://arcss.colorado.edu/Catalog/arcss001.html).

3. Results

The deepest snow was associated with the tallest, densest shrubs (Figs. 1a and 1b). These were often near water tracks or in riparian areas. Some, but not all, of the increase in snow depth associated with the tall shrubs was the result of in-filling of water track channels. However, the topographic depressions made by the water tracks were quite shallow and no more than 10 m wide, while the deeper snow associated with the tracks was 50–60 m wide (Fig. 1a). This, along with a lag correlation analysis between shrub height, snow depth, and local relief (McFadden 1998), established that the shrub canopy, rather than the topographic relief, was the main control on the snow.

There was about a 10-m downwind displacement of the deepest snow from the tallest shrubs (Fig. 2, top panels). Shrub height, stem diameter, and leaf area all declined more quickly downwind than did the snow depth, and these downwind changes roughly corresponded to the transition from *Salix* (willow)-dominated riparian areas to *Betula* (birch)-dominated shrubby-tussock tundra, to shrub-poor tussock tundra. The shapes of drift profiles in the lee of the shrubs were similar to
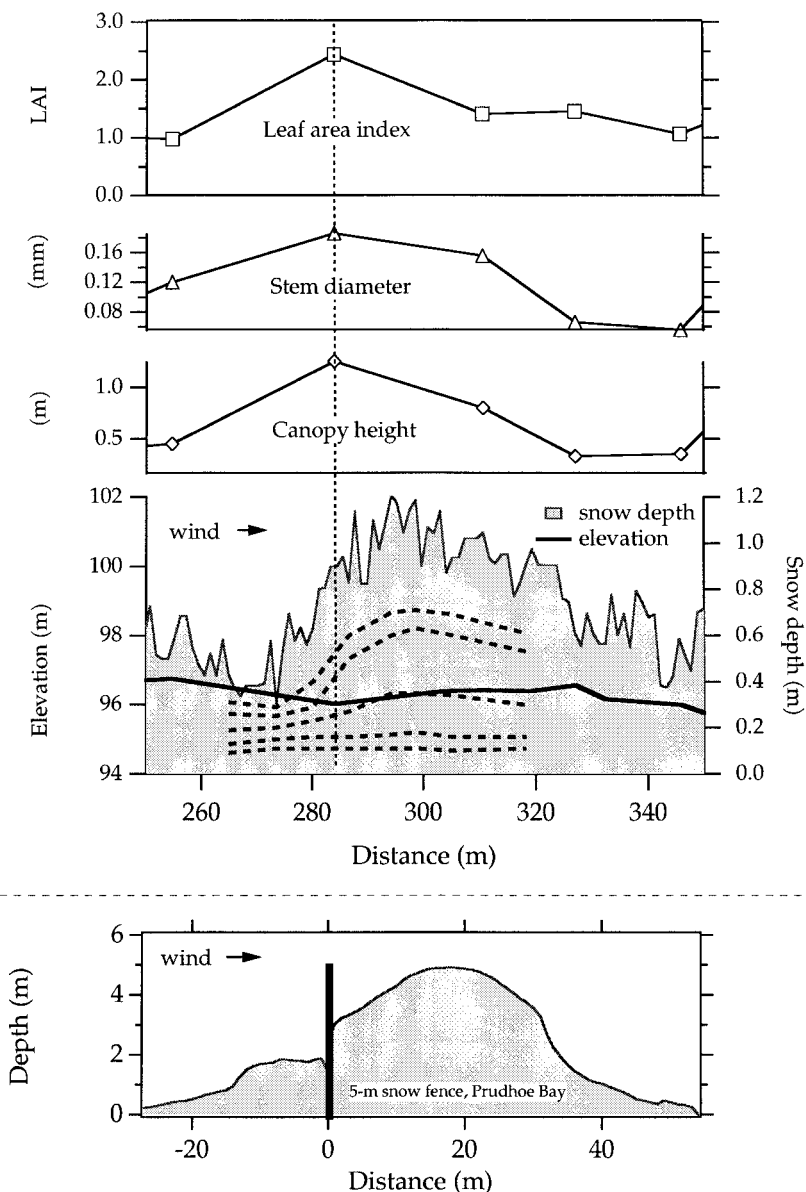
FIG. 2. Downwind variation in snow depth, canopy height, and other shrub characteristics, with an example of a drift in the lee of a snow fence to show the similarity. The shrub and snow sections are enlargements of part of the transect shown in Fig. 1a. The dashed lines in the snow cross section show how the individual snow strata increased in thickness where shrubs were taller and more abundant. The snow fence drift was measured at the 5-m ARCO LPC snow fence in Prudhoe Bay in 1992 (unpublished survey, M. Sturm).

the shape of profiles in the lee of snow fences (Fig. 2, bottom) and shelterbelts (Laycock and Shoop 1986; Tabler 1980, 1989; Peterson 1982; Peterson and Schmidt 1984; Pomeroy and Gray 1995). From this similarity we infer that shrubs increase the snow-holding capacity of the tundra by decreasing the near-ground wind speeds within and downwind of the shrubs, causing a net gain in snow due to wind transport.

Surprisingly, small differences in shrub density and canopy height (such as between tussock tundra and shrubby tussock tundra) produced significant differences in snow depths (Table 1). For example, the canopies of tussock tundra and shrubby tussock tundra were composed of a similar mix of plant species, with the erect shrubs (*Betula* plus *Salix*) comprising only a slightly higher proportion of the total canopy cover at the shrubby tussock site (35%) than at the tussock site (19%). In contrast, in riparian areas, erect deciduous shrubs (*Salix*) made up almost the entire canopy (91%), and these were substantially taller, thicker-stemmed, and leafier than at

TABLE 1. Vegetation characteristics and snow depths for the three classes of vegetation found at the study site.*

Variable	Tussock tundra	Shrubby tussock tundra	Riparian shrub
Canopy composition %	*Eriophorum vaginatum* 35 *Ledum palustre* 22 *Betula nana* 14 Mosses 13 *Salix pulchra* 5 *Vaccinium vitis-idaea* 5 Other 6	*Eriophorum vaginatum* 25 *Betula nana* 14 Mosses 19 *Ledum palustre* 11 *Salix pulchra* 11 *Vaccinium vitis-idaea* 5 Other 5	*Betula nana* 48 *Salix pulchra* 43 *Eriophorum vaginatum* 4 Other 5
Erect shrubs, % of canopy	19	35	91
Canopy height, m			
mean	0.10 ± 0.07 ($n = 200$)	0.13 ± 0.11 ($n = 200$)	0.50 ± 0.27 ($n = 200$)
maximum	0.38	0.5	1.4
Stem diameter, mm			
mean	5.4 ± 1.7 ($n = 5$)	7.8 ± 2.9 ($n = 20$)	13.2 ± 4.5 ($n = 30$)
maximum	8	15	22
Leaf area index (LAI)	0.48 ± 0.15 ($n = 14$)	0.63 ± 0.20 ($n = 10$)	1.45 ± 0.36 ($n = 16$)
Snow depth, m	0.51 ± 0.17 ($n = 180$)	0.69 ± 0.11 ($n = 184$)	0.72 ± 0.24 ($n = 213$)

* Canopy dominance is percent of points sampled; other data are means $\pm$ standard deviation. Erect shrubs include *Betula nana* and *Salix pulchra. Ledum palustre* (Laborador tea) is a supple evergreen shrub that becomes prostrate with the first snowfall of winter and so has little effect on snow-holding capacity.

the other two sites. Yet the mean snow depth in the shrubby tussock tundra area was closer to the snow depth in the riparian areas than to the depth in the tussock tundra areas. This finding suggests that there was a ''threshold'' shrub height and density above which snow-holding capacity increased as a step function, and that this threshold occurred at low shrub densities.

By combining vegetation and snow distribution maps (Fig. 3), we found that the shrubs not only created areas of deep snow within shrub patches and immediately downwind of them, but also produced zones of thin snow farther downwind that were closely associated with tussock tundra with limited shrubs. Shelterbelts in agricultural fields of the midwestern United States pro-
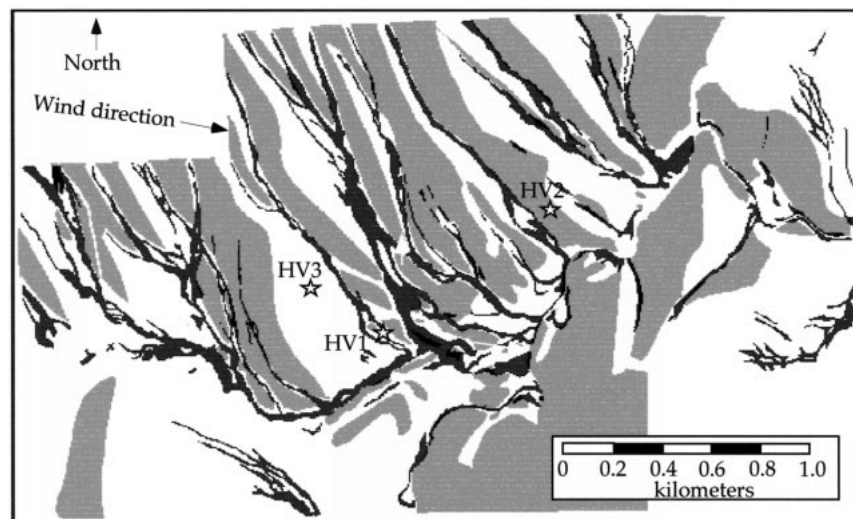

FIG. 3. Map showing the coincidence of areas of deep and shallow snow with shrubs.

TABLE 2. Snow depth, stratigraphy, density, thermal resistance, and interface temperatures in shrub and nonshrub sites.

	Tussock tundra	SE*	Shrubby tussock tundra	SE	Shrub	SE
No. of snow pits	16	—	18	—	11	—
Avg snow depth (cm)	52	4.3	64	5.2	87	5.3
Avg SWE** (cm)	13	2.1	15	2.0	25	4.3
Avg density (g cm^{-3})	0.23	0.02	0.25	0.01	0.27	0.01
% depth hoar	55	4.5	53	4.1	70	5.1
% wind slab	33	4.6	31	3.0	22	4.4
% other	12	2.1	16	2.3	8	1.1
Bulk thermal resistance (°C W^{-1})	7.3	—	9.0	—	11.7	—
Snow–ground interface temperature (°C)	−12.0	0.4	−11.3	0.4	−9.0	1.2

*SE indicates standard error.
**SWE indicates snow water equivalent.

duce similar zones of downwind snow depletion [see Pomeroy and Gray (1995), Fig. 60]. In both cases, the total wind-blown flux of snow is limited, so little snow is available for transport and deposition in downwind areas. A pattern of deposition and erosion (or alternately, deep and shallow snow) develops with the snow–shrub interactions controlling the depth over a much larger area than the zone covered by the shrubs.

The deeper snow associated with taller, denser shrubs was also a better insulator per unit thickness than the snow outside of shrub patches because it contained a higher percentage of depth hoar (Table 2). Depth hoar is a poorly bonded, highly insulative type of snow produced by metamorphism in response to the strong temperature gradients (Akitaya 1974; Trabant and Benson 1972; Colbeck 1983, 1987; Sturm and Benson 1997). Based on 36 thermal conductivity measurements keyed to the nine snow layers in the 1996 pack [for method see Sturm et al. (1997)], the thermal resistance (Table 2) was computed for shrub and nonshrub areas; it was considerably higher in the shrubs. As a consequence, snow–ground interface temperatures measured in April were 3°C higher in shrub areas than in nonshrub areas (Table 2).
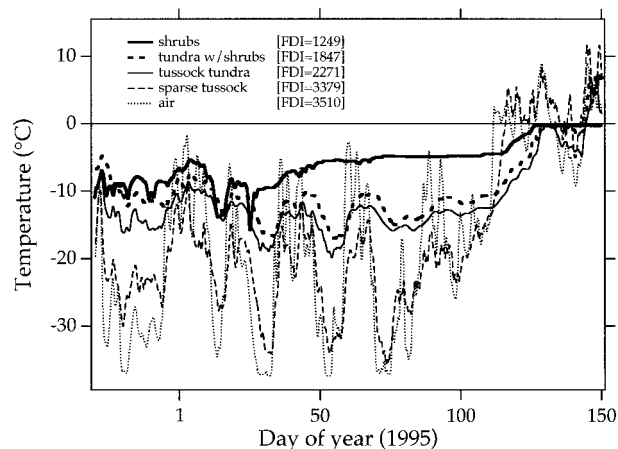

FIG. 4. Snow–ground interface temperatures and freezing degree index (FDI) as a function of vegetation.

Hourly snow–ground interface temperature records (Fig. 4) confirm the large (as high as 10°C), persistent (60 days or more) differences in winter soil temperature between shrub and nonshrub sites. The cumulative thermal effect of shrubs for a whole winter is suggested by comparing freezing degree indices (FDI: the accumulated sum of the daily average degrees below zero between 15 November and 1 May) for sites of varying degrees of shrub height and density. Values range from a low of 1249 for a shrub site, to a high of 3379 for a tussock tundra site, suggesting a 2.7-fold difference in winter heat loss. Similarly, we note that, over three winters (1993–96), the interface temperature at one tussock tundra site dropped below −6°C approximately 47, 55, and 62 days earlier in the winter than at nearby shrubby tundra site. This is a critical difference because unfrozen water is thought to be virtually absent in the soil at temperatures below −6°C.

4. A snow–shrub feedback hypothesis

Sublimation of blowing snow returns between 10% and 25% of the total winter snowfall to the atmosphere in the Arctic (Pomeroy and Gray 1995; Liston and Sturm 1998), with similar amounts returned from the Antarctic ice sheets (King et al. 1996; Van den Broeke 1997; Gallée 1998; Bintanja 1998). Snow grains that are saltating or in suspension during wind transport suffer rapid rates of sublimation, but the rates for quiescent grains are much lower. One direct consequence of an increase in shrubs, whether associated with climate warming or other causes, would be to increase the snow-holding capacity of the Arctic landscape. This would immobilize more snow during the winter and diminish the amount of sublimation, increasing the depth of snow on the ground, without any change in winter precipitation. A similar effect is well known in agriculture where wind barriers and crop stubble are used to augment the amount of winter snowfall available for groundwater recharge (Pomeroy and Gray 1995; chapter 7).

This deeper, more insulative (Table 2) snow would have a wide range of impacts on plants, including greater protection from winter desiccation and wind abrasion,

a potential reduction in the growing season length, and an increase in snowmelt runoff and summer soil moisture. The increased subnivian soil temperatures that we observed would produce conditions favorable to shrub growth (i.e., more decomposition and nutrient mineralization). If this hypothesis is correct, a feedback loop might exist, wherein the shrubs would create a deeper snowpack, which would keep the ground warmer in winter. This, in turn, would promote nutrient mineralization and more shrub growth.

In the Arctic, soil respiration occurs at temperatures as low as $-6°C$ (Flanagan and Veum 1974; Flanagan and Bunnell 1980; Clein and Schimel 1995; Zimov et al. 1993a; Coxson and Parkinson 1987). Below this temperature, the unfrozen soil water content is so low (Black and Tice 1988; Nakano and Brown 1972; Osterkamp and Romanovsky 1997; Zimov et al. 1993a) that microbial activity probably ceases. In our study, the snow–ground interface temperatures remained above $-6°C$ about 50 days longer beneath shrubs than where there were few or no shrubs (Fig. 4). Consistent with this, the highest arctic winter CO_2 efflux rates have also been found in shrub-covered riparian zones (Fahnestock et al. 1998). An increasing number of studies document the release of significant quantities of CO_2 during the winter (Kelley et al. 1968; Zimov et al. 1993a,b; Sommerfeld et al. 1993, 1996; Zimov et al. 1996; Brooks et al. 1997; Oechel et al. 1997; Fahnestock et al. 1998, Grogan and Chapin 1999), suggesting that overwinter decomposition and nutrient mineralization may be important. Indeed, as observed in one experiement, most of the decomposition and nitrogen mineralization of *Betula* leaf litter occurred outside the growing season (Hobbie and Chapin 1996). We suggest that undersnow conditions for decomposition and nutrient mineralization are more favorable where shrubs are present than where they are not.

The snow–shrub feedback loop would close if we could show that greater nutrient release during winter promotes the growth of shrubs at the expense of other tundra plants. Nutrient addition at snowmelt in Alaskan tussock tundra (Chapin et al. 1995; Shaver and Chapin 1995; Hobbie and Chapin 1998) has been shown to promote increased deciduous shrub growth (particularly of *Betula*) at the expense of the herbaceous plants and low evergreen shrubs.

5. Discussion

The first half of the proposed feedback loop, the winter impact of shrubs on snow (increased snow-holding capacity and reduced sublimation), is well established, both by this and other studies (Laycock and Shoop 1986; Tabler 1980, 1989; Peterson 1982; Peterson and Schmidt 1984; Pomeroy and Gray 1995). The second half of the feedback loop, the impact of snow on shrubs, is more speculative. The thermal impact of snow on shrubs (deeper snow leads to higher subnivian temperatures) is

predictable from the thermal properties of the snow, but the observed differences in subnivian temperature are large and have not been documented before, to the best of our knowledge. The extent to which this winter warming of soil stimulates nutrient mineralization and subsequent summer growth of shrubs remains to be shown.

The major uncertainty in the hypothesized snow–shrub positive feedback loop is whether summer effects might counteract positive winter effects on soil temperature and decomposition. One likely way this might occur is through increased shading by the shrub canopy. However, the magnitude of this effect is uncertain. When shrubs were removed from shrub tundra, McFadden (1998) found a 33%–47% increase ($p < 0.1$) in ground heat flux, but no significant change in soil temperatures. In a nutrient-addition experiment, a 2.7-fold increase in shrub biomass in tussock tundra reduced (but nonsignificantly) the maximum summer thaw by 6 cm, presumably because the summer surface heat flux was decreased (Chapin et al. 1995). But in both of these experiments, other factors (chiefly the abundance of mosses, which are an effective soil insulator) were also affected. However, in the boreal forest, where shading is substantially greater than in tundra, increased conifer cover (which promotes rather than hinders moss growth) reduces soil temperatures (Van Cleve et al. 1991) and therefore decomposition rates.

There are other complications that need to be considered as well. An increase in shrubs would alter mineralization rates through changes in litter quality (Nadelhoffer et al. 1991). *Betula* produces leaves that decompose rapidly, but also a large proportion of woody litter that decomposes slowly, so that the overall decomposition rate in laboratory microcosms is slow (Hobbie 1996). However, field mineralization rates in shrub tundra are higher than in other tundra types (Kielland 1990). In summary, the net effect of increased shrub growth in the tundra on summer processes is uncertain, and the combined effect of both summer and winter processes is even harder to judge.

From what we know at present, we would suggest that shrub canopy density is probably the critical factor in determining whether summer shading effects will dominate over winter warming effects with respect to decomposition and nutrient mineralization. At relatively low densities, as shown in Table 1, shrubs enhance the winter snowpack depth. At these low shrub densities, the shrub–snow feedback loop may operate, but the sparse canopy interaction with the low-angle summer sun is likely to be minimal and shading effects should be small.

If the proposed snow–shrub feedback loop plays a role in affecting widespread changes in arctic land surface properties, the foregoing discussion suggests *Betula* rather than *Salix* is likely to be the primary agent involved in the change. First, many of the common *Salix* species are restricted to locations in or near wet drainage
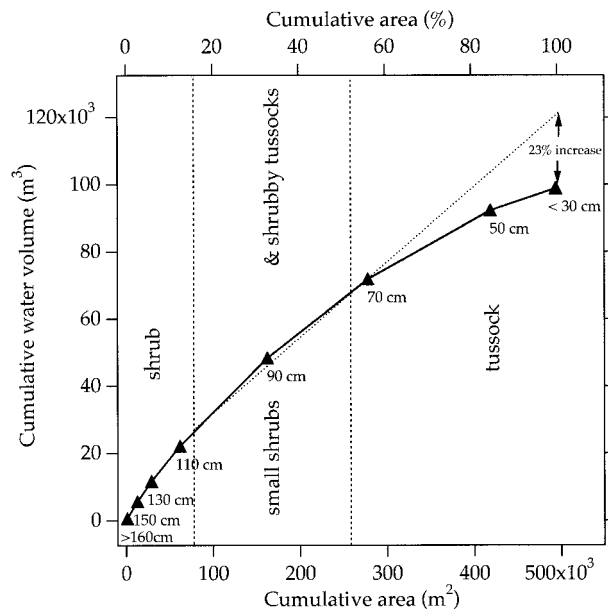
FIG. 5. Area and snow water equivalent (SWE) distribution by vegetation type and snow depth for part of the study area shown in Fig. 3.

channels. They occupy only about 6% of the tundra landscape in Alaska (Walker and Walker 1996). Second, *Betula* is already present in most tundra communities (Viereck and Little 1972) and is poised to expand. Third, *Betula,* rather than *Salix,* is the shrub species that responds most dramatically to nutrient addition (Chapin et al. 1995). Fourth, the palynological record indicates that there was a widespread increase in *Betula* in the Alaskan Arctic between 12 000 and 10 000 years B.P. (Ager 1983; Anderson and Brubaker 1993; Brubaker et al. 1995), and fifth, *Betula* is the species that contributed most strongly to enhanced winter snow accumulation at low shrub densities in this study.

6. Climatic and hydrologic implications

A simple regression model can be used to suggest some of the climatic and hydrological implications of an increase in the height and abundance of *Betula.* For part of the 6-km^2 region shown in Fig. 3 we have drawn 0.2-m contours of snow depth, based on thousands of depth measurements, then converted the contours to snow water equivalent (SWE) using a mean density of 290 kg m^{-3} (based on 1147 measurements, variance r^2 = 0.89). For each type of vegetation (shrub, shrubby tussock, or tussock tundra) we have measured the snow distribution. The area covered by all snow deeper than 150 cm, and the SWE associated with that area, has been plotted in Fig. 5. We have continued by plotting the cumulative area and SWE covered by snow deeper than 130 cm, and so on, in 20-cm increments. The SWE curve rises rapidly with increasing area at first because of the deep snow associated with dense shrubs. It rises

more gradually as greater amounts of tussock area are included. Overall, the 14% of the area covered by *Salix* shrub communities held 26% of the SWE. The 38% of the area covered by *Betula* in both dense stands of shrubs and sparse stands mixed with tussock tundra held 42% of the SWE, and the remaining 48% of the area covered by tussock tundra held 32% of the SWE.

The slope of the cumulative curve in Fig. 5 is a rough measure of the SWE-holding capacity for each type of vegetation, and changes in vegetation would result in changes in slope. The slope decreases from 0.35 for *Salix,* to 0.23 for *Betula* and shrubby tussock tundra, to 0.13 for tussock tundra. If all the tussock area was converted to shrubby tussock tundra by the increased growth of *Betula,* then the slope of the upper section of the curve would increase from 0.13 to 0.23, and the additional 0.10 m of SWE would be protected from sublimation. The total SWE for the area would change from 98 830 m^3 to 121 350 m^3, a 23% increase in available water (Fig. 5, dotted line). This increase is consistent with the 10%–25% SWE we estimate is currently being lost in the wind-blown tussock tundra areas due to winter sublimation, and is consistent with the measured differences shown in Table 1.

More generally, we suggest four important climatic implications of the snow–shrub interactions, each of which requires improved understanding of both winter and summer processes.

1) *CO$_2$ efflux:* Deeper snow might produce higher winter soil temperatures and therefore greater winter efflux, but the greater productivity of shrubs in summer could counteract this carbon loss.
2) *Runoff and soil moisture:* While reduction in winter water losses by sublimation might increase the size of the spring runoff peak in a more shrubby landscape, the snow cover could become more uniform and less concentrated, causing more of the meltwater to go into soil moisture recharge rather than runoff. A compensating increase in summer evaporation seems unlikely (McFadden et al. 1998) but again the annual balance needs to be considered.
3) *Sensible heat losses:* Increased snow depth associated with more abundant and larger shrubs could reduce winter sensible heat losses by 30%–60% (calculated from the FDI values shown in Fig. 4), but the effect on the net annual energy balance is complicated by canopy shading and changes in the summer energy exchange (Chapin et al. 2000), as discussed above. Active layer thickness will be closely tied to this balance.
4) *Snow albedo:* Increased snow depth associated with shrubs suggests a longer snow-covered period, but Hinzman et al. (1996) and Kane et al. (1997) have shown that the arctic snow cover melts in its entirety in 7–10 days, in large measure because the snow is relatively thin and the melt occurs close to the time of the annual solar maximum. Moreover, shrubs are

dark and protrude above the snow surface, reducing the winter albedo. Again, the balance between competing processes is difficult to predict.

7. Conclusions

We suggest here that snow and shrubs form a positive feedback loop that could change land surface processes in the Arctic. We think this possibility warrants further investigation and ought to be considered as an agent in promoting and accelerating the transition of the arctic land surface from moist graminoid tundra to shrub tundra. Because the growth of shrubs would also have a pronounced effect on summer conditions, coupled summer–winter studies will be needed to understand the balance of the processes.

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