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Interactions of shrubs and snow in arctic tundra: measurements and models

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Abstract In arctic tundra, where wind transport of snow is common, shrubs can significantly modify the distribution and physical characteristics of the snow cover. We examined interactions between shrubs and snow by measuring snow depths along three 1-km transects in arctic Alaska and then measuring plant canopy characteristics at the same locations during the following growing season. Snow depths correlated closely with shrub canopy height and stem diameter. Shrubs increased snow depths by 27%, independent of local variations in topographic relief. We also used a snow-transport and energy-balance snowmelt modelling system to perform a series of simulations over a 4 km^2 domain near the field site. A shrub increase was simulated by replacing the current tussock and wet tundra vegetation types with shrub tundra. The shrub expansion increased the domain-averaged snow depth by 20% and decreased blowing-snow sublimation fluxes by 60%. The snow cover change affected the timing and magnitude of all surface energy balance components during the melt, and increased runoff late in the snowmelt period. Shrubs increased snow accumulation by an amount approximately equal to the fraction of the total winter snowfall that is normally lost to sublimation, suggesting that an increase in shrub cover could significantly increase snow depths in the region, even without an increase in precipitation.

Key words sublimation; runoff; energy balance; evaporation; Alaska

INTRODUCTION

Snow covers Alaskan arctic tundra for 8–9 months of the year and provides as much as one-half of the annual precipitation, making it a dominant feature of the surface energy balance and hydrological cycle (Kane *et al.*, 1992). Landscape patterns of tundra snow cover develop from wind redistribution of snow, rather than spatial variability in precipitation (Benson & Sturm, 1993). Wind-blown snow accumulates in topographic depressions, on the leeward side of ridges (Kane *et al.*, 1991), and in stands of vegetation, which trap snow by reducing surface wind speeds (Benson & Sturm, 1993). Blowing-snow events cause a significant amount (10–50%) of the snowfall to be returned to the atmosphere by sublimation of the wind-blown snow particles (Liston & Sturm, 1998; Pomeroy & Essery, 1999). These processes produce a highly variable end-of-winter snow cover distribution. When the snow cover melts in the spring, a mosaic pattern of snow and vegetation develops, influencing energy and moisture fluxes between the land surface and the atmosphere (Liston, 1995, 1999; Essery, 1997; Neumann & Marsh, 1998). This affects the timing, volume, and spatial variability (Luce *et al.*, 1998) of snowmelt runoff.

In light of these effects, it is significant that ecological studies find a potential for relatively rapid changes in arctic vegetation in response to climate variability. Field experiments (Chapin *et al.*, 1995; Hobbie & Chapin, 1998), palaeo-reconstructions (Brubaker *et al.*, 1995), and latitudinal transects (Bliss & Matveyeva, 1992) suggest that one of the most important responses of Alaskan arctic tundra to changes in climate or nutrient availability could be an expansion of deciduous shrubs, especially dwarf birch (*Betula nana*), in areas currently occupied by tussock tundra. Although correlations between shrub vegetation and snow cover in tundra are well known (e.g. Billings & Bliss, 1959; Jonasson, 1981; Evans *et al.*, 1989; Schaefer & Messier, 1995), the previously available data do not allow us to distinguish between the covarying effects of vegetation and topographic relief or to quantify the effects of differences in shrub density. Here, we report on spatially distributed measurements of vegetation characteristics and snow cover across a landscape that included varying densities of deciduous shrubs. We use a three-dimensional snow-transport model and an energy-balance snowmelt model to simulate the effects of increased height and cover of deciduous shrubs on the end-of-winter snow-depth distributions, blowing-snow sublimation fluxes, and the timing and magnitude of snowmelt runoff.

METHODS

Field measurements

We measured vegetation and snow properties across a 3 km^2 landscape near Happy Valley, Alaska (69°06′N, 149°00′W, 440 m a.s.l.), located midway between the Arctic Ocean and the Brooks Range. The site was covered by three vegetation types: typical tussock tundra (the most common type in the region; Bliss & Matveyeva, 1992), shrub tundra in water tracks (areas of subsurface drainage), and a shrubby tussock tundra of intermediate species composition. In April 1996, when the winter snowpack had reached its maximum, we used a sled-mounted radar (Holmgren *et al.*, 1998) to measure snow depths at 1-m intervals along three 1-km transects across the study area. Steel rods were driven into the permafrost to mark the ends of each transect. In July we returned and measured elevation, plant species, and canopy characteristics along the same transects. Leaf area index (LAI, L, leaf area per unit ground area) was measured with an optical plant canopy analyser (model LAI-2000, LI-Cor, Lincoln, Nebraska, USA). Canopy height (h_c) was taken as the mean of the five tallest shrubs and stem basal diameter (d_{stem}) was measured using calipers on five random shrubs at each point. Sampling locations were identified using a theodolite with an infrared distance ranger, allowing the vegetation measurements to be co-located with the snow depth measurements to an accuracy of <2 m.

Model simulations

Simulations were performed over a 4 km^2 domain (Imnavait Creek, 68°37′N, 149°17′W, 900 m a.s.l.) near our field site for four winters from 1986 to 1990, a location and time period for which detailed observations were available to drive the models. Due to space limitations, only the winter of 1986–1987 results are presented here; all simulations are reported in Liston *et al.* (in press). We simulated the autumn and winter snow cover evolution (September–April) using a numerical snow-transport model (SnowTran-3D; Liston & Sturm, 1998), and the spring snowmelt (May–June) using an energy-balance model (Liston & Hall 1995; Liston *et al.*, 1999). Because the region experiences virtually no snowmelt during the autumn and winter, and little or no snow accumulation during snowmelt (Kane *et al.*, 1991), it was appropriate to model the processes of accumulation and melt separately. The primary components of SnowTran-3D are: the windflow forcing field; wind-shear stress on the surface; snow transport by saltation; snow transport by turbulent suspension; sublimation of saltating and suspended snow; and accumulation and erosion of snow at the surface. The required model inputs are: (a) temporal fields of precipitation, wind speed, wind direction, air temperature, and humidity; and (b) spatial fields of topography and vegetation type. The required snowmelt model inputs are temporal fields of wind speed, air temperature, and humidity. To examine the effects of increased shrubs, for each year we compared two different simulations: one using the current vegetation distribution and another representing a shrub increase, in which shrub tundra was substituted for the areas currently covered by tussock tundra and wet sedge tundra.

RESULTS

Field measurements

Snow depths ranged from 0.1 to 1.6 m, with deep snow in patches of tall shrubs in water tracks and thin snow in tussock tundra (Fig. 1). Drifts formed on the downwind side of the shrub patches, with the deepest snow displaced approximately 10 m from the shrubs (Fig. 1). Snow depths were about equally well correlated with canopy height ($r = 0.56$) and stem diameter ($r = 0.52$) (Fig. 1), and somewhat less so with leaf area index ($r = 0.39$, not shown). The weaker correlation between snow depth and LAI was because variations in snow depth were mainly related to the height of deciduous shrubs, whereas evergreen shrubs and herbaceous plants in tundra are short but contribute substantially to LAI. Relationships between the different canopy characteristics were strong ($d_{stem} = 3.75 + 0.11h_c$, $r^2 = 0.84$, $p < 0.0001$ and $L = -1.37 + 1.51 \log(h_c)$, $r^2 = 0.58$, $p < 0.0001$, not shown), suggesting that if measurements of one are available, relatively good estimates of the others could be generated for model parameterizations (e.g. Pomeroy, 1989; Liston & Sturm, 1998).

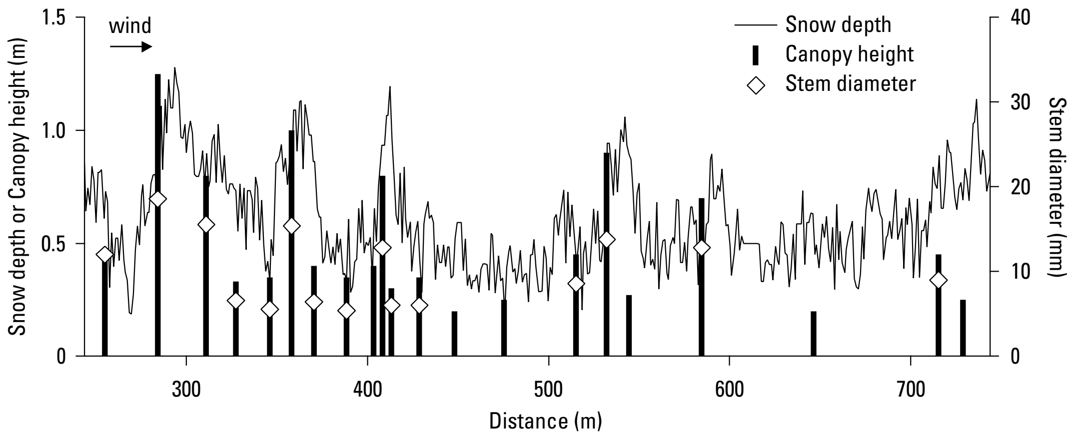

Fig. 1 Spatial variations in snow depth, shrub canopy height, and stem diameter along a transect across the study area. A 500-m segment from one of three 1-km transects is shown.

Some of the increased snow depth associated with shrubs was the result of in-filling of water track channels in which tall willow (*Salix* spp.) shrubs typically occurred. The channels were about 20 cm deep and had correspondingly greater snow depths (Fig. 2). In contrast, water track margins dominated by *Betula nana* shrubs were slightly higher than the surrounding terrain but still had deeper snow than did shrub-poor, tussock tundra areas (Fig. 2). This, along with the fact that the water track channels were only 5–10 m wide but the deeper snow associated with shrub vegetation in the entire water track area was typically 50–60 m wide (Sturm *et al.*, 2001), indicated that the shrub canopy, rather than topographic relief, was the main control on the snow cover. Overall, the shrubby tussock tundra and water track margin areas in which *Betula nana* was common had 27% deeper snow than did tussock tundra. It was surprising that the relatively small difference in canopy characteristics between typical

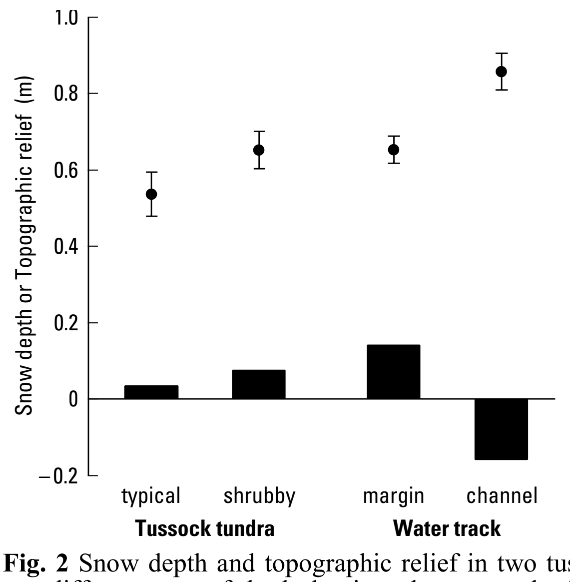

Fig. 2 Snow depth and topographic relief in two tussock tundra communities and in two different parts of shrub-dominated water tracks. Topographic relief was computed by subtracting a 50-m moving average of elevation from the measured elevation at each point. Data are means and error bars represent 1 standard error.

Table 1 Snow depth, shrub canopy height, stem diameter, and leaf area index in two tussock tundra communities and in two different parts of shrub-dominated water tracks (means ± standard deviations).

Variable	Tussock tundra: typical	shrubby	Water track: margin	channel
n	10	22	25	35
Snow depth (m)	0.51 ± 0.18	0.65 ± 0.22	0.65 ± 0.18	0.86 ± 0.28
Canopy height (m)	0.23 ± 0.05	0.26 ± 0.04	0.43 ± 0.12	0.85 ± 0.46
Stem diameter (mm)	5.4 ± 1.7	6.5 ± 1.3	8.6 ± 2.5	14.0 ± 5.3
Leaf area index	0.57 ± 0.11	0.60 ± 0.25	1.27 ± 0.38	1.47 ± 0.47

tussock tundra and shrubby tussock tundra produced as large a difference in snow depth as that between tussock tundra and water track-margin shrub tundra (Table 1).

Model simulations

Increasing deciduous shrub cover caused a 20% increase in the domain-averaged snow depth, with deeper snow over most of the domain but thinner snow on the dry tundra

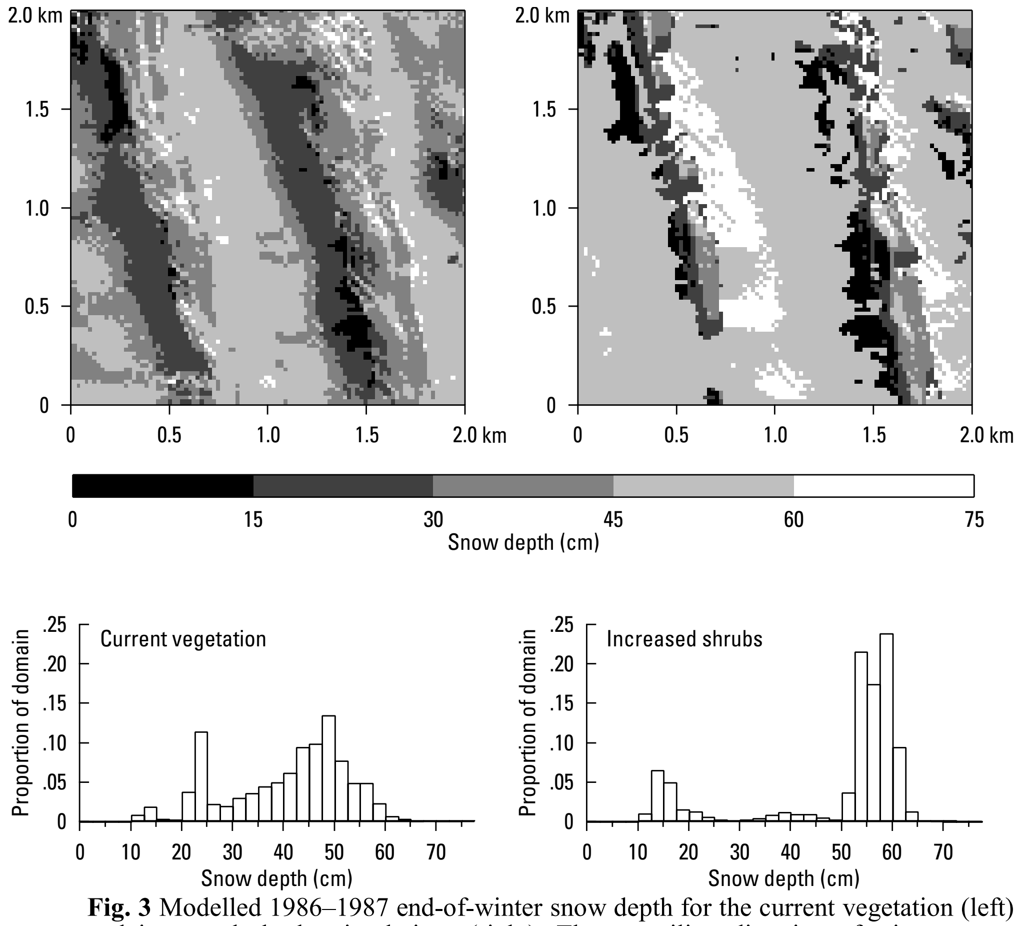

Fig. 3 Modelled 1986–1987 end-of-winter snow depth for the current vegetation (left) and increased shrubs simulations (right). The prevailing direction of winter storm winds, which are primarily responsible for the redistribution of the snow, is from the southwest (lower left in diagram). Also shown are the snow depth histograms corresponding to each simulation.

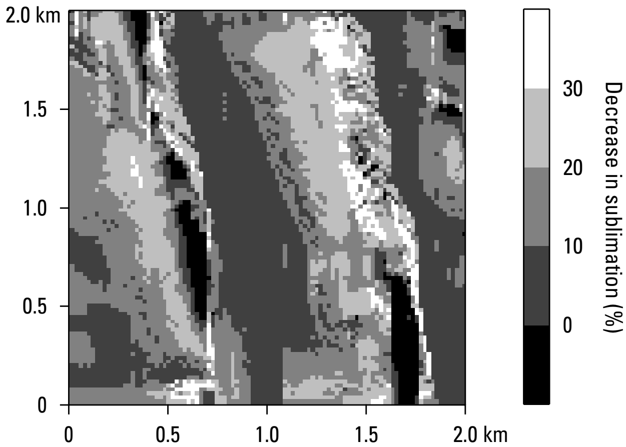

Fig. 4 The decrease in blowing-snow sublimation resulting from an increase in shrub cover for the 1986–1987 model simulation. Plotted are the differences between the fraction of the total winter precipitation that sublimated with increased shrubs minus the fraction that sublimated with the current vegetation.

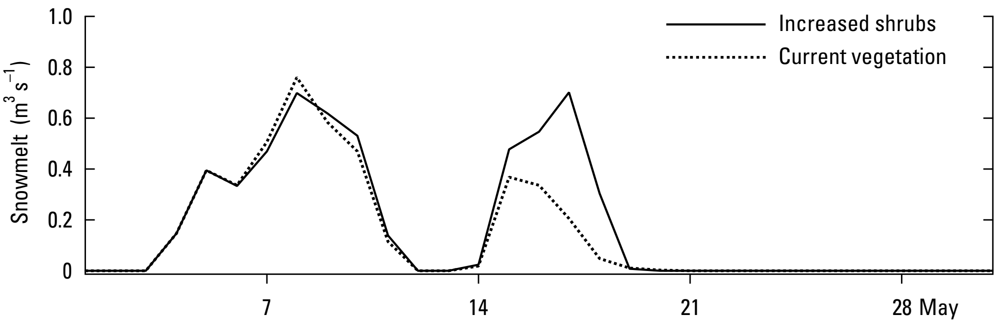

Fig. 5 Time course of domain-total snowmelt production in 1987, for simulations with the current vegetation and with increased shrubs.

ridges (Fig. 3). This was because snow held by shrubs upwind of the ridges was not available for transport to the dry tundra areas. The shrub increase produced a more highly differentiated snow cover over the domain, with a bimodal snow-depth distribution (Fig. 3). By trapping wind-blown snow, shrubs reduced the amount of snow lost to sublimation during the course of the winter by 20% or more over a large part of the domain (Fig. 4). In the spring, there were only small differences in the snow disappearance date because the maximum snow depths did not increase greatly, even though more of the domain was covered by deep snow. The shrub increase caused snowmelt to occur 4 days earlier over dry tundra areas that had reduced snow cover, while it delayed the melt date by 1–4 days over the larger part of the domain where shrubs had produced a deeper snow pack (not shown). The deeper snow accumulations with increased shrubs changed the timing and magnitude of snow meltwater production. A few days of freezing temperatures divided the snowmelt into two peaks; shrubs had their greatest impact during the second peak, when the shrub-covered areas of the domain became snow free (Fig. 5).

DISCUSSION

Spatial variations in snow depth were strongly related to deciduous shrub cover, consistent with reports of enhanced snow in shrub-dominated tundra in Alaska (Evans *et al.*, 1989; Kane *et al.*, 1991), Canada (Schaefer & Messier, 1995), and northern Sweden (Jonasson, 1981). The height and stiffness of the shrub growth form increased snow accumulation, an effect independent of local changes in topographic relief. The finding that shrubby tussock tundra accumulated as much snow as did much taller stands of *Betula*-dominated shrub tundra in water tracks suggests that the threshold at which the shrub growth form begins to modify tundra snow-holding capacity is relatively low. The shrub canopy also has important effects during the snow-free season: shrubs modify the surface energy balance by decreasing albedo, increasing net radiation, reducing ground heat flux, and increasing sensible heat flux to the atmosphere (McFadden *et al.*, 1998). These results suggest that structural characteristics such as canopy height are more important for predicting the *effects* of vegetation on the hydrologic and climate systems than are variables such as biomass, which are commonly used to describe the ecological *responses* of vegetation to environmental variations. Field manipulations in Alaskan tundra find little or no change in ecosystem biomass, due to compensatory effects of large shifts in the relative dominance of different plant growth forms (Chapin *et al.*, 1995). Thus, changes in plant growth form composition could represent both the most important responses and the greatest potential feedbacks of vegetation to climate variability in the Arctic (Chapin *et al.*, 1996).

Areas with shrubs had 27% deeper snow as compared the typical tussock tundra that covers most of the region. Likewise, the model-simulated increase in shrub cover increased the domain-averaged snow depth by 20%. Significantly, this is approximately equal to the fraction of the snowpack that is normally lost to sublimation during the winter (Pomeroy & Gray, 1994; Liston & Sturm, 1998). The model simulations showed that shrubs decreased sublimation by 20% or more over a large part of the domain. This suggests that a shrub expansion could significantly increase snow depths across the region, without any winter precipitation increase (Sturm *et al.*, 2001).

In the Arctic, during the brief snowmelt period when large volumes of water are released, subsurface storage is limited by a shallow thaw layer, and evaporation is limited by meteorological conditions. For this reason, 50–80% of the arctic snowpack water content typically goes into runoff (Kane *et al.*, 1991; McNamara *et al.*, 1998). The model-simulated increase in shrub cover increased snow meltwater production by 25%. Although this is within the range of interannual variability (Kane *et al.*, 1991), a persistent increase in snowmelt runoff due to a vegetation change could have large-scale effects because freshwater transport from arctic land areas to the Arctic Ocean represents a significant fraction of global runoff (Walsh *et al.*, 1998). While frozen soil conditions make it likely that more of the snowpack associated with increased shrub cover would go into runoff than soil moisture recharge, any additional soil moisture would not be compensated by increased evapotranspiration because tussock tundra and shrub tundra do not differ significantly in growing-season evaporation rates (McFadden *et al.*, 1998).

In summary, increased shrub cover strongly modified arctic hydrologic processes both temporally, because decreased winter sublimation losses caused more moisture to be available during spring snowmelt, and spatially, because snow increased in shrub-covered areas and decreased in ridge areas without shrubs and because snowmelt runoff increased the amount of water transferred from terrestrial to aquatic ecosystems.

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