Shrub tundra ecohydrology: rainfall interception is a major component of the water balance

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Abstract

As shrubs expand across the Arctic, they alter all cycles in the Earth system, including the water cycle. However, the coupling of shrubs with the water cycle during summer remains poorly understood. Rainfall interception, a major cause of divergent hydrological responses between vegetated and non-vegetated environments, is particularly poorly constrained. We quantified shrub rainfall interception and redistribution in birch and alder in the Western Canadian Arctic using networks of throughfall and stemflow gauges. We find that rainfall interception losses are a major component of the water budget, as effective rainfall was reduced by 15%–30% in the birches. Underneath alders, effective rainfall was almost as large or larger than gross rainfall, but they also left a rain shadow. The spatial variability in throughfall was substantial underneath both shrub species. Stemflow was a small but non-negligible component, as the alders concentrated ∼15% of rainfall to their few vertical stems, compared to the ∼8% that the birches funnelled along their numerous, predominantly skewed stems. The substantial small-scale variability in effective rainfall may create islands in which conditions for certain biogeochemical processes are particularly favourable. On larger scales, rainfall interception reduces the water yield and thus the runoff received by downstream ecosystems such as lakes. The interception losses are predicted to increase with shrub density in a way that also depends on climatic conditions, with large losses in many coastal environments. The extent to which shrub expansion leads to drier Arctic ecosystems is, however, unclear because of the complex interplay between many ecohydrological processes. Shrub rainfall interception is one major, previously overlooked piece of this puzzle.

1. Introduction

Widespread shrub expansion has been observed across the Arctic tundra (Tape et al 2006, Myers-Smith et al 2011). The expansion and increasing height and density of shrubs are closely related to rapidly rising temperatures and increasing disturbances such as wildfire and thermokarst (Osterkamp et al 2009, Myers-Smith et al 2011, Lantz et al 2013). However, shrubs do not only respond to external changes, but they are coupled bidirectionally to all major Earth system cycles. Shrubs alter the storage and fluxes of carbon, nitrogen and nutrients (Myers-Smith et al 2011). They also influence the energy cycle, e.g. by albedo reduction (Chapin et al 2000, Sturm et al 2001). Similarly, the water cycle responds to shrub expansion. By trapping snow and altering snowmelt processes in numerous ways, shrubs have a major impact on the water balance during the cold season (Sturm et al 2001, Pomeroy et al 2006). In summer, however, the coupling of shrubs with the water cycle remains poorly understood (Lafleur and Humphreys 2018). A particularly poorly constrained process is rainfall interception (van Dijk et al 2015). Our lack of dedicated observations of rainfall interception poses a limitation on our ability to predict how water resources will evolve in an increasingly warm and shrubby future.
Rainfall interception is a major water cycle component in vegetated environments (van Dijk et al 2015). Part of the rainfall never reaches the surface as it is captured by the plant canopy, from which it evaporates. Canopy rainfall interception tends to reduce the infiltration and water yield compared to bare surfaces (Brown et al 2005), with repercussions for downstream ecosystems such as the numerous, often endorheic, tundra lakes. The reduction in water yield is commonly also mediated by increases in transpiration (Brown et al 2005). In the shrub tundra, however, evidence for larger fair-weather evapotranspiration over shrub-covered compared to shrub-free tundra is patchy. The few measurements suggest that the shrub effect on evapotranspiration is often small and can be of either sign (birch: Lafleur and Humphreys (2018), birch/willow: Chapin et al (2000), McFadden et al (2003)). Shrub rainfall interception is hence possibly a major factor in the water balance difference between shrub-covered and shrub-free tundra environments.

Shrubs can intercept significant amounts of water. Interception losses of 0%–50% have been observed in semi-arid, temperate and alpine environments (Navar and Bryan 1990, Mauchamp and Janeau 1993, Dunkerley and Booth 1999, García-Estríngana et al 2010, Uehara and Kume 2012). While we lack observations of shrub rainfall interception in the Arctic tundra, these findings suggest it could be a major component of the summertime water balance. This is because interception tends to be large for light or intermittent rainfall and in windy conditions, which are common in the tundra (Uehara and Kume 2012, van Dijk et al 2015).

Shrub canopy characteristics also exert a control on interception (Dunkerley and Booth 1999). Generally speaking, taller and denser shrubs are expected to intercept more water. But also leaf and branch orientation and leaf wettability are important, species-dependent factors (Navar and Bryan 1990, Holder 2012). They influence not only the amount of water intercepted but also how the water is partitioned into throughfall and stemflow. By funnelling intercepted water to the stems, certain shrubs can concentrate large amounts of water (and nutrients) in small areas (Navar and Bryan 1990, Mauchamp and Janeau 1993, Dawson and Goldsmith 2018). Dripping from wet canopies similarly redistributes the rainfall (Dawson and Goldsmith 2018). Through its influence on the distribution and chemistry of water, rainfall interception can shape the hydrological and ecological conditions across spatial scales.

To quantify shrub rainfall interception in the tundra, we measured throughfall and stemflow in two types of shrub communities in the Western Canadian Arctic. The contrast between the more common low-stature birch shrubs and the taller alders allowed us to study the species dependence of rainfall interception. To estimate where shrub rainfall interception can potentially be a major component of the water balance, we applied a simple physical rainfall interception model across the Arctic.

2. Study site and period

The Trail Valley Creek (TVC; 68°45′N, 133°30′W) site is located in the Western Canadian Arctic, 70 km south of the Beaufort Sea (figure 1(a)). The rolling landscape is underlain by continuous permafrost (Zwieback et al 2019). The climate is dominated by long and cold winters, with a snow-cover period of ~8 months. Snow constitutes slightly more than half of the 250 mm of cumulative average precipitation (Dean et al 2016), with summer rainfall being ~100 mm on average.

Shrub expansion has been documented throughout the region (Lantz et al 2013). At TVC, tall erect shrubs are common on hillslopes and in creeks (Menard et al 2012). On hillslopes, two species dominate, both occurring in patches (figure 1(a)). With a height of 30–60 cm, birch (Betula glandulosa) is the smaller and more common one. The birch density is not uniform across the hummock-interhummock microtopography (figures 1(b)–(c)). The individuals preferentially grow in interhummocks, extending subhorizontally across the hummocks. Individual shrubs are often interlocked with one another, giving rise to a high density and leaf area index. The taller alders (Alnus viridis; 80–200 cm), by contrast, do not form a quasi-continuous canopy. Rather, the individual alders (diameter: 1–2 m, consisting of multiple stems) are clearly separated (Lantz et al 2013), with shorter shrubs (e.g. birch), graminoids and lichens being prevalent in the gaps (figures 1(e)–(f)).

The study period from 22 June to 28 August 2018 covered a substantial part of the growing season, as it was bracketed by major snowfall at either end (15 June; 30 August). The ~90 mm of rainfall during the study period occurred in 24 distinct, often intermittent events (periods with non-zero rainfall separated by more than 4 h; figure 1(d)). The events varied in magnitude from <2 mm (9/24) to >1 cm (1/24), and duration (from 1 to 25 h, mean: 7 h). The temperature was also variable, with a relatively cool June followed by warmer temperatures in July and cooling in August (figure 1(d)).

Leaf properties varied over time. The birch leaf cover was fully established by the beginning of the study period, and senescence (reddening) occurred rapidly during its final ten days. The alder leaf cover increased from ~60% to 100% during the first two weeks, with the leaves remaining green throughout.

3. Methods

3.1. Measurements of shrub characteristics

We measured multiple characteristics of birch and alder shrubs. In a birch patch, we designated two plots...
of 2 m diameter prior to the study period: one covered by comparatively sparse and low vegetation (B-S; figure 1(b)), the other by comparatively dense and tall shrubs (B-D; figure 1(c)). The comparisons were based on the plot-level average height (aggregation of five individual measurements) that we determined for 10 equidistant locations along a 60 m diameter transect (figure 1(a)). We also measured leaf area index (LAI) at the end of the growing season (28 August) using a non-destructive method based on light interception (LI-COR LAI-2200C; corrections for scattering and clumping but not for non-leafy components were applied according to the manufacturer’s recommendations). For the alders, we also chose two plots (individual shrubs) among 10 alders along a circular transect (figure 1(a)). A-S was among the smaller, A-T among the taller alders (figures 1(e)–(f)).

Wettable leaves have a high capability to retain water on the surface, thus increasing the interception capacity (Holder 2012). We determined the wettability via the contact angle $\theta$ between a drop and the leaf’s surface by analysing images of a sessile drop (0.03–0.04 mm) on the horizontal leaf surface (Holder 2012) of 10 alder and birch leaves each. Large contact angles ($\theta \gtrsim 110^\circ$), corresponding to low wettability, could indicate an adaptation against wet leaves or interception (Aryal and Neuner 2009, Dawson and Goldsmith 2018).

3.2. Throughfall and stemflow measurements
We measured throughfall with ~10 gauges per plot (table S1 is available online: stacks.iop.org/ERL/14/055005/mmedia), a sample size which for Rodrigo and Avila (2001) yielded a plot-level accuracy of ~10%, but the spatial variability and sampling error are themselves highly variable (Holwerda et al 2006, van Dijk et al 2015). Each plot was instrumented with automated tipping-bucket rain gauges (Onset RG3-M; bucket size: 0.2 mm; half-hourly recording interval) and non-automatic gauges (plastic bottles). The bottles (10.3 cm diameter) were read out periodically (10 times in total) by weighing. To reduce evaporation, we inserted the top upside down with the cap (perforated 4 times) still on, and added oil (figure 1(b)). At the birch plots, the throughfall gauges were distributed randomly, thus sampling both interhummocks and less densely vegetated hummocks (figures 1(b)–(c)). With the alders, we opted for a stratified block design to cover the upwind, central and downwind (with respect to the typical storm wind direction) parts of the canopy (figures 1(e)–(f)). To quantify the wind shadow effect, we installed two non-automatic gauges 0.5 and 1.0 m downwind from the canopy edge of
shrub A-S (figure 1(e)). However, the sampling outside the canopy was insufficient to quantify patch-scale rainfall partitioning for the alders, in contrast to the quasi-continuous birch canopies.

To quantify stemflow, we pursued separate strategies for alders and birch. At each alder plot, we fitted three stems with stemflow collectors (figure 1(f)): half-open plastic tubes that helically enveloped the stem (Garcia-Estringana et al. 2010). The flow was collected using one automatic gauge and two closed bottles. As the birch stems were too small to be fitted with collectors, we determined stemflow in a separate experiment (Garcia-Estringana et al. 2010). For six near-vertical (60°–90° inclination) and six inclined (30°–60°) shrubs, we measured stemflow during multiple artificial rainfall events (four per shrub, from 0.1 to >4 mm, well above the shrubs’ interception capacity). The severed shrubs were placed inside a container in their natural position (figure 2), and rainfall was applied uniformly with a nozzle-type rainfall simulator in dry conditions. Volumetric stemflow was determined by weighing the water accumulated in the small bag attached to the stem.

The automatic rain gauges were calibrated using the dynamic method (Calder and Kidd 1978). Repeat measurements (n = 13) indicated a calibration accuracy of ±1.8%.

The measurements were accompanied by control measurements of precipitation in nearby (<3 m) shrub-free areas. At each plot, an automatic rain gauge was collocated with a bottle to allow for estimation of evaporation losses in the latter.

Three instances of missing data occurred. One non-automatic stemflow collector overflowed (A-T, 27 July); the control bottle at B-D was found upside down on 17 August; one throughfall gauge (A-T) had zero-records during the final 12 d.

3.3. Estimating interception losses and rainfall redistribution

We estimated the fluxes—including interception losses, stemflow and throughfall—with an empirical multilevel model (Gelman 2007). The Bayesian model allowed us to account for the missing data, to handle the different recording intervals and to deal with various sources of uncertainty and variability. A further key advantage was that it naturally provided an uncertainty estimate via the posterior distribution.

We analysed the fluxes at the event level, separately for each plot. Throughfall T was considered to vary with location j, event magnitude $e_j$, and the event itself (thus implicitly accounting e.g. for different wind conditions):

$$T_j = \left( 1 - \alpha_i - \beta_j - \beta_j' P_i - P_0 - \gamma_0 \right) P_j , \quad (1)$$

i.e. modelled as a fraction of $P_0$, the amount measured by the control gauge. The loss fraction itself consists of an event component $\alpha_i$ (identical for all locations $j$); an event-invariant, location-specific component $\beta_j'$; a location-specific component that accounts for the average change in the throughfall fraction with event magnitude (normalized by a reference magnitude of $P_0 = 2$ mm), $\beta_j'$; and a location and event-specific noise term $\gamma_0$. They are random quantities. For instance, the $\beta_j'$ were assumed drawn from a population $\beta$ that represents the variable loss fraction within the plot. To account for the stratified sampling in the alder plots, the $\beta_j'$ were assumed drawn from three separate populations depending on $j$’s location with the shrub, and so were the $\beta_j'$.

The modelled measurements of $T_j$ accounted for the error properties of both automatic and non-automatic gauges. For the automatic rain gauges, the throughfall observation $t_j$ was assumed contaminated by a time-invariant, zero-mean calibration error $r_j$ (section 3.2) and a random error $\epsilon_{ij}$ whose magnitude corresponded to the bucket size (Ciach 2003)
\[ t_{ij} = (1 + \tau_i) T_{ij} + \epsilon_{ij}. \] (2)

The control observations of gross precipitation were modelled analogously: \[ p_i = r_i P_i + \epsilon_{pi}. \] The modelled observation for the non-automatic rain gauges, \[ T_{ij}, \] accounted for the longer observation period \( I \) by aggregating over all events \( i \in e(I) \) between successive weighings; the evaporation losses \( l_i \) during that period; and random errors \( \epsilon_{ij} \):

\[ t_{ij} = \left( \sum_{i \in e(I)} T_{ij} \right) - l_i + \epsilon_{ij}. \] (3)

The losses \( l_i \) were estimated by comparison of the plot’s automatic control gauge with its collocated non-automatic one. The uncertainty was estimated as the observed scatter for all plots (a conservative estimate because it conflates random errors from systematic variations, e.g. due to aspect). The loss estimation itself was also thought conservative, as evaporation in the open tundra (control gauges) was likely larger than underneath the shrubs (throughfall gauges). However, the estimated losses from the control gauges (≈1 mm) were much smaller than the throughfall and its spatial variability.

Stemflow was modelled separately for alder and birch. For the alders, the model of the stemflow \( S_{ij} \) for stem \( j \) during event \( i \) was analogous to that of throughfall (equation (1)). For instance, \( \beta_i^j \) encoded the average fractional stemflow (rather than fractional throughfall loss) for an event of magnitude \( p_i \). For the birch, we constructed a separate regression model for the birch, by relying on the regression model, similarly predicted the average plot-level stemflow and its uncertainties. The upscaling from individual shrubs in the experiment is, however, subject to representativeness errors, which we did not explicitly consider. Plot-level stemflow could have been over-estimated because of large gaps in the canopy, or underestimated because the interlocking of shrubs (not replicated in the experiment) could induce (i) larger interception capacities per unit area and (ii) divert stemflow to throughfall because touching branches can induce dripping. For the alders, by contrast, the cumulative stemflow was modelled as the sum of that at the instrumented stems and that of the non-instrumented ones. The latter were drawn from their population distribution, thus accounting for the sampling uncertainty. The cumulative shrub-level stemflow \( S_i \) was expressed as an equivalent rainfall depth by dividing the stemflow volume by the shrub area.

We estimated the interception loss \( I_i \) for event \( i \) from the plot-level throughfall \( T_i \), stemflow \( S_i \) and precipitation \( P_i \):

\[ I_i = P_i - P_i^c, \] (6)

where below-canopy effective rainfall

\[ P_i^c = T_i \cdot + S_i. \] (7)

The relative time-aggregated partitioning of gross interception into, respectively, interception loss, throughfall and stemflow was computed as

\[ \Lambda_i = \frac{\sum_i I_i}{\sum_i P_i^c}; \Lambda_T = \frac{\sum_i T_i}{\sum_i P_i^c}; \Lambda_S = \frac{\sum_i S_i}{\sum_i P_i^c}. \] (8)

All these quantities accounted for the measurement errors and sampling uncertainty. To analyse the within-plot spatial variability, we additionally derived the relative gauge-level throughfall at location \( j \) as

\[ \tau_j = \frac{\sum_i t_{ij}^c}{\sum_i P_i^c}. \] (9)

The Bayesian estimation required the specification of prior distributions. The priors were chosen to be wide, so as to let the data dominate the predictions. An overview of the priors, their rationale and the distributional assumptions of all quantities, can be found in the supplement. The supplement also details how we dealt with missing data. The Bayesian inference employed Hamiltonian Markov Chain Monte Carlo sampling in 4 chains, implemented in the PyMC3 package (Salvatier et al 2016), to sample from the posterior distribution (assuming perfect convergence after warm up) of all quantities of interest.

3.4. Potential circum-Arctic rainfall interception

To provide a rough estimate of potential shrub interception losses as a function of climatic regimes across the Arctic, we employed the van Dijk et al (2015) physical model for quasi-continuous canopies. With only one parameter (interception capacity \( c \)), it is
The two birch plots had average heights of 48.4 ± 4.1 cm. Shrub characteristics (similar to interception modules in land surface models [Davies-Barnard et al. 2014]). For each hourly time step, it balances the canopy water storage. Precipitation is the only input (provided the canopy is not saturated), whereas water is lost at the potential evaporation rate whenever the leaves are wet. Potential evaporation was estimated using the wet-bulb approach, as suggested by Pereira et al. (2016) for well-ventilated canopies like shrubs. The meteorological forcing was taken from the MERRA-2 re-analysis data set (Gelaro et al. 2017), one of the best globally available data records. However, biases remain (Gelaro et al. 2017). We implicitly accounted for these errors by calibrating the observed $\Lambda_f$ at the birch plots (quasi-continuous canopy): of 1000 values of $c$, we retained those for which the predicted $\Lambda_f$ was within the empirically determined $\Lambda_f$ plus/minus one standard deviation (equation (8)). By focussing on $\Lambda_f$, we minimized the impact of forcing errors in individual events. Assuming the retained values of $c$ were transferable across the Arctic (and averaging), we predicted relative interception losses at any location across the Arctic for July and August 2014–2018 that would occur if that location was covered by the same shrub canopy as at our site. Rather than constituting actual interception losses, these hypothetical predictions are intended to illustrate where the meteorological conditions are conducive to rainfall interception.

4. Birch rainfall interception

4.1. Shrub characteristics

The two birch plots had average heights of 48 cm (B-S) and 59 cm (B-D), compared to 52 ± 8 cm (mean ± standard deviation; n = 10) in the vicinity. The LAI mirrored the height, with values of 1.1 and 1.5 for B-S and B-D, respectively. The often horizontal birch leaves were found highly wettable according to the Aryan and Neuner (2009) taxonomy (observed contact angles $\theta = 54 \pm 9^\circ$; n = 20).

4.2. Interception losses and rainfall redistribution

Interception losses $\Lambda_f$ over the study period were substantial at the two birch plots, increasing with plant size and density. In the sparse plot B-S, $\Lambda_f = 16\% \pm 4\%$ (posterior mean ± standard deviation), as throughfall amounted to $\Lambda_f = 76\% \pm 4\%$ and stemflow to $\Lambda_S = 8\% \pm 2\%$ of above-canopy precipitation (figure 3(a)). $\Lambda_f$ was greater in the dense plot B-D, at 29% ± 5% (figure 3(b)), owing to less throughfall (4% ± 4%). At 8% ± 2%, stemflow $\Lambda_S$ was similarly a small but non-negligible part of the water balance. These predictions were based on the artificial rainfall experiments (figure 2(b)). Per unit area, stemflow amounted to $a = 8\% \pm 2\%$ of the precipitation $p$ for sufficiently large rain events $p > 0.7$ mm (equation (4)). The uncertainty in $a$ reflects the wide scatter in stemflow observed at fixed $p$ (figure 2(b)).

The amount of water reaching the surface varied considerably within the plots. While we were unable to account for the spatial variability in stemflow, the observed throughfall percentage $\tau_f$ exhibited a standard deviation of 11% (figures 3(c)–(d)). There was no consistent plot-scale pattern in the variability (figures 3(c)–(d)), which appeared to be controlled by small-scale variations in plant properties such as density.

The effective precipitation $P_{ef}$ increased with event size $p_e$ (figures 4(a)–(b)). So did the losses, as $P_{ef}$ remained substantially below $p_e$ even for the biggest event ($p_e \approx 20$ mm over 14 h). Quantitatively, the estimated average increase of the throughfall fraction with rainfall, $E(\beta')$, was small (posterior mean of 0.02/0.01 for B-S/B-D) compared to its population variability $\text{std}(\beta') \sim 0.05$ (table S2).

5. Alder rainfall interception

5.1. Shrub characteristics

The birch A-T was, with a mean height of 130 cm, marginally taller than average 115 ± 23 cm (n = 10). It was also taller than the second instrumented shrub,
A-S (100 cm), by ~25%. A-T’s LAI was also ~25% greater than that of A-S (2.1 and 1.6, respectively). The alder leaves were found to be highly wettable, but slightly less so than the birch leaves, with observed $\theta = 79 \pm 11^\circ$ ($n = 20$).

5.2. Interception losses and rainfall redistribution

Interception losses $\Lambda_I$ were small and perhaps negative within the perimeter of the two alder shrubs (figures 5(a)–(b)). They were likely larger for the tall (11% ± 13%) than for the short alder (2% ± 11%). This was reflected by a slightly divergent partitioning, as throughfall $\Lambda_T$ appeared smaller for the tall alder (72% ± 10% versus 86% [h % ± 9%]), whereas stemflow was likely larger (17% ± 7% versus 12% ± 6%).

The potentially negative $\Lambda_I$ and the large uncertainties are associated with substantial within-canopy variability in throughfall (figures 5(c)–(d)). Throughfall could be greatly enhanced on the upwind side of the canopy, compared to the central and downwind locations. It was also enhanced compared to the downwind rain shadow that extended $\geq$1 m beyond the canopy (with $\tau_l$ of ~70%–80%; figure 5(c)). With shrinking between-alder gaps, we would expect these edge effects to decrease, so that the overall interception loss would mirror that of the downwind part of the canopy, corresponding to $\Lambda_T \approx 13% \pm 15%$ (figures 5(a)–(b)).

Within the canopy perimeter, effective rainfall $P'_i$ increased quasi-linearly with event size $P_i$ (figures 4(c)–(d)). So did its stemflow component, although there was considerable scatter at a given event size (e.g. for $P_i \sim 8$ mm at A-T). Also the uncertainty was substantial, reflecting the low predictability of stemflow across space (population variability std($\beta'$) is ~60% of $E(\beta')$; table S2) and time.
6. Potential circum-Arctic shrub rainfall interception

Potential shrub interception losses \( \Lambda_I \) were predicted to be non-negligible throughout the Circum-Arctic (figure 6(a)). Due to the hypothetical uniform interception capacities, the predictions cannot account for the variability in shrub traits, but they do highlight climatic regimes that are conducive to rainfall interception. Especially some coastal areas with low average rainfall intensities are characterized by large potential losses (Behrangi et al. 2015, see). These include areas with increasing shrub cover such as the Yamal Peninsula and parts of the Western Canadian Arctic (Frost et al. 2013, Lantz et al. 2013). Shrub density is also important, as the denser canopy was predicted to intercept more rainfall than the sparser one (figure 6(b)), like in the instrumented birch plots.

7. Discussion and conclusion

Shrub rainfall interception is a major component of the tundra water balance. It reduced the effective below-canopy rainfall by \( \sim 15\%–30\% \) in two birch plots. Underneath alders, effective rainfall was almost as large as or larger than gross rainfall, but they also left a rain shadow. The divergent behaviour highlights the ecohydrological complexity of shrub expansion, as interception losses depend on shrub species and density (figures 3–5). A process-based interception model further predicted them to vary with location (figure 6), assuming hypothetical uniform interception capacities. The predicted losses were non-negligible (\( \gtrsim 5\% \)) throughout the circum-Arctic, but the resulting picture is patchy, likely also because rainfall interception is difficult to model globally (e.g. precipitation forcing; van Dijk et al. 2015). Notwithstanding these limitations, shrub expansion is expected to reduce infiltration into the soil and runoff generation in all tundra regions due to interception losses alone, most markedly so in many coastal regions (figure 6).

Whether soils will dry and lakes will shrink with shrub expansion also depends on concomitant changes in winter processes, in permafrost and atmospheric conditions, and in evapotranspiration (Riordan et al. 2005, Tetzlaff et al. 2013). While previous tundra studies (birch and willow) suggest, at best, small increases in evapotranspiration (Chapin et al. 2000, McFadden et al. 2003, Lafleur and Humphreys 2018), alder expansion has been linked to substantially increased evaporative losses in alpine environments (van den Bergh et al. 2018). Other poorly understood, and spatially variable, factors include changing infiltration capacities, changes in permafrost and hydrologic connectivities, and interception by litter and the understory (Pitman 1989, Wohlfahrt et al. 2006, Jafarov et al. 2018). It is hence not evident when and to what extent the water losses due to interception are exacerbated by other ecohydrological processes as tundra shrubs expand.

Rainfall interception also leads to small-scale redistribution of rainfall. This is again species specific (Navar and Bryan 1990), as alders concentrated \( \sim 15\% \) of rainfall to few vertical stems, compared to the \( \sim 8\% \) the birches funneled along their numerous,

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Figure 6. Potential relative interception losses \( \Lambda_I \) in July and August, extrapolated using a simple physical Rutter-type model calibrated with field observations. (a) Extrapolated losses for dense birch like at plot B-D. (b) Increase in relative interception losses, \( \Delta \Lambda_I \), for a change from sparse birch (like B-S) to dense birch (B-D). The extrapolation covered all land surfaces above 60°N that are not glaciated and where tree cover is below 12% (Hansen and Song 2018). The observations at TVC are shown by the circular marker.
predominantly skewed stems. Their tall and sparse nature also caused the alders to concentrate wind-driven rainfall on the upwind side of the canopy (figures 5(c)−(d)), although this effect may be reduced as gap infilling proceeds (Lantz et al. 2013). The rainfall redistribution, in concert with snow interception, may have important implications for biogeochemical processes (Myers-Smith et al. 2011, Sturtevant et al. 2012). By concentrating water and nutrients in small areas, shrubs could create islands in which conditions for e.g. methanotrophy are particularly favourable. In summary, rainfall redistribution is one of many processes by which shrubs modify ecosystem and permafrost conditions (Sturm et al. 2001, Myers-Smith et al. 2011).

The interception measurements highlight the poorly understood interactions between tundra shrubs and the Earth system (Myers-Smith et al. 2011). Rainfall interception is a major component of not only the water cycle, but it also affects the energy cycle (increased event and post-event latent heat fluxes; perhaps indirect effect on permafrost temperatures via soil moisture; van Dijk et al. 2015, Zwieback et al. 2019). Interception could also modify carbon and nutrient cycles (mediated for instance by soil moisture; Sturtevant et al. 2012) or the sediment budget (less erosion due to reduced quickflow; Brown et al. 2005). Due to the tightly coupled nature of these cycles, it is difficult to predict future water resources, ecosystem functioning and further shrub expansion (Myers-Smith et al. 2011, Tetzlaff et al. 2013). While many relevant processes, including rainfall interception, are represented in land surface and ecosystem models, the parameterizations are rarely optimized for Arctic environments (Best et al. 2011, Chadburn et al. 2017). Furthermore, these models vary widely in their dependence of rainfall interception on plant density, and they generally do not consider the species dependence (Best et al. 2011, Davies-Barnard et al. 2014). Accounting for the species dependence we observed will improve predictions of the water and energy cycles in an increasingly shrub-covered tundra.

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