Interaction between Shrub Encroachment and Water Infiltration on a Hillslope in Typical Steppe

Authors: Si-Yi Zhang, Zhi-Hua Zhang, Bin He, Zhi-Yun Jiang, Xiao-Yan Li, Xiao-Yan Li

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Abstract

The interaction between the surface hydrologic cycle and the shrub-encroached landscape at different slope positions remains poorly investigated. This study aims to explore the interaction between the water infiltration patterns affected by shrub encroachment at different hillslope positions. Soil water content and temperature were continuously measured at 10-min intervals at four or five depths under shrub patches and the grass matrix at four slope positions of a Caragana microphylla encroached hillslope from July 2009 to May 2013. The rainfall and meltwater infiltrations were estimated based on above data. Results showed that the rainfall infiltration ratios (IRs) at the grass matrix were as high as 0.78$±$0.08, except at the lower site, where it was only 0.47. The IRs of shrub patches increased from 0.38 at the top site to 0.77 at the lower site. The IRs were higher at the grass matrix than that at the shrub downslope edges at the top, upper, and middle sites of the hillslope due to the raised microtopography of the shrub mounds. However, at the lower site, IR was higher at the shrub patch than that at the grass matrix than due to more upper slope runoff input and higher infiltration capacity at the shrub patches. The preferential flow was not an important factor influencing the redistribution of water resources on the slope. Snow and ice were blown up by wind and accumulated in the shrub patches and their lees resulted higher water input to the shrub patches than that in the grass matrix during snowy years. Shrub encroachment changed the microtopography, soil property under different canopy and slope positions, and further affected the surface hydrological processes. The feedbacks between shrub encroachment and water infiltration varied at different sites of the hillslope and affected the development of shrub patches.

Full Text

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Si-Yi Zhang[12], Zhi-Hua Zhang[3], Bin He[12], Zhi-Yun Jiang[4], Xiao-Yan Li[56]*

[1] National-Regional Joint Engineering Research Center for Soil Pollution Control and Remediation in South China, Guangdong Key Laboratory of Integrated Agro-environmental Pollution Control and Management, Institute of Eco-environmental and Soil Sciences, Guangdong Academy of Sciences, Guangzhou 510650, China

[2] Guangdong-Hong Kong-Macao Joint Laboratory for Environmental Pollution and Control, Guangzhou 510650, China

[3] [Affiliation not provided in original text]

[4] [Affiliation not provided in original text]

[5] State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China

[6] School of Natural Resources, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China

*Correspondence to: X.-Y. Li, School of Natural Resources, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China, E-mail: xyli@bnu.edu.cn.

Abstract

The interaction between surface hydrological cycles and shrub-encroached landscapes at different slope positions remains poorly investigated. This study explores water infiltration patterns affected by shrub encroachment across different hillslope positions. Soil water content and temperature were continuously measured at 10-minute intervals at four or five depths under both shrub patches and grass matrix at four slope positions of a *Caragana microphylla*-encroached hillslope from July 2009 to May 2013. Rainfall and meltwater infiltrations were estimated based on these data. Results showed that rainfall infiltration ratios (IRs) at the grass matrix were as high as 0.78$±$0.08, except at the lower site where it was only 0.47. The IRs of shrub patches increased from 0.38 at the top site to 0.77 at the lower site.

The IRs were higher at the grass matrix than at the downslope edges of shrub patches at the top, upper, and middle sites due to the raised microtopography of shrub mounds. However, at the lower site, IR was higher at the shrub patch than at the grass matrix because of greater upslope runoff input and higher infiltration capacity at the shrub patches. Preferential flow was not an important factor influencing water resource redistribution on the slope. Snow and ice were blown by wind and accumulated in shrub patches and their lees, resulting in higher water input to shrub patches than to the grass matrix during snowy years. Shrub encroachment changed the microtopography and soil properties under different canopy and slope positions, thereby affecting surface hydrological processes. The feedbacks between shrub encroachment and water infiltration varied across hillslope sites and influenced the development of shrub patches.

Key words: Infiltration; rainfall; meltwater; shrub encroachment

1 Introduction

Shrub encroachment has been a worldwide phenomenon for over 150 years in arid and semi-arid regions, referring to the increase in plant density, coverage, and biomass of shrubs in grassland ecosystems [?, ?, ?, ?, ?]. Climate change and erosion are believed to be the main drivers of this process [?, ?, ?]. Shrub encroachment redistributes light, heat, water, nutrients, and other resources, consequently altering net primary production, species diversity, and ecosystem functioning [?, ?, ?, ?, ?]. The encroached vegetation interacts strongly with the environment [?, ?, ?], and these feedbacks can promote further encroachment, potentially leading to a new long-term stable "climax community" [?, ?]. The characteristics of shrub patches are related to soil water content and local precipitation, with optimal shrub coverage increasing as water resources increase [?, ?, ?].

Positive interactions between shrub encroachment and water resources in shrub patches have been widely documented. [?, ?] reported that soil water content at 60 cm depth under shrub patches was higher than under grass matrix, which was attributed to different $CaCO_3$ horizon characteristics. Dye experiments with equal solution volumes revealed higher infiltration depths and more preferential flows under shrub patches [?, ?, ?], indicating greater infiltration capacity [?, ?, ?]. Shrub patches typically exhibit lower runoff rates than grassland [?, ?, ?, ?]. [?, ?] and [?, ?] also reported that steady-state infiltration and sorptivity were greater under shrub canopies than in open areas, with positive shrub effects attributed to reduced livestock trampling. [?, ?, ?] found that soil macroporosity and macropore volume in shrub patches exceeded those in grass patches and increased with shrub root network density, suggesting that water could transport to deeper soil layers in shrub patches [?, ?]. Shrub root channels were considered preferential pathways for water movement, allowing water to reach deep soil layers [?, ?, ?, ?, ?]. Conversely, [?, ?] modeled water fluxes between inter-patches and shrub mounds, finding that shrub mounds could directly obtain more water from rain, but overland flow from inter-patches could only reach the border of shrub mounds without inundating them. Since most previous infiltration and runoff studies were conducted under artificial conditions, how infiltration functions in shrub patches under natural precipitation, and whether effects are positive in different parts of shrub patches (center and edge) and at different hillslope positions, remain unclear.

Snow represents an important soil water input that influences infiltration and storage [?, ?, ?]. Meltwater can form macropore flow in rooted soil, effectively storing water for plants [?, ?]. In arid and semi-arid regions, snowmelt improves soil moisture, creates conditions for seed germination and growth, and profoundly impacts water competition within and between species as well as vegetation spatial patterns [?, ?]. Water resource redistribution affects vegetation productivity and distribution [?, ?]. In the Arctic, deciduous shrubs obtained more water from snow than grass during the growing season, and this meltwater-focused feedback loop could explain shrub expansion [?, ?]. Additionally, shrub encroachment has substantially altered grassland landscape patterns, local radiation balance, and snow cover physical characteristics [?, ?], further modifying local microclimate, runoff, and soil water conditions [?, ?, ?]. Shrub patch biomass and height exceed those of grass inter-patches in severely disturbed conditions [?, ?], enabling shrub patches to trap and retain more snow and meltwater [?, ?, ?, ?, ?]. However, how these effects manifest at different slope positions and under varying snow conditions in northern China requires further investigation.

Therefore, this study aims to (a) investigate infiltration characteristics under natural rainfall at different slope positions with shrub encroachment, and (b) evaluate the effects of meltwater infiltration on water resources in shrub patches. This research explores the relationships between encroached shrub patch development and infiltration patterns at different slope positions. The results are significant for explaining the spatial distribution characteristics of encroached shrubs and predicting their future development trends under changing climate conditions.

2.1 Study Site

This study was conducted in Taipus Banner, Inner Mongolia, China. The area belongs to the typical Eurasian Steppe and has a continental temperate semiarid climate, with mean annual temperature of 1.6 °C and mean annual precipitation of 392 mm [?, ?]. July is the hottest month (average 17.8 °C) and January the coldest (average -17.6 °C). Sixty-five percent of precipitation occurs from July to September. Average annual pan evaporation reaches 1900 mm, while average annual wind velocity is 3–5 m s^{-1} with 20–80 days of force-seven winds or above, mainly in spring and winter. The annual frost-free period is approximately 100 days, from late May or early June to early September.

Zonal soils are chestnut soil and light chestnut soil, equivalent to Calcicorthic Aridisol according to USDA Soil Taxonomy. Soil textures are primarily sand and sandy loam. Dominant plant species include *Stipa krylovii* Roshev., *Cleistogenes* *squarrosa* (Trin.) Keng, *Artemisia frigida* Willd., and *Leymus chinensis* (Trin.) Tzvel [?, ?]. *Caragana microphylla* Lam. expansion has increased in recent decades, with encroached grassland area exceeding 5.1 × 10^6 ha [?, ?] and shrub coverage reaching 40.1% [?, ?].

One *C. microphylla*-encroached hillslope was selected for this study [Figure 1: see original paper]. This west-facing slope is 128 m long with an average gradient of 12.5% [?, ?]. The slope was divided into four sites from ridge to valley: top, upper, middle, and lower [Figure 1: see original paper]. Shrub patch sizes were 3.93, 5.86, 5.84, and 7.68 m^2 at the top, upper, middle, and lower sites, respectively, with canopy heights of 0.43, 0.55, 0.47, and 0.41 m [?, ?]. Aboveground biomass of shrub patches at the four sites was 343, 400, 403, and 428 g m^{-2} from top to lower sites, respectively, while grass matrix biomass was 108, 140, 141, and 185 g m^{-2} [?, ?]. Canopy coverage of shrub patches was 93-95%, and grass matrix coverage was 68-75% during peak season [?, ?]. Rooting depths were 60-70 cm in shrub patches and 20-25 cm in the grass matrix [?, ?].

2.2 Soil Water Content and Temperature Measurement

Eight soil profiles were instrumented at the top, upper, middle, and lower sites (two per site) [?, ?]: one at the downslope edge of a *C. microphylla* shrub patch, and the other in the grass matrix approximately 1 m from the upslope edge of the shrub patch [Figure 1: see original paper]. Five ECH_2O 5TE sensors (Decagon Devices, Pullman, Washington, USA) were installed in each profile to monitor soil water content (, m^3 m^{-3}) and soil temperature (T , °C) at depths of 10, 20, 40, 60, and 100 cm. At the middle site, Decagon Drain Gauges replaced the 5TE sensors at 100 cm depth to detect soil water drainage [Figure 1: see original paper]. A total of thirty-eight ECH_2O 5TE sensors were installed across the four sites. All and T data, plus drainage where available, were logged at 10-minute intervals using 5-channel Decagon Em50 data loggers. These sensors provide accurate, precise, and continuous measurements with accuracy of \$±0.012m^{3}\$ m^{-3} for moisture and \$±\$0.3°C for temperature [?, ?, ?]. Experiments began on June 8, 2009, with data from July 1, 2009, or later used to account for profiling and sensor installation disturbance . Monitoring continued until May 16, 2011, at the top, upper, and lower sites, and until May 21, 2013, at the middle site .

2.3 Meteorological Observations

A Dynamet weather station (Dynamax Inc., Houston, TX, USA) was established at the slope center to measure meteorological data. Rainfall was measured using a tipping bucket rain gauge (Model TE525, Campbell Scientific, Logan, UT, USA). Air temperature (T , °C) was recorded with a temperature and humidity probe (Model CS500, Campbell Scientific, Logan, UT, USA) at 2 m above ground. Wind speed and direction were detected by a windvane and anemovane (Model 03001, RM Young Co., Traverse City, MI, USA) positioned at 3 m above ground. Snowfall data were obtained from the Taipus Banner Weather Station (41.88°N, 115.27°E, 1468.9 m a.s.l.).

2.4 Infiltration Ratios Estimation

Rain events were discretized using a minimum interevent time of 24 h. Soil water storage (SWS, mm) of a 1 m profile was calculated as:

$$SWS = \sum_{k=1}^{n} \theta_k \times D_k$$

where (m^3 m^{-3}) represents measured by 5TE sensors at soil layer k, D is the depth represented by (mm), and n represents the number of 5TE sensors in the 1 m profile. At the top, upper, and lower sites, n = 5, with D = 150, 150, 200, 300, and 200 mm for k = 1, 2, 3, 4, and 5, respectively. At the middle site, n = 4, with D = 150, 150, 200, and 500 mm for k = 1, 2, 3, and 4, respectively. Infiltration amount (I, mm) in a rainfall event was estimated as the maximum difference in SWS before and after the rainfall event (before the next rainfall). The infiltration ratio (IR) was estimated as the slope of linear regression of I against rainfall amounts during the experimental period [**?**, **?**].

2.5 Preferential Flow Detection

Preferential flow (PF) during natural precipitation was detected by analyzing response sequences of at different soil layers. Only events with >1 mm rainfall were analyzed, as smaller rainfall cannot infiltrate deeper than the first sensor. A response to rainfall was identified when its increase exceeded 0.01 m^3 m^{-3} during a rainfall event, based on sensor precision and noise levels of 0.01 m^3 m^{-3} [**?**, **?**]. PF was considered to have occurred when a deeper sensor responded before or simultaneously with a shallower sensor, or when a shallower sensor did not respond [**?**, **?**, **?**].

2.6 Meltwater Infiltration Estimation

When soil freezes, decreases as soil water transfers to ice. During frozen periods, soil water is protected from evaporation. After thawing, nearly returns to pre-freezing levels. Based on this assumption and ignoring evaporation during this period, meltwater infiltration was calculated as the difference between maximum

SWS before the first spring rain (after thawing) and SWS just before soil freezing in the previous winter [Figure 2: see original paper].

3.1 Precipitation and Wind Characteristics

Rainfall characteristics in the experimental area during the nearly four-year period (July 1, 2009, to May 21, 2013) are shown in [Figure 3: see original paper]. A total of 144 rainfall events (excluding snowfall) occurred, accumulating 904.71 mm. These were primarily short, small storms: 46 events (31.94%) were <1 mm, and 96 events (66.67%) were $ 5mm.Rainfallevents > 10mmaccountedforonly13.19^{-1}.Maximum10 − minuteintensityrangedfrom0.20to73.15mmh{-1}, withonly10.42^{-1}$ and only one exceeding the 63.23 mm h^{-1} infiltration rate of grass matrix at 0.5 mm suctions [?, ?]. Snowfall amounts were 39.5, 49.5, 29.1, and 45.1 mm during winters/springs of 2009–2010, 2010–2011, 2011–2012, and 2012–2013, respectively. Winter and spring winds were primarily from W, WSW, SW, and SSW directions, with speeds mainly ranging 2–10 m s^{-1} (average 5.2 m s^{-1}, maximum 18.8 m s^{-1}) [Figure 4: see original paper].

3.2 Rainfall Infiltrations

Rainfall infiltration varied by slope position and land cover. At the top, upper, and middle grass matrix sites, IRs were as high as 0.78$±$0.08, while at the lower grass matrix site, IR was only 0.47 [Figure 5: see original paper]. Shrub patch IRs increased from 0.38 at the top site to 0.77 at the lower site [Figure 5: see original paper].

Yearly total infiltration showed similar patterns [Figure 6: see original paper]. At the top and upper sites, grass matrix had higher yearly total infiltration than shrub patches, with greater differences at the top site. At the lower site, yearly total infiltration was higher at the shrub patch than at the grass matrix.

Yearly infiltrations in 2010 were available at all sites, ranging from 69.4 mm at the top shrub patch to 194.5 mm at the upper grass matrix. In 2011 and 2012, complete yearly data were available at middle sites. The 2011 yearly infiltration was 212.4 mm at the middle shrub patch—the maximum across all sites during the entire experimental period—and much higher than the 138.3 mm at the middle grass matrix. In 2012, yearly infiltration at the middle shrub patch was 123.1 mm, lower than the 155.6 mm at the middle grass matrix. From 2010 to 2012, mean yearly infiltration at the middle shrub patch was 152.1$±52.2mm, insignificantlyhigherthanthe143.4±$10.5 mm at the middle grass matrix based on two-tailed paired sample t-test (p=0.818).

PF ratios were only 4.1% and 2.4% at grass matrix and shrub patches, respectively , with 19 PF events recorded total. Most PF events occurred at 60 cm in grass matrix and 40 cm in shrub patches . Grass matrix had higher PF ratios than shrub patches. No PF events were recorded at top sites. At grass matrix, most PF events occurred at the middle site, followed by the lower site. At shrub patches, the highest PF ratios occurred at the middle site. All 19 PF events originated from different rainfall events, with rainfall depth ranging 1-37.85 mm, rain intensity 0.05–9.60 mm h^{-1}, and maximum 10-minute rainfall intensity 1.20–57.90 mm h^{-1}.

3.3 Meltwater Infiltrations

Meltwater infiltration varied across years [Figure 7: see original paper]. In snowless years (2009-2010 and 2011-2012), meltwater infiltration was low ($ $5 mm) except at the middle grass matrix site (6.3 mm), with no infiltration at shrub patches at both upper and lower sites. In these years, meltwater infiltration was higher at grass matrix than at shrub patches. In snowy years, meltwater infiltration was relatively higher, ranging 5.17-12.94 mm in spring 2011 [Figure 7: see original paper]. In snowy years, meltwater infiltration was higher in shrub patches than in grass matrix, except at the middle site in winter 2010–2011.

Meltwater infiltration was particularly high at the middle grass matrix and shrub patch in spring 2013 [Figure 8: see original paper]. Soil temperature dropped chronically below 0 °C from 1 a.m. and 6 a.m. on November 13, 2012, at the middle grass matrix and shrub patch, respectively. Before soil freezing, their SWS values were 137.6 and 102.91 mm, respectively. After soil freezing, no rainfall was recorded. As soil water transferred to ice, liquid successively decreased from 10 to 60 cm depth, gradually reducing liquid SWS of the whole profile. Positive soil temperature at 10 cm depth was first recorded at 4 p.m. on March 7, 2013, at the middle grass matrix, and at 12 a.m. on March 8, 2013, at the middle shrub patch. During these two days, air temperature increased rapidly, reaching 12.0 °C at 3 p.m. After soil temperature at 10 cm depth crossed the freezing point, increased quickly and successively at each soil layer. Liquid SWS of the whole profile surged rapidly at both sites, reaching 224.4 and 232.7 mm at 7 p.m. on March 8, 2013, respectively. Meltwater infiltration reached 86.8 mm at the middle grass site and 129.8 mm at the middle shrub site.

4 Discussions

Lower IRs and PF ratios at downslope edges of shrub patches compared to grass matrix (except at the lower site) relate to slope topography and sensor installation positions. Shrub patches form mounds that create raised micro-topography [FIGURE:1 and FIGURE:9] because shrubs protect ground from livestock trampling and erosion while accumulating wind and water sediment

[?, ?, ?, ?]. Under these conditions, upslope water flow first reaches the upslope edge of shrub mounds, where water primarily infiltrates or bypasses the mounds, leaving less water for downslope edges. The 5TE sensors were installed at downslope edges of shrub patches with relatively higher slope gradients [?, ?], generating more runoff and reducing infiltration. Therefore, shrub patch microtopography caused downslope edges to generate more local runoff while storing less upslope water, explaining the low IRs—consistent with [?, ?], who reported lower soil moisture at downslope edges compared to upslope edges after rainfall.

Higher IR at downslope edges of shrub patches at the lower site resulted from greater upslope runoff and abundant water flowing over or around shrub mounds to gather at downslope edges. Upslope runoff formed ponded water, increasing infiltration because shrub patches had higher infiltration rates [?, ?] and deeper infiltration under ponding conditions [?, ?, ?]. Additionally, the lower site shrub patch had the highest aboveground biomass and root depth, higher soil organic matter [?, ?], and more sand and silt [?, ?], generating more macropores and increasing infiltration [?, ?]. However, the lower grass matrix site had the lowest total infiltration among grass matrix sites, likely because more clay deposited there blocked macropores and reduced infiltration capacity [?, ?].

PF ratios at experimental sites did not exceed 5%, much lower than the 17-54% reported at the Shale Hills Critical Zone [?, ?]. This difference may relate to soil types and rainfall characteristics. Shale Hills Critical Zone soils formed from shale residuum and colluvium, which were poorly developed due to cold weather and contained abundant rock that enhanced PF formation. Our experimental sites had chestnut and light chestnut soils developed from aeolian sediment with relatively uniform texture throughout the profile, which is not conducive to PF formation. Another reason is the scarcity of heavy rainfall events. The most influential PF factors are water input amounts and peak input intensity [?, ?], with PF typically occurring when water input exceeds a threshold [?, ?]. As shown in [Figure 3: see original paper], rainfall >10 mm accounted for only 13.19% of events. Higher aboveground biomass at shrub patches [?, ?] also intercepted more rainfall, reducing net rainfall reaching the ground [?, ?]. Lower PF ratios in shrub patches thus connect to their low IRs, which equate to lower water input.

Meltwater infiltration originates from two sources: local snow/ice and upslope runoff. In snowless years, weak meltwater flow bypassed shrub mounds, allowing grass matrix to receive upslope meltwater while downslope edges of shrub mounds could not, resulting in lower meltwater infiltration at shrub downslope edges compared to grass matrix. In snowy years, snow and ice were trapped and retained on shrub patches and their lee sides. Strong meltwater flow from upslope and shrub mound tops reached downslope edges, increasing meltwater infiltration there [Figure 9: see original paper]. Due to higher infiltration capacity, shrub patches had greater meltwater infiltration. In typical years, meltwater infiltration did not exceed 15 mm, equivalent to about 20 mm of rainfall infiltration. However, in years with heavy snow, shrub patches retained substantial snow and ice. When spring weather warmed rapidly, the snow/ice stack melted quickly, generating flood flows over the slope [Figure 9: see original paper]. Compared to most years, this meltwater flow infiltrated more [Figure 7: see original paper] and reached soil layers of 60 cm or deeper [Figure 8: see original paper].

Meltwater infiltration increased in spring. In snowless years, increased only slightly and quickly dropped below pre-freezing levels. The effect period—when spring (before first rain) exceeded pre-freezing winter —was usually <10 days. In snowy years, increased substantially and the effect period typically lasted >20 days, continuing until vegetation greenup. Particularly in spring 2013, at middle grass and shrub sites remained above pre-freezing levels until the experiment ended, lasting >73 days. This increased from meltwater infiltration represents an important soil water resource in semiarid regions, greatly influencing vegetation sprout and regreening [?, ?, ?]. The heavy, deep meltwater infiltration in spring 2013 would significantly impact local vegetation growth [?, ?].

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5 Conclusions

Shrub patches retained more water resources at the lower hillslope site, and meltwater can be an important water resource for shrub patches during snowy years. Preferential flow may not be an important factor influencing water resource redistribution on the slope. Downslope edges of shrub patches retained lower rainwater resources than grass matrix at top, upper, and middle sites. These downslope edges at middle, upper, and top sites would degrade due to insufficient water resources, while upslope edges would expand toward the slope top. However, as shrub patches expand upslope, runoff resources and their IRs decline. Thus, shrub patch size would stabilize when degradation and expansion balance. Shrub patches at the lower site would expand in all directions and achieve larger sizes because they can retain more water resources.

Data availability. No data sets were used in this article.

Author contributions. XYL and SYZ conceived the study and developed the storyline. XYL, SYZ, ZHZ, and ZYJ conducted the experiments. SYZ analyzed the data. SYZ, ZHZ, and ZYJ wrote the initial manuscript. DF, BH, and YCZ reviewed and improved the text.

Competing interests. The authors declare no conflict of interest.

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Table:

Table 1 Preferential flow (PF) characteristics of different sites.

Sites	Period	Begin	Rain events	PF events	PF ratio (%)
			Total	>1 mm	20 cm
Top grass	Jul. 1, 2009–May 16, 2011	684	163	0	0
Top shrub	Aug. 1, 2009–May 16, 2011	653	163	0	0

Sites	Period	Begin	Rain events	PF events	PF ratio (%)
Upper grass	Jul. 1, 2009–May 16, 2011	684	163	1	0
Upper shrub	Jul. 17, 2009–May 16, 2011	668	163	1	0
Middle grass	Jul. 1, 2009–May 21, 2013	1420	163	4	1
Middle shrub	Jul. 1, 2009–May 21, 2013	1420	163	2	0
Lower grass	Aug. 1, 2009–May 16, 2011	653	163	2	0
Lower shrub*	Jul. 1, 2009–May 16, 2011	543	163	1	0

*Missing period: Nov. 1, 2009–Mar. 21, 2010

Figures:

Figure 1 Diagrammatic sketch of the experimental hillslope with *C. microphylla* patches interspersed in sparse grass matrix, and sites for soil moisture sensors and meteorological tower instrumentation.

Figure 2 Meltwater infiltration estimation. Soil water storage (SWS, black line) and soil temperature (red line) crossing soil frozen and the first rain after soil thawed are shown. The red dash line shows 0 °C. Black dot lines show the frozen soil period. The green dot line shows SWS just before soil frozen and thawed. The blue dot line shows the maximum SWS after soil thawed and before the first rain.

Figure 3 Characteristics of rainfalls at the experimental area from July 1, 2009, to May 21, 2013. The grey solid line shows the density of rainfall amount and the grey vertical lines show the occurrence of rainfall events; yellow columns show the count of rainfall events; the blue dash line shows the cumulative percent of rainfall amount; the blue bubbles show rainfall amount, rainfall duration, and their sizes show rainfall intensity.

Figure 4 Wind speeds and direction in January, February, March, November, and December of the experimental period at 3 m above the middle of the slope.

Figure 5 The relationships between changes in soil water storage (ΔSWS) and rainfall amounts (P).

Figure 6 Yearly rainfall infiltration at different sites in 2009 and 2010. Rainfall infiltration in 2009 were since July 1 except the top shrub site and the lower grass site, which were since August 1, 2009.

Figure 7 The meltwater infiltration at different sites and periods.

Figure 8 Meltwater infiltration at the middle site in the period of 2012–2013. (a) Rainfall and air temperature (T) at 2 m above ground; (b) soil water storage (SWS) and soil temperature at 10 cm depth at the middle shrub site; (c) soil water content ( ) at 10, 20, 40, and 60 cm depth at the middle shrub site; (d) soil water storage (SWS) and soil temperature at 10 cm depth at the middle grass site; (e) soil water content ( ) at 10, 20, 40, and 60 cm depth at the middle grass site.

Figure 9 Photo of meltwater flow on the slope. Photo taken on March 7, 2011. Snow and ice were retained at the lee side of the shrub patch and melted on the south side first. Note that snow and ice were present on the shrub mound earlier than this photo, melting earlier because shrub stems had lower albedo and absorbed more radiation. Photo courtesy of Si-Yi Zhang.

Note: Figure translations are in progress. See original paper for figures.