Shrub Hydropedology: Preferential Water Availability to Deep Soil Layer

The complex interactions between shrub traits, soil structure, and soil water dynamics are not well understood yet. This study investigated rainfall partition by *C. microphylla* L., spatial soil water pattern, soil hydraulic conductivity, and soil macropores to ascertain preferential water flow to deep soil layer by shrub. Results indicated that high variability in throughfall existed within individual shrub stand: average coefficient of variation was 0.36 ± 0.13 for shrub and 0.15 ± 0.13 for interspace grass. Throughfall was less at the center of the shrub patch (30–60% of rainfall) than the outward positions at the edges of the canopy (70–90% of rainfall). Soil water responded differently to rainfall, soil depth, and vegetation type and showed high variability within shrub patches and on the slope. Greater and deeper infiltration was observed beneath *C. microphylla* L. canopy than interspaces grass after rainfall with large amount and high intensity, suggesting that macropore flow dominated in shrub patches. X-ray CT showed that macroporosity was over six times greater in soil under *C. microphylla* L. than interspace grass. Soil hydraulic conductivity for shrub at saturation and the pressure heads of −30, −60, and −150 mm were 3, 2, 2.5, and 2 times those of grass, respectively. Shrub patches had a significant lower bulk density and higher porosity than grass patches at the top 0- to 30-cm depth. Soil hydraulic conductivity was significantly correlated to organic matter content, total N, bulk density, and porosity. This study suggests that rainfall partition by shrub’s canopy and subsurface soil macropores induced by root architecture results in preferential water flow into deep soil layer, which might favor competitive advantages for water by shrubs under arid conditions.

**Abbreviations**: SWC, soil water content.

**Hydropedology is a new emerging interdisciplinary science** that focuses on synergistic integration of pedology with hydrology to enhance the holistic study of soil–water interactions and landscape–soil–hydrology relationships across space and time, aiming to understand pedologic controls on hydrologic processes and properties as well as hydrologic impacts on soil formation, variability, and functions (Lin, 2003, 2010; Kutílek and Nielsen, 2007; Lin et al., 2008). The interdisciplinarity of hydropedology, according to Kutílek and Nielsen (2007), is associated to the interaction among pedology, soil micromorphology, soil hydrology, environmental protection, and plant physiology.

Biota has been recognized as an important factor on the genesis and hydrological processes of soils; however, until now there was a lack of studies on coupling pedology and plant–soil–hydrology. We are still at the early stages of understanding how to describe the many processes influencing flow and transport when plants are present (Jury et al., 2011). How subsurface biota are controlled by and yet also influence hydrologic processes is a frontier area of hydropedology and ecohydrology research (National Research Council, 2012). Previous studies indicated that soil properties, including parent texture, soil depth, calcium carbonate accumulation, and argillic horizon development, have strong influences on water, nutrient, and recruitment strategies available to plants (Hamerlynck et al., 2000; Maestre et al., 2003; Bestelmeyer et al., 2006) and often vary at several spatial scales (Scull et al., 2003), but the role of soil heterogeneity in the patterning of soil water and vegetation distribution is poorly documented (Bestelmeyer et al., 2006). Knowledge gaps still exists how to relate complex heterogeneity of spatial plant pattern and soil architecture to soil hydrological processes within the vadose zone at various scales.

Shrubs are the dominant vegetation of the world’s extensive arid and semiarid regions and can play key roles as ecosystem engineers by altering the physical and biological soil environment beneath their canopies as well as the characteristics of plant populations,
communities and ecosystems (McKell, 1975; Hunter and Aarsen, 1988; Callaway, 1995; Scholes and Archer, 1997; Wright et al., 2006; Shachak et al., 2008; Lev-Yadun et al., 2009; Cushman et al., 2010). Shrub patches are usually patterned and interspersed in herbaceous plant or bare soil matrix (Aguiar and Sala, 1999). Patterns reported include gaps, labyrinths, stripes (“tiger bush”), and spots (“leopard bush”), which occur in semiarid and arid regions of Africa, Asia, Australia, North America, and China (Aguiar and Sala, 1999; Rietkerk et al., 2004; Li et al., 2013). Shrub patches and bare ground couple together in a landscape mosaic of sources and sinks of water, sediments, and nutrients (Reynolds et al., 1999; Wilcox et al., 2003). Shrub patches are characterized by greater water storage capacity, increased soil organic carbon, larger nutrient inputs, greater soil biological activity, and higher net primary productivity than the adjacent intercanopy area (Puigdefàbregas, 2005), leading to the so-called “fertility islands” (Schlesinger and Pilmanis, 1998), “resource islands” (Reynolds et al., 1999), and “hydrologic islands” (Rango et al., 2006). D’Odorico et al. (2007) have reported that there is a positive feedback between soil moisture and woody vegetation establishment and that the contrast between the soil moisture beneath the canopy and interspace increases (with wetter soils under the canopy) with increasing levels of aridity. Bestelmeyer et al. (2006) stated that woody plant dynamics and self-organizing processes perhaps might also be constrained by subtle (and often unrecognized) soil heterogeneity, and they found that the probability that patches were presently vegetated or bare over a 60-yr period was negatively related to surface calcium carbonate and positively related to subsurface clay content. Li et al. (2009) demonstrated important connection between aboveground stemflow and belowground preferential flow in desert shrubs, revealing important interrelationships between hydropedology and ecohydrology and how soil moisture and plant growth influence each other.

In general, previous studies mainly focus on ecohydrology of shrub encroachment into grassland emphasizing the role of variation in climate and grazing pressure (see review by D’Odorico et al. 2011 and Eldridge et al., 2011). Beyond these factors, feedback processes between shrub traits and soil structure may play an important role that is not well understood yet. Shrub has a great effect on soil structure and soil water distribution at scales of individual plant, patch, slope, and watershed (Li, 2011; Li et al., 2012). The aboveground shrub canopy not only serves as an umbrella to protect soil against the impact of rain drops but also can affect rainfall partition leading to heterogeneous input of rainwater and solutes and therefore influence spatial and temporal distribution of soil water content and soil nutrient status (Levia and Frost, 2003; Johnson and Lehmann, 2006). Increased input of matter and water in throughfall, canopy drip, stemflow, or litter would induce concentration of elements in surface horizons through biocycling (Levia and Frost, 2003). Meantime, the belowground roots also affect soil architecture, subsurface flow, and soil fertility through accumulation of organic matter, preferential flow and leaching along root channel, stabilization of soil aggregates, and protection of soil surface against erosion (Li et al., 2009, 2013; Johnson and Lehmann, 2006). Unlike abiotic factors (e.g., soil texture and rainfall regime), the control exerted by composition and structure of shrub community on soil moisture variability and their resultant effects on soil structure and hydraulics remains poorly understood (D’Odorico et al., 2007). There are few empirical studies available that are able to ascertain the degree to which shrub pattern formation and dynamics are constrained by underlying soil architecture and geomorphic context, and the specific soil and hydraulic attributes mediating vegetation change are rarely addressed (Bestelmeyer et al., 2006). Therefore, we used C. microphylla L. in the Inner Mongolia grassland as indicator shrub to investigate characteristics of water flow into the vadose zone from the perspective of hydropedology. The specific objectives of this study were to: (i) explore rainfall partition by canopy of C. microphylla L. shrub and its impact on heterogeneity of soil water content; (ii) relate spatial patterning of shrub to soil moisture distribution on the slope catena; (iii) investigate effects of shrub on soil architecture by X-ray computed tomography and soil hydraulic conductivity; and (iv) discuss preferential water flow to deep soil layer associated with architecture of the aboveground shrub canopy and belowground soil macropore structures.

Materials And Methods

Study Area

This study was conducted at the Farmland and Grassland Ecosystem Observation Station of Beijing Normal University (42°07′59.2″N, 115°26′31.5″E), located in Taipus Banner, Inner Mongolia of North China. This area belongs to the Inner Mongolia grassland, which are representative of the Eurasian steppe region. The grassland is quite different from North American prairies and African savannas in terms of climate, soils, and dominant plant functional types, despite of some taxonomical similarities at the levels of genera and families (Bai et al., 2008). In the typical steppe ecosystem of the Inner Mongolia grassland, C. microphylla L. shrub expansion due to grazing increased during recent decades, forming landscape characterized by a mosaic of shrub and grass patches (Li et al., 2013) (Fig. 1). It is estimated that area of C. microphylla L. encroached grassland amounted to more than 5.1 × 10⁶ ha (Zhou, 1990; Zhang et al., 2006a).

The study area has continental temperate semiarid climate. Based on 55-yr meteorological records, mean annual precipitation is approximately 392 mm with 65% occurring from July to September. Mean annual pan evaporation amounts to 1900 mm. Mean annual temperature is 1.6°C with a maximum monthly temperature of 17.8°C (July) and a minimum monthly temperature of −17.6°C (January). The zonal soils are chestnut soil and light chestnut, which are equivalent to Calcare Orthic Aridisol according to USDA Soil Taxonomy. In the soil profile, calcite resulting from the dissolving and leaching of CaCO₃ by rainwater is
commonly found in the form of either nodules or layers. Depth of the calcic deposits varies from near the surface to a depth of a meter or more. Soil textures were mainly sand and sandy loam. The dominant plant species found in the natural steppe were Caragana microphylla C. microphylla L. We selected Leymus chinensis L. encroached grassland as experimental sites, which are characterized by mosaics of alternate shrub and grass patches (Fig. 1). For the shrub patches, many annual grasses, including Stipa krylovii Roshev., Cleistogenes squarrosa (Trin.) Keng, Artemisia frigida Willd., and Leymus chinensis (Trin.) Tzvel (Qiu et al., 2011; Li et al., 2013).

Rainfall Partition by Shrub Canopy

We selected C. microphylla L. encroached grassland as experimental sites, which are characterized by mosaics of alternate shrub and grass patches (Fig. 1). For the shrub patches, many annual grasses, including Stipa krylovii Roshev., Cleistogenes squarrosa (Trin.) Keng, Artemisia frigida Willd., and Salsola collina Pall., were growing under the canopy of the C. microphylla L. shrub. Interspace patches had significantly greater coverage of shrub patches amounted to 21% in the study area. The size of interspace grass patches was 2.4 times greater than that of shrub patches, which ranged from 1.13 to 3.75 m² (Li et al., 2013). Total aboveground biomass was 2 to 3 times higher for the shrub patches than the interspace (Li et al., 2013).

Four C. microphylla L. stands were chosen to measure throughfall and stemflow during rainy seasons (May to September) in 2011. Throughfall was collected using plastic containers. Throughfall was measured automatically with a tipping bucket rain gauge (Model TE525) with a data logger (CR1000, Campbell Scientific) recording data at 10-min intervals. We used the same procedure as C. microphylla L. to measure throughfall for interspace grass.

Soil Water Measurements and Soil Property Analysis

Three complementary experiments were conducted to investigate the effect of C. microphylla L. on spatial and temporal soil water dynamics. Experiment I was to ascertain temporal soil water dynamics and infiltration amount beneath canopy of C. microphylla L. as compared with interspace grass at point scale. We installed eight ECH2O 5TE sensors (Decagon Devices) to continuously measure soil water content during rainy seasons of 2011 (Li et al., 2013). Two soil profiles were instrumented: one was beneath C. microphylla L. shrub canopy and the other was in the interspaces grass, approximately 1 m from the upside edge of the C. microphylla L. canopy. Four 5TE sensors were installed in each soil profile to monitor soil moisture at the soil depths of 10, 20, 40, and 60 cm, and a Decagon’s EM50R logger (a five-channel, self-contained data recorder) was used to record data at 10-min intervals. Infiltration amount into a certain soil layer during a rainfall event was calculated as:

\[ I(i) = (\theta_{\text{max}}(i) - \theta_0(i)) \times D(i) \]  

where \( I(i) \) is infiltration amount (mm) of the \( i \)th soil layer, \( \theta_{\text{max}} \) is the maximum volumetric water content (m³ m⁻³) of the \( i \)th soil layer after rainfall event, \( \theta_0 \) is the volumetric water content (m³ m⁻³) of the \( i \)th soil layer preceding the rainfall event, and \( D(i) \) is the depth of the \( i \)th soil layer (mm) over which the measurements were made. During the experimental period, no infiltration was observed in soil layers below 40 cm.

Experiment II was to examine variability in soil water within shrub patches as compared with grass patches after rainfall and during drought period at patch scale. We measured gravimetric soil water content (SWC) after a series of rainfall events with different amount and during dry spells of 8 to 15 d. Each soil water measurement was made under different C. microphylla L. stands for fear of repeated disturbance by soil excavation. Soil samples for measuring gravimetric SWC were taken in five points across the edges of the shrub canopy and three points for the adjacent grass patches. Soil sampling depths were 0 to 10 cm, 10 to 20 cm, 20 to 30 cm, 30 to 40 cm, 40 to 50 cm, and 50 to 60 cm at 10 cm segments.

Experiment III was to explore soil water pattern at the slope scale, and we measured surface volumetric soil water (0–10 cm) by FDR
probes at 1-m intervals along 50-m transects immediately after rainfall events characterized by different amount and intensity. Measurement locations were designated as either shrub or grass, depending on the presence or absence of standing shrub canopy above the sample location. Mean and variance were calculated separately for shrub canopy and interspace grass, we used F-tests to compare mean and variance values.

Soil samples for property analysis under shrub and grass patches were collected at depths of 0 to 10 cm, 10 to 20 cm, 20 to 40 cm, and 40 to 60 cm. They were air-dried and then sieved to pass a 2-mm screen. For grain size distribution, sand fraction (2000 to 50 μm) was measured by sieving, and the silt (50–2 μm) and clay (<2 μm) fractions were determined by the pipette method. Organic carbon content was determined by the method of Walkley and Black (1934) and converted to organic matter content by multiplying by 1.72. Total nitrogen content was determined by the Kjeldahl method (Bremmer and Mulvaney, 1982), and total phosphorus was determined by the Bray-1 procedure (Olsen and Sommers, 1982).

**X-Ray Computed Tomography for Soil Macroporosity**

Soil cores for X-ray computed tomography were sampled at the center beneath *C. microphylla* L. canopy and interspace grass in August 2012. There was one core for shrub and one for grass. Plexiglas cylinders with 4-mm wall thickness, 10-cm diameter, and that were 50 cm long were used to house intact soil. The aboveground grass and *C. microphylla* L. were clipped to ground level and litter was completely removed to expose bare soil before soil sampling. To protect the samples during transport from field to laboratory, cores were placed in sealed plastic bags and were wrapped carefully with sponge and packed with wheat straw.

A GE HISPEED FX/I Medical Scanner (General Electric Company), a 64 slices spiral CT, was used to scan soil cores at an energy level of 120 kV and 300 mA with 0.625-mm scanning interval. The GE HISPEED FX/I Medical Scanner was an advanced high-speed medical X-ray based three-dimensional scanning system, developed as an area detector scanner employing flat panel amorphous silicon arrays. The procedures for CT image analysis and thresholding for getting the binary images and macroporosity are listed in Fig. 2. The CT scanning images were cut to exclude the area outside the soil column, and the edge of each soil column was also cut to eliminate any possible artificial features along the edge using ImageJ version 2X computer software package. The thresholding for getting the binary images was determined by an artificial macropore using plexiglas cylinders with already known diameter inserted within the disturbed soil core, which was also scanned by CT. First we assumed one threshold value for the thresholding sample and calculated the macropore size on the basis of the image analysis using ImageJ version 2X computer software, and we compared it with authentic size. If the difference between them was too large, then we selected another threshold value until the difference was reduced to less than 1% (Fig. 2). Second, we used this threshold value to translate CT images into binary images with black and white color indicating macropores and soil matrix, respectively. After thresholding, the macroporosity was obtained as the volume fraction of pores using ImageJ.

**Soil Hydraulic Conductivity Measurements**

We measured unsaturated and saturated hydraulic conductivity of soils beneath both *C. microphylla* L. canopy and interspace grass. Tension disc infiltrometer with a 20-cm baseplate (Plexiglas infiltrometer model SW 080B) was used to measure unsaturated hydraulic conductivity \([K(h)]\) at pressure heads \((h)\) of −30, −60, and −150 mm [referred to as \(K(30), K(60),\) and \(K(150)\), respectively]. There were four replicates for both shrub and interspace grass sites. Measurements of \(K(h)\) were made in accordance with procedures outlined by Ankeny (1992). Before measurements, vegetation was clipped to ground level and litter was completely removed to expose bare soil. The soil was then carefully leveled with minimal disturbance to facilitate infiltration measurements while maintaining the native pore structure. At each site, a sharpened ring was inserted a few millimeters into the soil and a thin (5 mm) layer of moist contact sand was then applied to the ground surface and leveled. Then tension infiltrometer measurements were done from low to high tension until steady state (Wilcox et
al., 2003; Li et al., 2008). The relationship developed by Ankeny et al. (1991) was used to calculate the hydraulic conductivities at different tensions.

Saturated hydraulic conductivity ($K_s$) was determined by the constant hydraulic head method in the laboratory (Klute and Dirksen, 1986; Jury and Horton, 2004). Surface soil cores (61 mm in diameter and 40 mm long) were sampled at the center below *C. microphylla* L. canopy and interspace grass patches. There were three soil cores for shrub and three for grass. Intact saturated soil cores were fixed within a Guelph permeameter, supplied with water at the top, using a Marriote bottle to maintain a stable hydraulic head and measuring the volume of water that flowed through the soil. Stable $K_s$ values were calculated by averaging the last five values until the differences were less than 5% for individual 10-min intervals (Li and Shao, 2006). $K_s$ was then calculated using following Eq. [2]:

$$K_s = \frac{Q \times L}{A \times t \times \Delta H}$$

where $K_s$ is the saturated hydraulic conductivity (mm h$^{-1}$), $Q$ is the water volume (ml), $L$ is the length (cm) of the soil core, $A$ is the cross-sectional area of the soil core (cm$^2$), $t$ is the time (min), and $\Delta H$ is the difference in hydraulic head across the soil column (cm).

**Results and Discussion**

**Rainfall Interception, Throughfall, and Stemflow**

Partition of precipitation by vegetation canopy comprises three fractions: (i) interception, which is retained on the vegetation and is evaporated after or during rainfall, (ii) throughfall, which reaches ground by passing directly through or dripping from tree canopies, and (iii) stemflow, which flows to the ground via trunks or stems (Crockford and Richardson, 2000). Throughfall measured beneath canopy of *C. microphylla* L. stand and interspace grass patch at 50 by 50 cm grids indicated that high variability in throughfall existed within individual shrub stand, while grass had a relative uniform distribution (Fig. 3). Average coefficient of variation was $0.36 \pm 0.13$ for shrub and $0.15 \pm 0.13$ for grass. Throughfall was less at the center of the shrub patch (30–60% of rainfall) than the outward positions near the edges of the canopy (70–90% of rainfall), while throughfall ranged from 60% to 100% of rainfall for the interspace grass. The magnitude of spatial variability decreased with increasing rainfall amount (Fig. 4). High variability in throughfall implies that shrub canopies can result in spatial heterogeneity of the net rainwater input into the soil and affect subsequent soil water dynamics as compared with grass. Average incident throughfall and stemflow increased with increasing rainfall depth and followed a positive linear function (Fig. 5). Average percentage of throughfall and stemflow were 76.04% and 3.11%, respectively for shrub, while throughfall accounted for 92.12% of rainfall for interspace grass.
Spatial Patterns of Soil Water Content Distribution at Different Scales

At the point scale, soil water dynamics with high resolution measurements at 10-min intervals beneath *C. microphylla* L. canopy in the study site was studied in detail by Li et al. (2013), who found that soil moisture was not always greater in shrub patches than in the interspace grass patches but was strongly affected by precipitation size and calcic layers. Soil water content within the top soil layer of grass responded more rapidly to rainfall as compared with shrub where water content was often increased below 40 cm (Li et al., 2013). In this study, no responses of soil water at varying soil depths (10–60 cm) were detected for rainfall events less than 5 mm. During the experimental period, nine rain events larger than 5 mm with a total amount of 106 mm were well recorded; others were not included because of sensor damage. Infiltration beneath *C. microphylla* L. canopy and adjacent interspace showed that 107.3 mm of water infiltrated beneath the shrub canopy and only 57.8 mm infiltrated in the adjacent interspace grass, or approximately 101% and 55% of measured precipitation, respectively (Fig. 6). This agrees with findings of Bhark and Small (2003), who had reported approximately 140% and 68% of precipitation infiltrated in soil beneath shrub canopy and interspace grass in shrub land of central New Mexico. Figure 6 also shows that infiltration is quite different for three 6.6-mm rainfall events, of which no infiltration occurs for shrub when rainfall intensity is less than 5 mm h⁻¹, suggesting that more infiltration in shrub patches than grass was mainly attributed to overland flow during rainstorm from upside interspace grass patches (Reynolds et al., 1999; Wilcox et al., 2003; Puigdefábregas 2005). Field runoff measurements indicated that runoff efficiency averaged 20% in the interspace grass plots, about 2.3 times of that in the shrub plots (Peng, 2012). Infiltration in the shrub patch was significantly correlated to rainfall amount (correlation coefficient was 0.84) and antecedent soil water content (correlation coefficient was −0.91) at the 0.05 level, while infiltration in the interspace grass was only significantly correlated to rainfall amount (correlation coefficient was 0.92) (Fig. 6).

At the patch scale, greater variability in soil water content existed within shrub patches: average coefficient of variation was 0.13 ± 0.05 for shrub and 0.08 ± 0.04 for grass. Moreover, soil water content tended to be higher at the center position near stem than the adjacent area under canopy because of point recharge by stemflow (Bhark and Small, 2003). Shrub responded differently to rainfall and soil depth as compared with interspace grass. Although no significant differences in soil water content were found between shrub...
and grass, for the rainfall events of 6 mm, 9 mm, and 11 mm, shallow soil water content (0–10 cm) was higher for grass than shrub but vice versa for the deep soil water (20–60 cm) (Fig. 7). However, in the case of rainfall events of 23.4 mm, soil water content in the surface layer (0–10 cm) was higher in shrub patches than in grass patches but no significant contrasts at the deep soil layers (10–60 cm) (Fig. 7). Soil water content was not obviously greater for shrub than grass at the patch scale as compared with infiltration at the point scale in Fig. 6, which was mainly attributed to the following possible reasons: (i) higher evapotranspiration for shrub than grass would consume more water although infiltration in shrub soil was high (Peng et al., 2013), (ii) rainfall events with low amount and intensity could not produce runoff for shrub but intercept more water by shrub canopy than grass, and (iii) higher variability in soil water in shrub patches because of different individual plants and varying soil profiles. This would increase the variance, which is not reflected by the single profiles shown in Fig. 6. These suggest that interactions between shrub and soil water dynamic are complex and need further detail study in the future.

Similar trend in surface soil moisture was observed in the slope (Fig. 8). Soil water was significantly greater beneath *Caragana microphylla* L. canopies than interspaces grass under rainfall events of 12.5 mm ($F = 5.98, p = 0.018$) and 29.7 mm ($F = 13.53, p = 0.001$) but vice versa for rainfall event of 0.8 mm ($F = 10.26, p = 0.002$). Moreover, soil moisture tended to be higher on the upper position of the shrub patches. The center of the shrub patch was characterized by high soil water content under large rainfall but low soil water content under small rainfall (Fig. 8). This conforms to results of spatial distribution of throughfall (Fig. 3) and stemflow. Peng (2012) had reported that threshold values were 0.5 mm and 1.0 mm for throughfall and stemflow, respectively for *C. microphylla* L.; therefore, more rainfall was intercepted by shrub canopy resulting in lower soil water for shrub patches than grass under small rainfall events. However, for the rainfall events with larger amount, on the one hand, more throughfall and stemflow input and less runoff was produced from the shrub patch resulting in more infiltration into soil; on the other hand, more additional runoff from interspace grass could run on shrub patch.

**Macropore Characteristics of Soil by X-Ray Computed Tomography**

By means of X-ray computed tomography, we found that mean macroporosity of the soil column beneath *C. microphylla* L. shrub canopy was 3.61 ± 5.74% (mean ± SD), which was over six times of that of the interspace grass (0.62 ± 1.37%). The total surface areas, macropore perimeter, macropore number, and mean macropore size were 1902.33 cm$^2$, 2.15 × 10$^4$ cm, 2.24 × 10$^5$, and 1.996 mm, respectively for soils under *C. microphylla* L. canopy, which were about 6.92, 3.69, 3.0, and 1.6 times higher than those of grass soil.
Figure 9 shows vertical distribution of macroporosity at 0.625 mm intervals in the soil column. It is evident that grass has more soil macropores in the top soil; however, larger quantity of macropores are distributed in the deep soil for shrub. For the grass patch, macroporosity showed a rapid decrease from 0 to 22 mm soil depth and then was relatively stable at soil depth between 22 and 400 mm. In contrast, macroporosity for shrub patch increased quickly from 99 mm to the soil depth of 122.5 mm and then decreased sharply to the soil depth of 135 mm. Macroporosity remained stable at soil depth between 135 and 400 mm and then increased below the 400-mm soil depth. The peak of the macroporosity curve corresponded well with positions of abundant roots (Fig. 9). Higher macroporosity for *C. microphylla* shrub than grass suggests that more water could be easily concentrated on the deep soil layer by preferential flow through macropores. However, macroporosity was influenced by many factors such as vegetation and soil types, terrain, soil fertility, and organism; one soil core for each vegetation and high variability in macroporosity in the current study would just reflect local feature. Complex interactions between macropore structure and shrub traits need further detail study.

**Soil Hydraulic Conductivity and its Relations to Soil Properties**

There were no significant differences in organic matter content and total N between grass and shrub at the top surface soil (0–10 cm); however, organic matter content and total N were significantly higher in shrub patches than grass patches in the subsurface soil layers (10–60 cm) (Table 1). The shrub patches had a significant lower bulk density and higher porosity than the grass patches at the top 0- to 30-cm depth, and this trend also agreed with the values of 30 to 60 cm, though no significant differences were found. Shrub patches had lower sand content and higher silt and clay content than grass patches, but the difference was not statistically significant except clay content. Differences in clay content were striking, as average clay content was 4.5% for grass patches and 25% for shrub patches, which was in part attributed to overland flow and
Table 2. Hydraulic conductivity (mean ± SD) (mm h⁻¹) for shrub and interspace grass patches.

<table>
<thead>
<tr>
<th>Vegetation types</th>
<th>$K_s$</th>
<th>$K(30)$</th>
<th>$K(60)$</th>
<th>$K(150)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass</td>
<td>31.06 ± 0.25b</td>
<td>20.76 ± 4.7b</td>
<td>9.91 ± 1.18b</td>
<td>4.25 ± 0.40b</td>
</tr>
<tr>
<td>Shrub</td>
<td>95.53 ± 22.77a</td>
<td>28.45 ± 1.87a</td>
<td>24.62 ± 1.30a</td>
<td>9.58 ± 9.58a</td>
</tr>
</tbody>
</table>

† Values in columns within same column followed by the same letter means no significant difference between shrub and grass at $p = 0.05$ level.

Determining $K$ at different tensions allows one to estimate the relative importance of macropores to the movement of water into and through the soil (Mohanty et al., 1994; Wilson and Luxmoore, 1988; Wilcox et al., 2003). We consider the difference in infiltration between saturate conditions and a tension of 30 mm as representing macropore flow and the difference in infiltration between tensions of 30 and 150 mm as representing mesopore flow. Therefore, the above results demonstrated that macropore flow was the preferential infiltration into the vadose zone of the shrub patches.

Correlation analysis in Table 3 shows that $K_s$ and $K(h)$ are significantly and positively correlated to soil organic matter, total N, and porosity but negatively correlated to bulk density. A significant decrease in bulk density with an associated increase in total porosity of soil under shrub canopy is probably related to greater amount of organic matter deposition and loosening of soil by root action (Lampurlanes and Cantero-Martinez, 2003).

**Shrub Control on Water Infiltration and Implications**

Results of this study demonstrated the effect of biotic processes induced by C. microphylla L. shrub on soil hydrologic processes. Shrub canopies resulted in spatial heterogeneity of the rainwater...
input by throughfall and stemflow, and higher and deeper infiltration existed beneath shrub canopy under large rainfall as compared with interspace grass, which corresponded well with higher macroporosity and soil hydraulic conductivity for soils in shrub patches. The shrub’s preferential water flow into the deeper soil layer is the result of coupled biological–pedological dynamics, and it stems from the ability of vegetation to actively engineer the soil architecture and properties. The biotic functions of *C. microphylla* L. shrub on hydropedological processes might be listed as follows.

1. Aboveground, shrub canopies interact with rainfall to influence soil structure by reducing raindrop impact and patterns of soil water and temperature through interception and shading the soil surface (Dunkerley, 2000; Li et al., 2013).

2. Plant litter accumulation, faunal burrowing, bioturbation, and root turnover operate concurrently to form “fertility island” (Schlesinger and Pilmanis 1998), which has higher organic matter content, total N, porosity, and lower bulk density, ensuring high water holding capacity and infiltrability. Moreover, *C. microphylla* L., a leguminous deciduous C₃ shrub, can fix atmospheric N (Liu et al., 2004). The higher N content of the soil under the shrubs is likely to give shrubs a competitive advantage over the grasses in times when nutrient availability is reduced.

3. Belowground roots can increase porosity and form macro-pore flow paths that enhance infiltration and drainage, and ultimately aeration (Feeney et al., 2006; Li et al., 2009). Germann et al. (2012) reported that infiltration improved with increasing root density up to a maximum of about 7500 m m⁻³. In the present study, Fig. 10 shows that grass roots mainly distribute in the shallow soil layer (0–40 cm), but *C. microphylla* L. shrub roots mainly distributed in the deep soil layers (20–120 cm). In the case of grass, 78% roots distributed in the 0- to 20-cm soil depth. In contrast, 71% of roots distributed in the soil depth of 20 to 120 cm for shrub, implying that *C. microphylla* L. root architecture contributes to preferential water flow to the deep soil.

4. Shrub patches can trap sediments carried by overland flow and wind, resulting in higher clay content in the soil under shrub canopy, which may have a direct effect on microbial communities because soils with higher clay content have the capacity to preserve or protect the microbial biomass (Gallardo and Schlesinger, 1992). Moreover, the runoff from interspace grass areas may infiltrate in shrub patches (Reid et al., 1999).

Our infiltration data and observations during rainfall events suggest that lateral redistribution of water via surface runoff is the key process underlying the higher infiltration under shrub canopy. In the study area, 12% rainfall events are larger than 10 mm, but they contribute more than 50% of the total rainfall amount. Because the size of the interspace grass patches was 2.4 times greater than the shrub patches in the study site (Li et al., 2013), we expect that runoff water from the grass patches would be caught by the shrub...
The present study shows complex interactions between vegetation, soil structure, and soil water dynamics. For the *Caragana microphylla* shrub, we speculate that the aboveground shrub canopy trait and belowground soil architecture coordinates each other to evolve a mechanism for high diversity communities with both high productivity and high resilience to droughts (Yang et al., 2011).

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