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Mosaic-pattern vegetation formation and dynamics driven by the water–wind crisscross erosion

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SUMMARY

Theoretical explanations for vegetation pattern dynamic emphasized on banded pattern-forming systems on the dynamics of the spot pattern. In this context, we explore the patch pattern forming and development in the desertification land. We hypothesized that spatial heterogeneity of microtopography and soil properties with different patch sizes would determine vegetation pattern dynamics theory. The spatial heterogeneity of microtopography and soil properties with different patch sizes were studied. Differences between the inside and outside of the canopy of soil carbon content and soil total nitrogen content were significantly increasing with patches sizes. Sampling location across vegetation patch was the main factor controlling soil properties. Soil nutrient content and saturated hydraulic conductivity were the largest, while bulk density and the coarse sand content were the lowest at the sampling location of half-way between taproot and downslope edge of the canopy. The height of the mound relative to the adjacent soil interspace between shrubs increased as patches diameter increased at the upslope of the taproot. Hydrological and aeolian processes resulted in spatial distributions of soil moisture, nutrition properties, which lead to patch migrated to downslope rather than upslope. A conceptual model was integrated hydrological and nutrient facilitation and competition effects among the plant-soil in mosaic-pattern patch formation and succession process.

1. Introduction

Drylands cover about 41% of the Earth's land surface and about 25% of dryland areas are affected by desertification (D'Odorico et al., 2013). Aiming at rangeland regeneration and preventing soil erosion, vegetation restoration projects are a common and effective method to combat desertification in denuded landscapes of many arid regions (Fearnehough et al., 1998). Eco-hydrological interactions have been mostly demonstrated for arid and semiarid landscapes with distinctly different vegetation patterns, such as bands (Merino-Martín et al., 2012), rings (Ravi et al., 2007), stripes (Mauchamp et al., 1993) and spots (Couteron and Lejeune, 2001). Vegetation pattern dynamics and plant – habitats relationships may be applicable to ecological restoration and determine which species and patterns are suitable in the degraded deserts (Merino-Martín et al., 2012; D'Odorico et al., 2013; Hufford et al., 2014; She et al., 2014).

Vegetation pattern dynamics associate with long-range competition over the limited water and nutrient resources, which are spatial heterogeneous distribution in the arid region (Valentin et al., 1999; Rietkerk and van de Koppel, 2008; Meron, 2011; Yizhaq et al., 2014). Many authors had inferred from their observations that the banded patterns should migrate upslope, as the upslope edge consisted of young and pioneer plant, and the downslope edge consisted of decayed plants (Aguiar and Sala, 1999; Deblauwe et al., 2011; Muñoz-Robles et al., 2011). In particular, the spatial heterogeneous distribution of erosion and sedimentation reflects an upslope shift of the erosional and depositional fronts due to the band's morphological peculiarities (Deblauwe et al., 2011). Some other researchers studied on the dynamics of rings-pattern-forming systems and found that fertile islands around the shrub were formed through the deposition of wind borne fines firstly, and then ring pattern emerged and developed through hydrological processes (Ravi et al., 2007, 2010). Despite of the recent theoretical efforts to explain the dynamics of banded pattern-forming systems on gentle slopes or the dynamics of the

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spots patterns on the flat ground, respectively, we still have a poor understanding of the vegetation pattern dynamics on the steep slope and vegetation pattern forming on the desertification land (Couteron and Lejeune, 2001).

Theoretical explanations for vegetation pattern dynamic in the arid region emphasize the role of vegetation patches in mediating interception, infiltration, runoff, and patterns of sediment transport, especially at the top soil (Ludwig et al., 2005). Runoff and sediment transport processes result in the formation of heterogeneous landscape with a mosaic of nutrient rich soil patches – known as "fertility islands" – bordered by unfertile bare soil (Charley and West, 1975). In turn, the heterogeneity of soil physicochemical properties determined vegetation pattern dynamics (Hufford et al., 2014). Furthermore, the microtopography under the vegetation patches influences vegetation pattern dynamics, for example, aeolian deposits cause vegetation dieback or biomass reducing in the center of vegetated dunes by changing the microtopography in desert shrubs (Charley and West, 1975; Fearnehough et al., 1998; Ravi et al., 2008; Li et al., 2010). Field methods for quantifying patches, soil properties and microtopography processes is a suitable way to study the pattern dynamics, but field method requires long-term monitoring programs to provide reliable data (Deblauwe et al., 2011; Muñoz-Robles et al., 2011). In this study, the different dimensions of shrubs replaced vegetation pattern processes to study the vegetation pattern dynamics.

Here, we studies the soil microtopography, patches size and spatial heterogeneity of soil properties responding to vegetation patch dynamics through replicated different patches sizes on the steep hillslopes, which had natural restorated about 15 years from denuded desert in the water–wind erosion region. We hypothesized that the differences between inside and outside of the patches in soil nitrogen, organic carbon contents would be lower on the small patches and greater in the large patches, based on the assertion that as "fertility islands" accompanying with a redistribution of soil nutrients during erosion and deposition processes (Charley and West, 1975). We hypothesized that (1) microtopography and hydrological and nutrient processes co-driven mosaic-pattern vegetation formation in the water–wind erosion crisscross regions; (2) the differences of microtopography, soil properties between the different size patches would determine the vegetation migration direction and dynamics for the mosaic-pattern vegetation formation and succession process.

2. Methods

2.1. Study area

The study area was located at the Liudaogou watershed (110°21′–110°23′E, 38°46′–38°51′N, 1080–1270 m) of Shenmu County in the southern part of the Mu Us desert, which is water–wind erosion crisscross regions. It was characterized as continental semi-arid and seasonal wind climate. According to data available at the study site from the National Meteorological Information Center of China, mean annual precipitation was 437 mm, about 77% of which occurred from June to September in intense rainstorms. Mean annual potential evapotranspiration was 785 mm, and mean aridity index was 1.8. Mean annual gale days (>Beaufort force 8) was 16.2, and gales occurred mainly in spring. Detailed meteorological data were shown in Fig. 2. The soil of this study is an Aeolian sandy soil, which is prone to wind erosion in spring and winter, and to water erosion in summer and autumn (She et al., 2014). The Chinese government implemented "the Grain to Green" program to reduce soil erosion in 1998, from when vegetation restoration was natural succession through fencing in the study region. Vegetation restoration and subsequent plant-soil succession changed the landscape, from movable sand dunes to those covered by sand-stabilizing shrubs. The landscape was characterized by fixed and semi-fixed sand dunes, and vegetation dominated by psammophytic shrubs and grasses (e.g. *Artemisia ordosica*, *Artemisia sphaerocephala*, *Salix cheilophila*, *Lespedeza davurica*, *Astragalus adsurgens*).

Artemisia ordosica (*A. ordosica*) was a squat shrub forming a rounded bush up to 30–50 centimeters and grown in a vegetation patch pattern with individual clumps of plants up to 180 cm across the canopy. Its tangled branches and stem were woody and corky (Huang et al., 2010). *A. ordosica* was long-lived about 10 years and the population recruitment was generally realized by reproduction from seed. Three categories of *A. ordosica* size (based upon its canopy diameter) were designed in this study: Small (<80 cm), Medium (80–160 cm), Large (>160 cm) patches. Canopy diameter was measured at 40 cm above ground level. We selected two slope aspects, one was windward slope of 15 degrees and north aspect, and the other was leeward slope of 25 degrees and south aspect on August, 2012. In each slope, we selected fifteen shrub clumps with three categories, and five repeats for each size.

2.2. Experimental setup

Beneath each shrub, samples from soil surface at depth of 5 cm were collected, as the soil properties changes were easily detectable at this depth of the vegetation patches (McClaran et al., 2008). The soil sampling locations were (Fig. 1): (1) at the upslope edge of the outer canopy (UC), (2) half-way between the upslope edge of the canopy and the taproot (UT), (3) half-way between the downslope edge of the canopy and the taproot (DT), (4) at the downslope edge of the outer canopy (DC). The UT and DT were inside of the patch pattern, while the DC and UC were outside of the patch pattern.

Soil bulk density and soil volumetric water content were measured using the soil cores (volume, 100 cm^3) by the volumetric ring method. Disturbed soil samples were collected using a soil auger (4 cm inner diameter), and then air-dried and subsamples were sieved using 2-mm and 0.25-mm sieves. Soil particle size analyses were carried out on subsamples (<2 mm) using the laser diffraction technique with a Longbench MasterSizer 2000 (Malvern Instruments, England, UK) to calculate the percentage of clay, silt, fine sand and coarse sand contents. Soil subsamples (<0.25 mm) were used for soil organic carbon content (SOC) determination by the dichromate oxidation method and soil total nitrogen (TN) determination by the modified Kjeldahl method. Undisturbed soil samples (Top 5 cm) were collected in cylinders (5 cm length and 20 cm^2 cross-section area) to measure saturated hydraulic conductivity (K_S) by the constant head method (Wang et al., 2013).

We measured the length (L) along the slope and across the taproot, width (W) along the contour line and height (H). And also, we measured the distance between the taproot and the upslope edge of the canopy. Then, we calculated the taproot position (TP) by ratio of the distance between the taproot and the upslope edge of the canopy to the length of the shrub canopy.

Microtopography variability has traditionally been characterized with measurements of the relative elevation of the soil surface over a specified distance (length scale) or size interval (Sankey et al., 2012). The height of the mounds was measured using two meter sticks: one placed vertically at the interspace between the shrubs and the other placed horizontally along the contour line. Bubble levels were attached on the meter sticks to make sure that they were straight. To take measurements of the microtopography of the mound, ten measurements at five locations were taken under each shrub. The measurement locations were (Fig. 1): (1) upslope edge of the outer canopy (UC), (2) half-way between the taproot and the upslope edge of the canopy (UT), (3) half-way between the taproot and the downslope edge of the canopy (DT),

Fig. 1. The soil sampling locations: the upslope edge of the outer canopy (UC), half-way between the upslope edge of the canopy and the taproot (UT), half-way between the downslope edge of the canopy and the taproot (DT), the downslope edge of the outer canopy (DC) and taproot locations (TR).

(4) downslope edge of the outer canopy (DC), and (5) taproot locations (TR). At each point, the height of the mound was reported as the average of the two measurements (the center of mound to the two edges of mound along the contour line).

2.3. Data analysis

Data in this paper were expressed as mean ± standard error (SE) of mean. One-way ANOVA was performed to test differences in soil carbon content, soil total nitrogen content, soil moisture and bulk density between inside and outside of vegetation patches. Three-way ANOVA was performed to test the effects of sampling location, patch size and slope aspect on soil carbon content, soil total nitrogen content, soil bulk density, and soil moisture. All statistical analyses were performed using the software program SPSS, ver 12.0 (SPSS Inc., Chicago, IL, USA), figures were drawn using SIGMAPLOT version 8.0 (Systat software Inc., San Jose, CA, USA).

3. Results

3.1. Soil properties around vegetation patches

Soil organic carbon and nitrogen contents were higher inside the patches compared to upslope and downslope edge areas, consisted with the notion of "fertility islands" formation (Fig. 3a and b). The analysis of soil nutrients properties confirmed our assumptions concerning the differences between inside and outside of canopies (Fig. 1). The differences of soil carbon content ($F_{2,27}$ = 5.46, P = 0.01) and soil total nitrogen content ($F_{2,27}$ = 5.32, P = 0.01) were significantly increasing with patches sizes, while the bulk density was gentle decreasing ($F_{2,27}$ = 2.59, P = 0.09). Inside of the plant canopies, soil moisture was largest in medium patches, and was lowest in large patches. Soil carbon content ($F_{1,38}$ = 10.14, $P < 0.01$) and total nitrogen content ($F_{1,38}$ = 11.72, $P < 0.01$) were significantly higher and bulk density were significantly ($F_{1,38}$ = 8.18, $P < 0.01$) lower in soils inside canopies of the plants than those at outside canopies only in the large patches. Soil moisture showed no significantly changes between outside and inside of the plant canopies in all three sizes patches.

Sampling location factor comparing with other factors, was the main factor controlling soil properties which affected patch pattern dynamic as illustrated by the Three-way ANOVA analyses. Sampling location significantly affected soil carbon content, soil total nitrogen content and soil bulk density (Table 1). Significant interactive effects on bulk density, soil moisture were found with sampling location and slope aspect ($P < 0.05$, n = 120).

Different soil properties were associated with sampling locations. Soil organic content ($F_{3,106}$ = 4.64, $P < 0.01$; Fig. 4a) and soil total nitrogen content ($F_{3,106}$ = 7.04, $P < 0.01$; Fig. 4b) were significantly high at the half-way between the taproot and the downslope edge of the canopy (DT), but were significantly low at the upslope edge of the canopy (UC) and at the upslope edge of the canopy (DC). Bulk densities ($F_{3,106}$ = 3.88, P = 0.01; Fig. 4c) were significantly high at the UC and DC, but were low at the DT. Soil moisture ($F_{3,106}$ = 3.88, P = 0.10; Fig. 4d) was not significantly different between the sampling locations, and the largest was at UT.

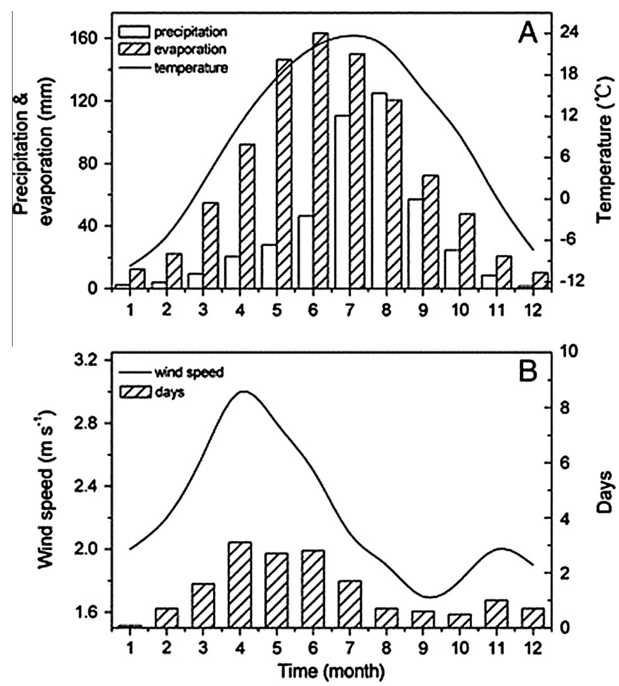

Fig. 2. Time series of (A) monthly average precipitation, evaporation, and temperature; (B) monthly average wind speed and days of gale (>Beaufort force 8).

Soil particle size analyses showed that there was more accumulation of fine particles (silt and fine sand) under the canopy (UT and DT) compared to the edge of the outer canopy (DC and UC) (Table 2). The average coarse sand content in the center of the shrub mounds was 56.55% (considering all shrubs studied), while total content of silt, clay and fine sand was 43.45%. In contrast, the edge of the dunes had average 59.55% coarse sand content and 40.45% content of silt, clay and fine sand. Contents of silt, clay and fine sand were larger in DT than UT. The corresponding value of saturated hydraulic conductivity was largest in DT, but lowest in UC. In conclusion, saturated hydraulic conductivity was the largest and the coarse sand was lowest at the half-way between the taproot and the downslope edge of the canopy.

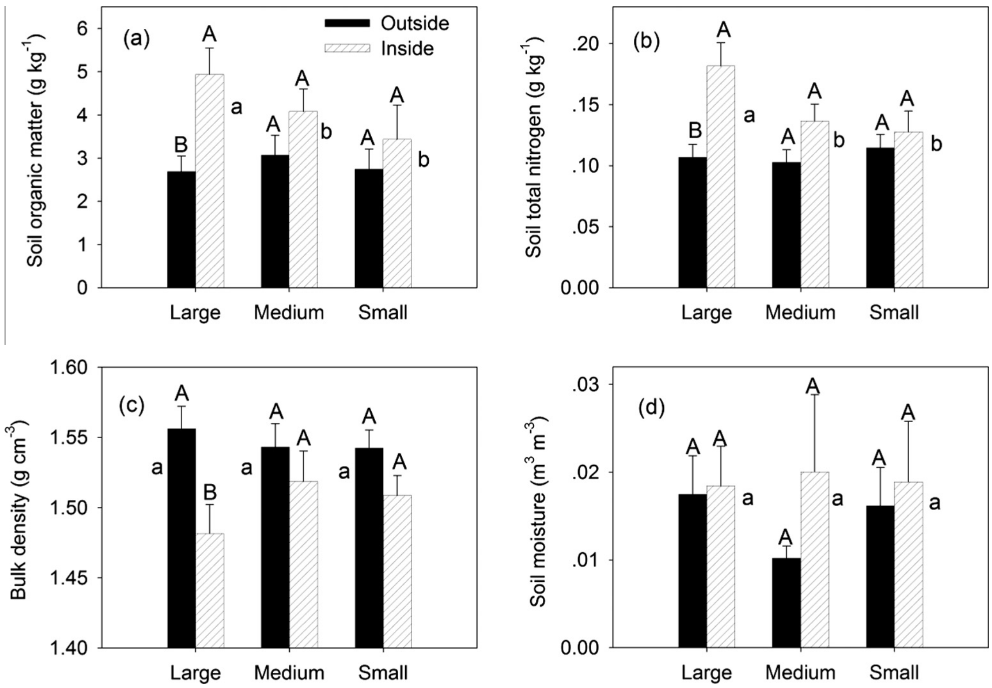

Fig. 3. The differences of soil organic carbon, soil total nitrogen, bulk density and soil moisture between the inside and outside of the vegetation canopy at the small patch, medium patch and large patch. The different capital letters means the significant differences between inside and outside of each patch at the 0.05 level. The different lower letters means the significant differences among the different sizes patches of the soil properties changings between outside and inside of plant canopies at the 0.05 level.

Table 1
Statistical results of three-way ANOVA analysis of the effects of sampling location (*S*), patches size (*P*) and slope aspect (*A*) on soil properties including soil carbon content (SOC), soil total nitrogen content (TN), soil bulk density (BD), and soil moisture (*M*) ($n = 120$).

		SOC ($g\ kg^{-1}$)		TN ($g\ kg^{-1}$)		BD ($g\ cm^{-3}$)		*M* ($m^3\ m^{-3}$)	
	df	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Sampling location (*S*)	3	**3.31**	**0.02**	**5.44**	**<0.01**	**3.53**	**0.02**	0.48	0.70
Patches size (*P*)	2	1.07	0.35	2.05	0.14	0.27	0.76	0.17	0.84
Slope aspect (*A*)	1	4.02	0.06	0.00	0.98	3.64	0.06	2.10	0.15
$S * P$	6	0.53	0.79	1.17	0.33	0.63	0.71	0.47	0.83
$S * A$	3	0.20	0.90	0.59	0.62	0.16	0.93	0.61	0.61
$P * A$	2	1.21	0.30	1.34	0.27	**3.79**	**0.03**	**4.51**	**0.01**
$P * S * A$	6	0.07	1.00	0.24	0.96	0.44	0.85	0.42	0.86

Note: Bold values are statistically significant (*P*).

3.2. Microtopography and taproot position around vegetation patches

The height of the mound relative to the adjacent soil interspace between shrubs increased as patches diameter increased at UC, UT and TR of both slopes (Table 3). However, the heights of mounds at the DC in the medium and large patches were negative, which means that DC was eroded by wind or water. The maximum height of mound was about 16.44 cm at the TR of the large patches in the windward slope. We calculated the taproot position, and found that TP decreased as patches diameter increased (Table 3). The lower TP indicated the shrub clumps were growing to the downslope rather than upslope.

4. Discussion

4.1. Patch dynamics based on soil nutrients process

The higher concentration of nutrients beneath shrub canopiescomparing with the surrounding bare area forming what called ‘fertile islands’ has been well documented in arid and semi-arid ecosystems (Li et al., 2008; Joseph et al., 2013). Our results agreed well with those of Li et al. (2008), who found that fertile islands beneath canopies of shrub patches developed gradually with the growth of *A. ordosica.* Soil carbon and total nitrogen contents showed a trend of accumulation in soils beneath plant canopies with increasing patch sizes. However, soil nutrients were significantly higher beneath plant canopies only at the large patches, in accordance with the results that nutrients started to accumulate in quantities sufficient to form a fertile island only during later developmental stages of individual plants (Reynolds et al., 1999).

Soil properties in the study region were extremely heterogeneous at the different sampling locations along the slope. The highest soil nutrient contents located at the half-way between the taproot and the downslope edge of the canopy (DT). Our result was inconsistent with the results of studies conducted by Aguiar and Sala (1999) and Deblauwe et al. (2011), that soil at the upslope location under the canopies were more fertile than at the downslope location. We concluded that the nutrients were formed from the plant and litter under the canopies, and the nutrients were transported to the downslope by the hydrological processes. Furthermore, runoff sediments, hindered by vegetation, were so barren that decreased the soil nutrients content at the upslope of the canopies.

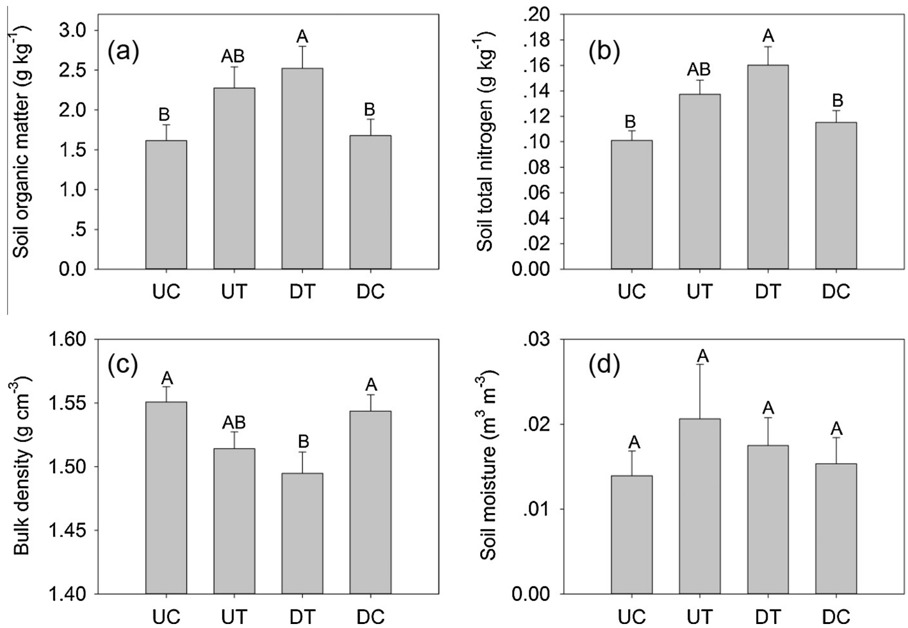

Fig. 4. Differences of soil organic carbon, soil total nitrogen, bulk density and soil moisture at the different positions of all patches. Means with different letters indicate statistically significant differences ($p < 0.05$) among different position determined by ANOVA. Error bars indicate standard errors. UC: the upslope edge of the outer canopy, UT: half-way between the taproot and the upslope edge of the canopy, DT: half-way between the taproot and the downslope edge of the canopy, DC: the downslope edge of the outer canopy.

Table 2
Soil particle size distribution and saturated hydraulic conductivity (*Ks*) at the different locations of all the patches in this study.

Location	$D_{0.5}$	<0.002 mm	0.002–0.02 mm	0.02–0.2 mm	0.2–2 mm	*Ks* (mm min^{-1})
UC	221.56(5.94)	0.04(0.02)	1.30(0.17)	39.53(2.38)	59.13(2.50)	3.92(0.22)
UT	217.56(5.30)	0.03(0.01)	1.38(0.16)	41.03(2.04)	57.56(2.15)	4.01(0.22)
DT	212.01(5.91)	0.03(0.01)	1.46(0.20)	42.98(2.18)	55.53(2.31)	4.34(0.24)
DC	222.8(5.92)	0.02(0.01)	1.14(0.18)	38.86(2.39)	59.97(2.50)	4.18(0.23)

Note: Standard error of mean in brackets. UC: the upslope edge of the outer canopy. UT: half-way between the taproot and the upslope edge of the canopy, DT: half-way between the taproot and the downslope edge of the canopy, DC: the downslope edge of the outer canopy, $D_{0.5}$: median diameter of particles.

Table 3
Heights of the mounds at the five measurement points and taproot position (TP) under the three size patches in windward and leeward slopes.

Position	Windward slope			Leeward slope		
	Small	Medium	Large	Small	Medium	Large
UC	4.33(1.45)	3.44(1.37)	6.67(1.2)	2.08(0.81)	4.67(0.81)	12.17(2.87)
UT	4.44(0.93)	4.00(1.13)	12.00(1.59)	3.67(0.84)	7.08(0.99)	16.08(3.71)
TR	6.22(1.12)	7.11(1.27)	16.44(1.24)	4.42(1.03)	11.42(1.39)	15.42(2.36)
DT	4.78(1.23)	6.22(1.61)	8.67(2.57)	0.17(0.93)	−1.58(2.22)	1.67(2.61)
DC	1.11(0.92)	−1.89(1.06)	−1.67(1.1)	−1.42(0.61)	−0.58(0.57)	−1.92(2.06)
TP	0.48(0.02)	0.44(0.03)	0.42(0.03)	0.47(0.02)	0.43(0.02)	0.39(0.02)

Note: UC: the upslope edge of the outer canopy, UT: half-way between the taproot and the upslope edge of the canopy, DT: half-way between the taproot and the downslope edge of the canopy, DC: the downslope edge of the outer canopy, TR: the taproot point, TP: the taproot position.

4.2. Patch dynamics based on soil hydrological process

One of the most crucial conditions to the development of patches patterns was the low infiltrability of bare soils and thus their ability to produce overland flow (Ludwig et al., 2005). The infiltration experiment results were consistent with previous studies that infiltration rates in the fertility island were greater than in bare interspaces (Ravi et al., 2007). The highest saturated hydraulic conductivity and the lowest coarse sand content were at the half-way between the taproot and the downslope edge of the canopy. The higher saturated hydraulic conductivity was caused by the downslope location under shrub community containing the larger amount of fine soil particles in the range of 0.002–0.2 mm, the higher soil organic matter content and the lower bulk density. Our results corroborated the findings of Wang et al. (2007), who suggested that differences in the hydrological responded to the vegetation covers were attributed to the differences in soil properties and particularly porosity in the arid woodlands of northwest China. The highest soil moisture content at the upslope of the taproot under the canopy, was caused by the taproot trapping the runoff and sediment production (Muñoz-Robles et al., 2011).

Additionally, we found that the taproot position decreased with the patch size and the vegetation patches growing. Our results did not support the recent studies that the vegetation pattern migrated upslope at the gentle slope (Aguiar and Sala, 1999; Deblauwe et al., 2011; Muñoz-Robles et al., 2011). On the one hand, fertile islands had significantly great effects on the spatial distribution of plant productivity, as well as vegetation dynamics and ecosystem processes (El-Bana et al., 2002). Soil nutrient contents, concentrated at the locations of the half-way between the taproot and the downslope edge of the canopy, were beneficial to plant growth to the downslope and patches migration to the downslope. On the other hand, the dynamics of mound microtopography involved a complex interplay between soil and plant resources and disturbance (Li et al., 2008). In agreement with the work reported by Mabbut and Fanning that upslope migration did not occur in the arid systems on the steep slope because of the mound on upslope location was more thick than downslope (Mabbutt and Fanning, 1987). When the mound developed enough thick and lasted for a long time, it might impose the pressure on plant physiological activity and growth, limit oxygen availability to roots, shift in biomass allocation patterns and cause the seedling to die (Weaver and Albertson, 1936; Ravi et al., 2008; Liu et al., 2014). The results from this study also suggested that water redistribution occurred downslope from the taproot position to the downslope edges, because the soil under the downslope edge of canopy was eroded. The microtopography of mound played an important role in the water redistribution, plant growth and seedling establishment, and then controlled the vegetation pattern dynamics.

4.3. Implications for vegetation patch pattern dynamics

The fertile islands often become relatively stable features in the landscape because the shrub species colonizing the islands are often long-lived and the amount of its recruitment is low. Long-lived plant species and fertile islands were driving the increased patchiness of the landscape. The patches pattern migration arises from small changes in the soil texture, soil phy-chemical properties, soil depth (Sela et al., 2012), microtopography (Noy-Meir, 1973; Pelletier et al., 2012), soil infiltration rate and the flow of surface water (Ravi et al., 2007). Patches migration was the consequence of localized death (retreat) and recruitment (colonization) of shrub (Fig. 5). We summarize the dynamics of patch pattern development in relatively distinct stages on the steep slope in the study region:

Small patches: At this stage pioneer species appeared and developed on the bare soil in desertification ecosystems (Fig. 5). Soil resources, including soil organic content and soil total nitrogen content, might not be efficiently accumulated under small canopies of young plants during the initial stages of patch development (Zhang et al., 2011). As a result, fertile islands at this stage were either very weak or non-existent. The small patches only could trap aeolian sand and runoff sediments, and arouse the microtopography changes.

Medium patches: The soil and vegetation showed strong positive interactions with each other as the plants matured. A small proportion of adult plants created a subcanopy microclimate with the shaded and fertile island (D'Odorico et al., 2010; He et al., 2010), enhancing the infiltration rate, water-holding capacity, soil moisture and soil nutrients than in gaps (Armas and Pugnaire, 2005; Yizhaq et al., 2014). The higher soil moisture under the canopies increased the vegetation growth rate and biomass. The root biomass augmentation allowed the vegetation to extract soil water from a larger area (Casper et al., 2003; Joseph et al., 2013), which, in turn, enhanced the growth rate and added nutrients to the soil.

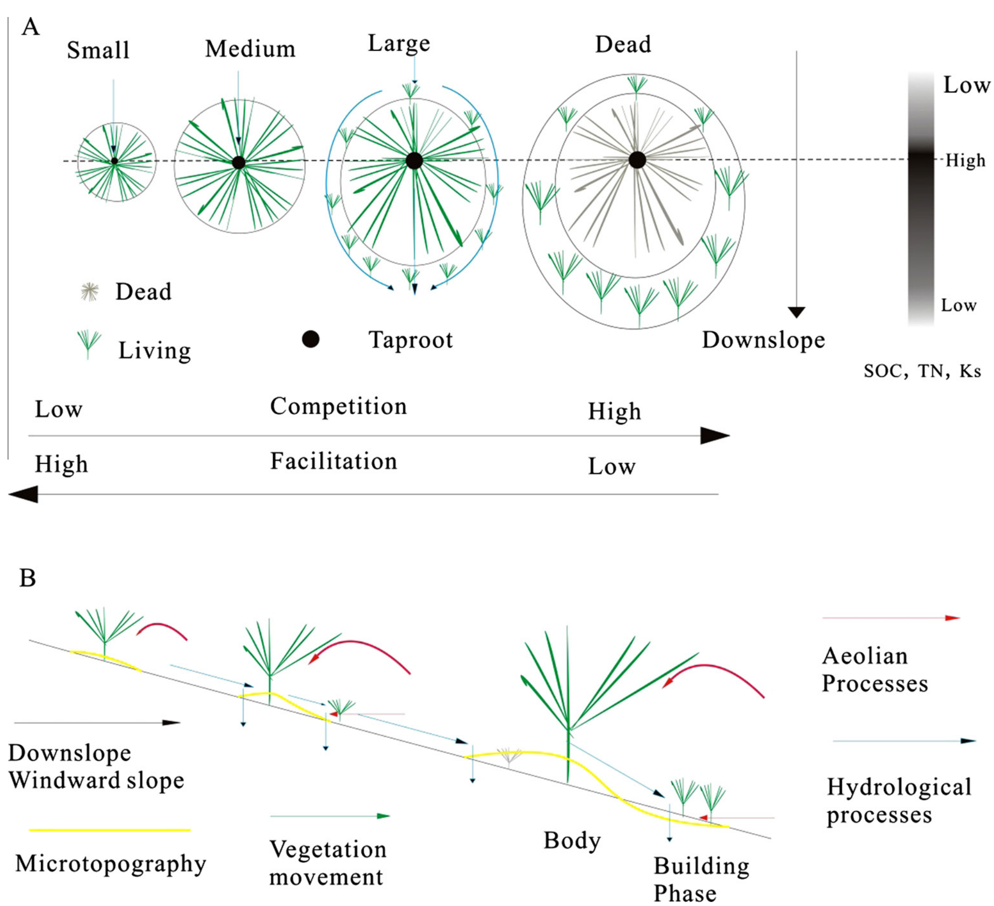

Fig. 5. Conceptual diagram showing the vegetation pattern dynamics on the steep slope in the Mu Us Desert within hydrological, aeolian processes and the microtopography modify.

The medium patches could keep trap aeolian sand and runoff sediments by the plant, and the sediments deposited at upslope of the taproot location. However, the soil in downslope of the taproot location was eroded by the hydrological process in leeward slope and deposited in windward slope, as the leeward has a larger gradient, and larger erosion power (Table 3, Fig. 5).

Large patches: Fertile island effect enhanced with plant growth, it created a neighborhood with aerial protection that promoted both seed accumulation and seedling establishment (Aguiar and Sala, 1999; He et al., 2011; Joseph et al., 2013). Nutrient availability had significant effects on seedling performance and was largest at the downslope under the canopy. Further, the large patches keep trap aeolian sand and runoff sediments at upslope of the taproot location, while erosion at the downslope of the taproot location by the hydrological processes. The higher mound at upslope of the taproot location restricted seedling emergence and the seedling survival rate under the canopy (Harris and Davy, 1988; Liu et al., 2014). Both the mound height and soil nutrients characteristics determined the patch pattern dynamic that the seedling emergence had more possibility at the downslope of the taproot than upslope, and the shrub was growing with the direction to the downslope.

Active growth (building phase) occurred mainly at the downslope of the canopy, where the balance between competition and facilitation was more favorable for young plants. With the shrub clumps emergence and the seeding growth, adult shrubs acted as nurses for juvenile plants, improving their water status, nutrient content, and growth rate (Armas and Pugnaire, 2005; Valiente-Banuet and Verdú, 2008). Richards and Caldwell (1987) measured the soil water potential in field and suggested that water absorbed from moist soil by deeper roots was transported to roots into dried upper soil layers. The juvenile plants would use moisture from subsurface moisture through the hydraulic lift of adult shrub. The mechanisms underlying this facilitation effect were mainly the improvement of microclimatic conditions and soil physical and chemical properties under shrub canopies (Armas and Pugnaire, 2005).

Late patch: With the vegetation growing up, positive interactions (plant facilitation) between the adult and juvenile bodies turned into negative interactions (competition) at this stage, depending on the fine-scale heterogeneity in environmental conditions, resource availability and biotic interactions, beneath and around the shrubs (Armas and Pugnaire, 2005; Valiente-Banuet and Verdú, 2008). Firstly, while competitiveness of the adult bodies at old stage became weakness, competitiveness of the beneficiary individuals became strong. Secondly, the adult bodies and the juvenile bodies competed with the limited water and nutrient resources in the arid region. Further, the microtopography changed and the heights of mound at this stage were largest at the taproot location. The mounds changed the soil infiltration, water redistribution, seedling recruitment and determined the vegetation building phase (Weaver and Albertson, 1936; Ravi et al., 2008; Liu et al., 2014). As a result, the old shrub died and began to collapse, the landscape evolved towards to a heterogeneous distribution of vegetation and soil resources with the formation of shrub-dominated fertility islands (Dunkerley and Booth, 1999).

Once the shrub cover was lost, aerial protection disappeared and ground competition between the survival plants dominated over any facilitation effects (Aguiar and Sala, 1999). The mortality of shrubs might increase, leading to a thinning of the patches pattern. Armas and Pugnaire suggested that there were no net negative effects between adult plants for the positive effects counterbalance negatives effects (Armas and Pugnaire, 2005). And last, vegetation patterns optimized the capture and storage of water and resources to maximize plant productivity in arid landscapes (Ludwig and Tongway, 1995). These results showed that a pioneer species, *A. ordosica*, facilitated the fertile island forming, mound emergence and the vegetation regeneration, all of which derived mosaic-pattern vegetation formation and dynamics on the steep slope in the water–wind erosion crisscross region.

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