Journal of Hydrology 538 (2016) 355–362

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

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

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ARTICLE INFO

*Article history:*
Received 23 January 2016
Received in revised form 2 April 2016
Accepted 14 April 2016
Available online 22 April 2016
This manuscript was handled by Geoff Syme, Editor-in-Chief

*Keywords:*
Vegetation patch dynamics
Nutrient processes
Aeolian process
Microtopography

## 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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http://dx.doi.org/10.1016/j.jhydrol.2016.04.030
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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),