

Ecohydrological interactions within banded vegetation in the northeastern Chihuahuan Desert, USA

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ABSTRACT

Landscape patterns, consisting of alternating densely vegetated bands and sparsely vegetated interbands, occur in semi-arid and arid regions of Africa, Asia, Australia and North America. The structure of vegetation patterns has been well documented, but a wide array of underlying environmental factors and ecological processes have been suggested, with no consensus regarding the genesis and persistence of these patterns. The purpose of this study was to assess ecohydrological interactions within this banded pattern by quantifying reallocation of rainfall and soil sediments. Even subtle redistribution impacted plant biomass production and species composition. Although runoff losses from interbands accounted for only 4% total rainfall, reallocation supported tree species and bunchgrasses that would not be sustained if precipitation were evenly distributed. Additionally, a rainfall threshold was identified. When storm totals exceeded 16 mm, even the densely vegetated bands were unable to capture all the rainfall and run-on from the upslope sodgrass interbands; a portion of the runoff from interbands flowed through the vegetated bands and continued downslope into the next interband. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS resource reallocation; source; sink; runoff; infiltration; semi-arid

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INTRODUCTION

Closely spaced, alternating dense and sparse vegetation form landscape patterns that are easily recognized on aerial photos but may be undetectable in the field (Lefever and Lejeune, 1997). Vegetation may be arranged in dense bands, stripes and stipples or spots with a matrix of sparser vegetation and bare soil (a two-phase mosaic) (d'Herbes *et al.*, 2001). Some patterns are comprised solely of herbaceous plants (MacFadyen, 1950; Worrall, 1959; Hemming, 1965) but most are mixed stands of woody and herbaceous species (White, 1969; Chappell *et al.*, 1999). There are region-specific common names for these patterns. Banded and striped patterns in Africa are often referred to as 'tiger bush' (Wu *et al.*, 2000). Mogote is the regional name used in northern Mexico (Lopez-Portillo and Montana, 1999). *Acacia aneura* (mulga) is the dominant woody component in large expanses of banded vegetation in Australia. Hence, they are referred to simply as 'mulga'.

A summary of the extensive body of work on banded vegetation, dating back to 1941, can be found in Tongway *et al.* (2001). These two-phase vegetation mosaics are associated with various geologic parent material, soil types and plant species and have been documented in regions where annual precipitation ranges

from 50 to 820 mm. Commonalities include gentle slope gradients (<3%), runoff in the form of sheet-flow and surface soils that are prone to physical crusting. However, banded vegetation is absent in some areas that share similar features. Thus, further inquiry is needed.

A variety of environmental factors and processes have been implicated in pattern formation and function including disturbance (Hemming, 1965; Dunkerley, 2002), aeolian forces (Clayton, 1966), topography (Sherratt, 2005), edaphic heterogeneity (Warnock, 1997), burrowing animals and soil fauna (Whitford, 1998; Ludwig *et al.*, 2005), plant-induced abiotic feedbacks (Couteron and Lejeune, 2001; Lejeune *et al.*, 2004; D'Odorico *et al.*, 2006; Gilad *et al.*, 2007) and climate change (Barbier *et al.*, 2006).

Cearley (1996) described a banded vegetation sequence in the northeastern Chihuahuan Desert. He attributed the pattern to surface resource partitioning of rainfall and sediment, variability in soil depth, or both. Warnock (1997) completed a detailed soil survey of the pattern and concluded that sparse and dense vegetation coincided with shallow and deep soil depths, respectively, to a root limiting layer. The objective of this field study was to quantify redistribution of rainfall runoff and soil sediments within a vegetation sequence and test the hypothesis that redistribution contributes to pattern genesis and persistence.

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METHODS

Study area

The study site is situated on a gently sloping (1.3% gradient), slightly concave pediment below Cretaceous limestone hills (Cearley, 1996; Warnock, 1997). Surface soil textures are silt loam and silty clay loam. The winter season is typically cool and dry. Spring and summer are warm and dry punctuated with rainfall in the form of convective thunderstorms. Mean annual precipitation at Ft. Stockton, located 50 km NW of the study site, is 310 mm (CV = 42%) (National Climate Data Center, 2005), whereas annual potential evapotranspiration is 973 mm (USDA Risk Management Agency, 2004) (Figure 1). Most rainfall (74%) occurs between May and October. The coldest month is January, with a mean air temperature of 8 °C. Maximum mean air temperature is 28 °C in July.

Four distinct plant community types (cts) occurred continuously as a parallel sequence downslope (Figure 2); sequence lengths ranged from 75 to 190 m (Cearley, 1996). Proceeding downslope, an interband consisting of widely scattered tarbush (*Flourensia cernua*) with a sparse cover of *Scleropogon brevifolius* sodgrass, was followed by a band of tarbush and a dense cover of *Aristida purpurea* bunchgrass, which was succeeded by

a mosaic of mesquite (*Prosopis glandulosa*)-sodgrass and juniper (*Juniperus pinchotii*)-bunchgrass cts. During this investigation a fourth plant community, dominated by *P. glandulosa* and *Buchloe dactyloides*, was distinguished from the juniper-bunchgrass ct. The delineation was based on species composition and productivity. *B. dactyloides* in the mesquite-sodgrass ct was dead or dormant, but still standing in the interspaces among the trees. *Bouteloua curtipendula* was the dominant bunchgrass in the juniper-bunchgrass ct.

Field procedures

Beginning in May 1998, precipitation and runoff were collected measured for 1 year. Runoff behaviour was evaluated for two complete pattern sequences. Five 1 m × 1 m microcatchments were established within each of the four plant communities for a total of 40 microcatchments (Figure 3). Metal frames, inserted approximately 5 cm into the soil, formed the perimeter of the microcatchments. Infiltration was assumed to be equal to rainfall volume minus runoff volume. Canopy interception, stemflow and throughfall were not considered in this study.

Runoff flowed from each microcatchment into a collection bag situated in a buried bucket. Runoff was measured to the nearest 10 ml. Sediment was allowed to precipitate, to get filtered and oven-dried following procedures described in Thurow *et al.* (1986). Soil was excavated with a bucket auger and depth of wetting front was recorded adjacent to each plot after every storm event.

Percent basal plant cover in each microcatchment was estimated in August 1998, October 1998, and March 1999. Plant species nomenclature followed Hatch *et al.* (1990). Percent cover of biological soil crusts, rock fragments, plant litter and mineral soil was also estimated on the same three dates. In March 1999, a ten-point frame was used to measure microrelief at three locations within each microcatchment. A bucket auger was used to determine depth to root restrictive layer adjacent to each microcatchment (McDonald, 2001).

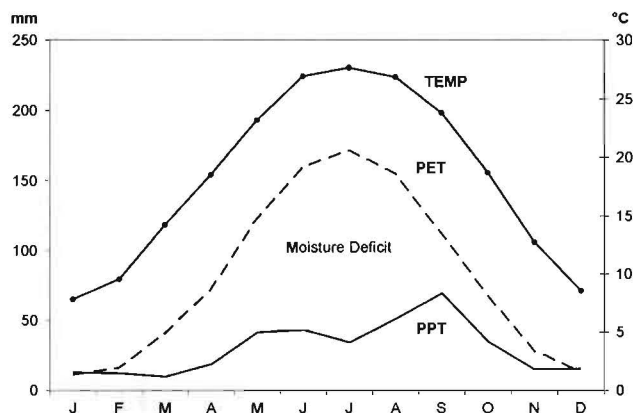


Figure 1. Mean monthly precipitation (PPT), potential evapotranspiration (PET) and temperature (TEMP) 1971–2000 at Ft. Stockton, Pecos County, Texas.

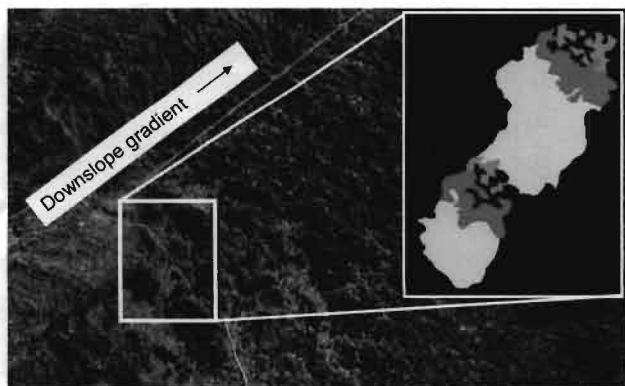


Figure 2. Digital aerial photograph with delineations of four plant communities within a banded pattern in the NE Chihuahuan Desert, USA.



Figure 3. Photograph of runoff microcatchment in tarbush-sodgrass plant community within a banded pattern in the NE Chihuahuan Desert, USA.

Calculation of rainfall redistribution

The study area was delineated on a 1996 digital orthophotograph and relative proportions of each plant community type were calculated with ArcView 3.2 GIS software (Environmental Systems Research Institute, Inc., 1996) (Figure 1). This allowed us to quantify source : sink ratios and assess rainfall redistribution.

Statistical analyses

All statistical analyses were conducted using SAS Version 6.12, according to SAS User's Guide (SAS Institute, Inc., 1985) or Cody and Smith (1997). Basal plant cover, soil surface features, runoff depth, sediment loss and wetting front depth were analysed by community type using PROC GLM with the MANOVA statement. When differences were detected, Fisher's LSD test was performed. Mean runoff depth and mean sediment loss were calculated for each ct for large storms (rainfall depth that generated runoff from most microcatchments) and for small storms. Fisher's LSD was used to calculate significant differences among those mean values. PROC CORR was used to calculate the correlation of microrelief with basal sodgrass cover, basal bunchgrass cover, rock cover, mineral soil, and biological soil crusts.

RESULTS

Vegetation

The four plant communities differed in their overall physiognomy and cover (Table I). Bunchgrass cts were typified by sideoats grama (*B. curtipendula*), purple threeawn (*A. purpurea*), plains bristlegrass (*Setaria leucopila*), and vinemesquite (*Panicum obtusum*). Sodgrass-dominated cts supported buffalograss (*B. dactyloides*) and burrograss (*S. brevifolius*). Basal plant cover was greatest in the tarbush-bunchgrass ct and lowest in the mesquite-sodgrass ct. Cover within three of the four communities did not vary significantly among observation dates. Ephemeral forbs increased basal plant cover between August and October in the Juniper-bunchgrass ct.

Soils

Soil surface features further defined the differences between the bunchgrass and sodgrass cts. Biological soil crust cover was highest in the mesquite-sodgrass ct, which also exhibited the highest percent exposed mineral soil (>70%, Table I). Litter cover, in the form of juniper duff, was consistently highest in the juniper-bunchgrass ct. Percent cover of rock fragments was greatest and litter cover lowest in the tarbush-sodgrass ct. Microrelief was similar in the bunchgrass-dominated cts and significantly lower in the sodgrass cts.

Runoff

Cumulative rainfall for the 12-month study period was 186 mm. Storm depth influenced runoff response. Small rainfall events (<16 mm) generally initiated runoff from

Table I. Basal plant cover and soil surface features in four plant communities arranged in a banded pattern in NE Chihuahuan Desert, USA.

% Cover	Plant community															
	Tarbush-sodgrass				Tarbush-bunchgrass				Mesquite-sodgrass				Juniper-bunchgrass			
	Aug 1998	Oct 1998	Mar 1999	Aug 1999	Aug 1998	Oct 1998	Mar 1999	Aug 1999	Aug 1998	Oct 1998	Mar 1999	Aug 1999	Aug 1998	Oct 1998	Mar 1999	
Basal plant	12.6B ^a	18.6Ba ^b	20.9Ba	31.5Aa	43.4Aa	40.7Aa	40.7Aa	4.0Ba	3.5Ca	2.3Ca	11.7Bb	36.1Aa	11.9BCb			
Microbiotic crusts	2.1ABa	0.0Aa	6.8ABa	2.5ABa	1.7Aa	0.4Ba	0.4Ba	4.5Aa	5.0Aa	10.7Aa	0.0Ba	3.0Aa	2.2ABa			
Litter	3.5Ba	2.0Ca	3.8Ca	39.5Aa	21.3ABb	28.2Bab	8.3Ba	8.3Ba	13.2Ba	13.3Ca	43.5Aa	28.1Aa	45.3Aa			
Rock fragments	23.2Ab	33.5Aa	34.9Aa	1.0Bab	0.5Bb	4.1Ba	1.8Ba	1.8Ba	3.8Ba	1.2Ba	1.0Ba	0.7Ba	0.3Ba			
Mineral soil	58.7ABa	45.9Bb	33.6Bb	25.5Ca	33.1Ba	26.6Ba	81.3Aa	81.3Aa	74.5Aa	72.5Aa	43.8BCa	32.1Ba	40.3Ba			
Microrelief (mm)	— ^c	— ^c	0.31B	— ^c	— ^c	0.63A	— ^c	— ^c	— ^c	0.36B	— ^c	— ^c	0.61A			

^a For comparisons across communities at the same date, means followed by the same upper case letter are not different at $P = 0.05$ using LSD mean separation tests.

^b For comparisons within communities across dates, means followed by the same lower case letter are not different at $P = 0.01$ using LSD mean separation tests.

^c No data collected.

the sodgrass cts, but not from the bunchgrass communities. In all communities, runoff was less than 6% during small storms. Percent contributions to runoff during large storms were 24, 3, 20 and 8%, respectively. Runoff volume (ml m^{-2}) differed markedly among the four cts (Figure 4). Microcatchments in the tarbush-sodgrass ct yielded the greatest runoff followed by the mesquite-sodgrass microcatchments. The tarbush-sodgrass ct shed seven times more water per unit area than tarbush-bunchgrass ct and three times more than juniper-bunchgrass ct.

Sediment loss

Sediment loss varied with storm size (Figure 5). During small storms, the tarbush-sodgrass ct generated the most sediment (0.3 g m^{-2}), whereas the other three communities yielded almost none. Compared with an average of 0.03 g m^{-2} of sediment lost in small storms in the mesquite-sodgrass ct; large storms produced an average of 15.4 g m^{-2} . Likewise, sediment production from the juniper-bunchgrass ct increased from 0 to 11.3 g m^{-2} . Runoff from the tarbush-bunchgrass ct contained the least amount of sediment, 2.1 g m^{-2} during large storms compared with none from small events.

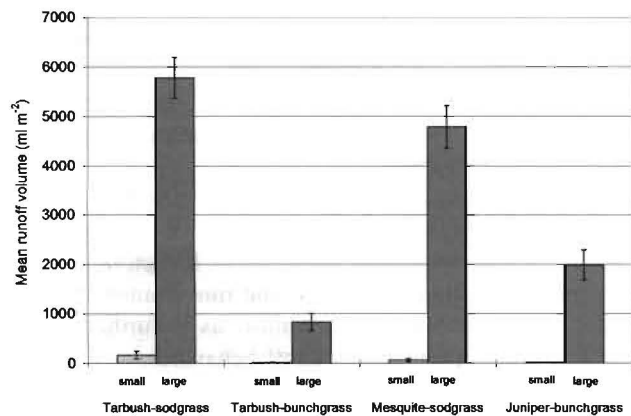


Figure 4. Mean (± 1 SE) runoff volumes during small and large storms from four plant communities within a banded pattern in the NE Chihuahuan Desert, USA.

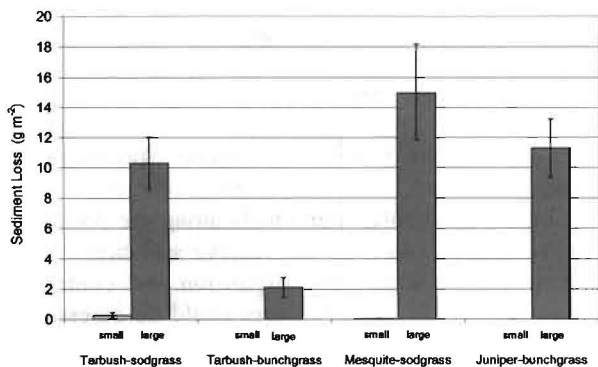


Figure 5. Mean (± 1 SE) sediment loss during small and large storms from four plant communities within a banded pattern in the NE Chihuahuan Desert, USA.

Wetting depth

Mean wetting depth was greatest in the tarbush-bunchgrass ct, followed by the juniper-bunchgrass ct (Figure 6). Infiltration depth was significantly less in the sodgrass cts. When analysed by storm class, there was no significant difference among cts for small storms, but large storms induced significantly more infiltration in bunchgrass cts.

Resource redistribution

The study site encompassed about 2.5 ha. The tarbush-sodgrass ct occupied 1.65 ha (65%) of the site, tarbush-bunchgrass ct 0.53 (20%), mesquite-sodgrass ct 0.17 ha (7%) and juniper-bunchgrass ct 0.19 ha (8%). The ratio of source area (runoff-generating sodgrass cts) to sink area (run-on receiving bunchgrass cts) was 2.4 : 1.

Differences among wet, dry and average years are characterized by the frequency and contribution of small versus large storms. During the study period, storms were almost equally divided between small and large, but large storms accounted for 91% rainfall total. Frequencies of small storms were 79 and 87% in 1992 and 1941–2000, respectively, but represented less than half of the precipitation.

Microcatchment runoff data were used to compute the depth of water leaving or entering each plant ct according to sequence position. Runoff depths from microcatchments were multiplied by relative ct area. This volume was then applied to the relative area of the ct downslope. Resource redistribution was computed for three different annual precipitation totals represented by:

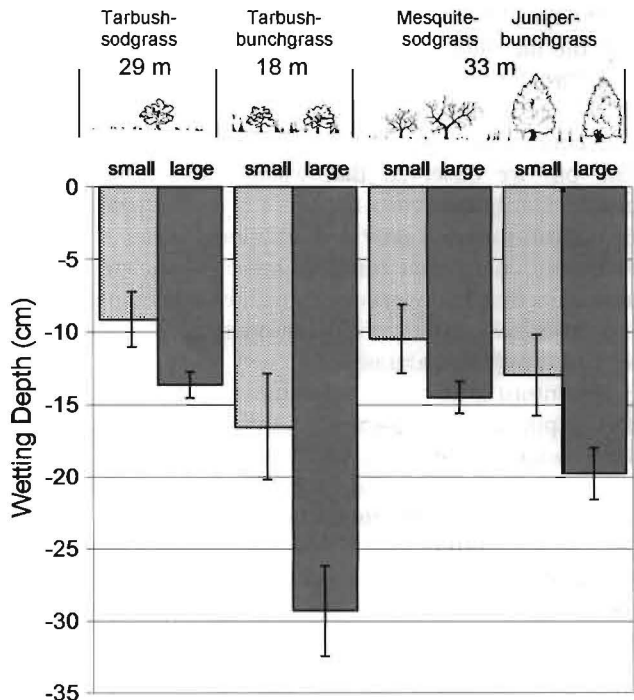


Figure 6. Drawing of vegetation sequence with mean plant community lengths. Note: drawing not to scale. Mean (\pm SE) wetting depths for small and large storms within four plant communities within a banded pattern in the NE Chihuahuan Desert, USA.

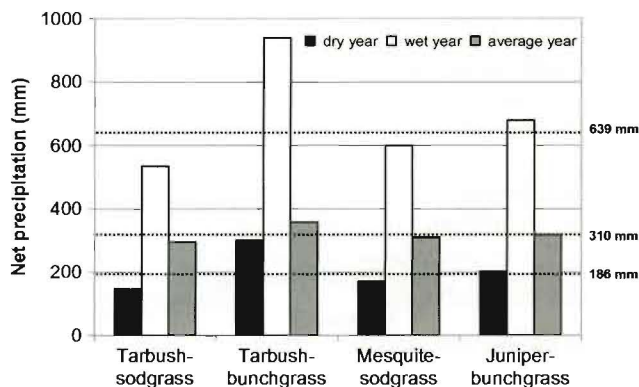


Figure 7. Net precipitation assuming 100% infiltration of run-on computed for 1992, a dry year (186-mm rainfall), mean rainfall 1941–2000 (310-mm rainfall) and 1998, a wet year (639-mm rainfall) in four plant communities within a banded pattern in the NE Chihuahuan Desert, USA.

(1) the study period (a dry year), (2) a wet year (1992) and (3) the long-term mean (1941–2000) (Figure 7).

Net precipitation was consistently higher in the vegetated bands compared with the interbands. Net precipitation in the tarbush-bunchgrass ct always exceeded actual precipitation and was greatest during dry years, followed by wet years and reduced to only 115% actual precipitation for an average year. The opposite is true for the sodgrass source cts where net precipitation is nearly equal to measured precipitation during an average year compared with an unusually wet or dry year.

DISCUSSION

Results of this study support the assertion that ecohydrological interactions contribute to vegetation banding on the Stockton plateau in West Texas. Vegetation structure on the study site was strongly related to measured rates of runoff and soil sediment losses. The entire study site received the same amount of rainfall, but we observed that water resources were not evenly distributed across the site. Large, contiguous areas of tarbush-sodgrass provided additional water resources to mostly continuous bands of tarbush-bunchgrass situated immediately downslope. Small, elongated patches of juniper-bunchgrass received run-on from a proportional area of mesquite-sodgrass.

In contrast to an earlier assessment by Warnock (1997), soil depth to root limiting petrocalcic layer did not vary significantly among the four cts, and mean depths exceeded 70 cm. Antecedent moisture content was also similar among communities when the study was initiated (McDonald, 2001).

Runoff responses observed during the study period were extrapolated to a relatively wet year (1992), a relatively dry year (1998) and to the available period of record (1941–2000). Redistribution of water would be more pronounced during dry and wet years than during average years. Erratic rainfall patterns favour the bunchgrass cts, not the sodgrass cts. If runoff behaviour observed during the study period is representative of the

overall hydrologic response of the pattern to storm depth, then rainfall characteristics are likely a fundamental mechanism of this and possibly other landscape patterns.

During large storms, this pattern may behave similar to a mulga pattern in Australia (Tongway and Ludwig, 1990). The mulga grove–intergrove pattern had a downslope sequence of three plant communities: (i) ephemeral forbs and grasses forming a treeless, sparsely covered runoff zone, (ii) a grassy transfer zone immediately above a (iii) mulga grove with a dense understory of perennial forbs and grasses forming a run-on zone. When small storms occurred at our West Texas study site, the tarbush-sodgrass acted as a water source for the tarbush-bunchgrass sink. Likewise, the mesquite-sodgrass ct supplied run-on to the juniper-bunchgrass sink. However, during large storms, data indicate that bunchgrass communities may act as water transfers rather than sinks; if infiltration capacity is exceeded some overland flow will pass through the bunchgrass cts.

The proportion of source and sink areas that develop may be related to rainfall. In regions with relatively low rainfall, larger source areas would be necessary to support sink areas. The desert bands described by MacFadyen (1950) and Hemming (1965) occurred in a region of Somalia that receives about 150-mm rainfall annually and the source to sink ratio was 4:1 compared with 2.4:1 found at this site in the Chihuahuan Desert, where annual precipitation is 310 mm. These ratios are also dynamic. Valentin and d'Herbes (1999) compared photos from 1962 to 1995 and found the band:interband ratios varied from 0.51 to 2.33. The ratio increased from 1.13 in 1962 to 2.3 in 1992.

Because microcatchments were intentionally placed to avoid woody plants, the influence of woody plant canopy on resource reallocation cannot be determined by this study. Additionally rainfall and runoff intensity data rather than event totals would allow us to further define and evaluate the impact of runoff behaviour.

Band migration was not part of this study, but efforts to measure upslope movement have been performed elsewhere (Montana *et al.*, 2001). New recruits of woody species were not observed, and dead, mature trees were seen along the downslope edge of the juniper-bunchgrass band. This could be interpreted as evidence of pattern migration, but Lopez-Portillo and Montana (1999) suggested that the downslope margins of mesquite stripes in the Chihuahuan Desert, Mexico, contract while the remainder of the pattern is stable and that migration is not essential for pattern subsistence. Specifically, as the mesquite stand matures evaporative demand exceeds available water supply. Individuals along the downslope edge die because they do not receive sufficient run-on. Band migration or possibly expansion and contraction in response to wet and dry years could be assessed by remote sensing of aerial photography. Microbiotic crusts were ubiquitous on soil surfaces in the sodgrass (source) communities. Their role in infiltration and runoff warrants further investigation.

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