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Islands of hydrologically enhanced biotic productivity in natural and managed arid ecosystems

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Abstract

The objective of this paper is to examine the spatial variability of islands of enhanced hydrologic activity and its application to remediation of degraded arid and semi-arid ecosystems. Factors causing high spatial variability of water in arid regions include precipitation, soil, physiography, and vegetation. Inherent heterogeneity of arid lands causes areas of runoff and run-on which lead to development of islands of hydrologically enhanced biotic productivity. These hydrologic islands are observed at the individual plant scale as well as in large area patterns of banded vegetation, playettes and playas, and beaded drainage networks where run-on and infiltration stimulate vegetation growth. To remediate degraded rangeland, it may be prudent to mimic nature by diverting water to target areas to create patterns similar to natural islands of hydrologically enhanced biotic productivity. Installation of structures such as water ponding dikes can promote changes to natural vegetation patterns at a landscape scale.
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1. Introduction

Conversion of grasslands to shrublands is a serious problem throughout the Chihuahuan Desert. Peters and Havstad (2006) emphasized the importance of cross-scale interactions for establishing vegetation pattern. Variability of water delivery (amount, timing, etc.) is a critical factor that affects all five hierarchal scales, from plant/interspace to geomorphic unit. On an average annual basis (1915–1995), the Jornada Experimental Range (JER) receives 245 mm of precipitation, placing it in the arid climatic zone (<250 mm), although higher elevations in the mountains of the Jornada Basin are in the semi-arid climatic zone (250–500 mm). If this 245 mm of precipitation input were evenly distributed throughout the year, the landscape would appear very stark. Fortunately, there is an asymmetric precipitation regime, in which 53% of the annual total arrives in pulses between July and September, with a secondary peak in the winter months (see Snyder and Tartowski, 2006). This heterogeneous precipitation regime is one of the many reasons that more surface and near-subsurface water is available at certain times of the year in the Jornada Basin, causing some areas to be very productive.

In order to produce runoff and areas with accumulated water, spatial and temporal variations in atmospheric, land surface, and subsurface characteristics are necessary. Spatial distribution of precipitation is determined by elevation and topography as well as local weather patterns. Convective storms, typical of summer rainfall in deserts, distribute precipitation unevenly across the landscape, depending on the storm track of each event. These discontinuities in precipitation, in conjunction with distinct boundaries and transition zones between soil, physiographic, and vegetation types, support discontinuous areas of increased biotic production.

Several investigators have documented the presence of "islands of fertility" or "resource islands" in the Chihuahuan Desert and other arid and semi-arid ecosystems at the scale of individual plants (Noy-Meir, 1985; Schlesinger et al., 1990). In general, most ecosystem function in desertified ecosystems is located under vegetation as opposed to the barren interspaces between shrubs. Biotic processes, such as deposition of plant litter beneath the shrub canopy, produce feedbacks that create and maintain these islands of fertility. Shrubs remove essential nutrients and water from soil in the shrub interspaces and transport them to the shrub island (Schlesinger and Schmidt, in press). Certain shrubs, such as mesquite (*Prosopis glandulosa*) and acacia (*Acacia constricta*), possess nitrogen-fixing bacteria in their root systems that accumulate nitrogen beneath the shrub canopy (Virginia and Jarrell, 1983; Lajtha and Schlesinger, 1986). Soil water infiltration rates are greater under shrub canopies as a result of protection from raindrop impact and compaction and increased organic matter, which improves soil crumb structure (Schlesinger et al., 1999; Wainwright et al., 1999, 2000). Stemflow and throughfall are also concentrated beneath the shrub canopy (Martinez-Mesa and Whitford, 1996; Abrahams et al., 2003).

In addition to increased nutrient availability in these small "islands of fertility" or "resource islands," a low annual average precipitation requires hydrological discontinuities to promote enhanced vegetation production. In this paper, we refer to areas with increased availability of run-on or accumulated water as "islands of hydrologically enhanced biotic productivity" and discuss how these hydrological islands can be produced, established, and maintained. Fertile islands and hydrological islands at multiple spatial scales exist not only in the Jornada Basin, but are also characteristic of other arid and semi-arid regions (Whitford, 2002). Delivery of precipitation is temporally and spatially heterogeneous; the subsequent irregular distribution of water further increases heterogeneity, and the biological response to water availability is heterogeneous due to differences in soil and plant characteristics. This situation creates a positive feedback that reinforces heterogeneity across scales and also increases the dynamics of the system. Although resource islands are usually examined at the plant scale, hydrological islands are obvious at a range of scales. The objective of this paper is to examine factors that affect runoff/run-on, scales of islands of hydrologically enhanced biotic productivity, and application to remediation of degraded rangelands.

2. Spatial heterogeneity characteristics affecting runoff generation in arid regions

2.1. Precipitation

Various characteristics of precipitation interact with soil properties and resulting infiltration rates to determine amount of surface runoff that will occur. As a result, the same rainfall intensity that produces 15 mm of runoff in one area may produce little or no runoff in a nearby area because of differences in soil type, antecedent moisture, and vegetation cover. Additionally, precipitation amount, duration, pattern and extent, type and sequence of storm events, and seasonality all influence the redistribution of precipitation. The southwestern United States is noted for great variability in precipitation from location to location, time to time, season to season, and year to year. Convective precipitation is dominant in the Jornada Basin, as it is throughout the Southwest. Thunderstorms in this region are the primary runoff generators and are typically of short duration (1–2 h), high intensity (up to 250 mm h^{-1} for 5 min is common), and over a very limited area (Renard, 1988). In such climates, the coefficient of variation of precipitation is large. At the JER, the mean annual rainfall ranges from 213 to 349 mm and averages about 245 mm.The coefficient of variation of precipitation ranges from 25% to 43%, with a median value of 36%. Most rainfall events in the Jornada Basin last for an hour or less (Wainwright, in press).

Runoff generated at one site can become run-on for another site that may have had no direct precipitation. Parsons et al. (1999) reported that run-on water flowing in hillslope rills at two southwestern sites had transmission losses an order of magnitude greater than infiltration losses in adjacent interrill areas. Effects of the run-on process are very important to the biotic productivity of desert regions.

2.2. Evapotranspiration

Evaporation from a free water surface in the Jornada Basin averages about 2460 mm yr^{-1} or about 10 times the average annual precipitation (Gile and Grossman, 1979). Average annual potential evapotranspiration in the northern part of the Chihuahuan Desert is about 1690 mm yr^{-1} or about seven times the average annual precipitation (Whitford, 2002). This large discrepancy between available water (free-standing and loosely bound soil water) and available energy for water evaporation assures that any excess water at or near the surface will be quickly depleted by evaporative processes. Therefore, the available water storage capacity of dry impoundments, playa lake beds, and soil is usually large, and some portion of precipitation (or run-on) will enter into storage.

2.3. Soils

In the southwestern United States, soil formations reflect the persistent absence of moisture. Infiltration rates are controlled by soil type, but the overall rate and amount of infiltration is low (Renard, 1988). Low infiltration amounts are due to the short duration of precipitation events, relatively shallow soil depths in mountainous and hilly desert regions which limit size of the soil water reservoir, the common occurrence of impervious caliche (i.e. calcium carbonate) layers, the presence of impeding layers (e.g. surface crusts), and the absence of impediments to overland flow (Renard, 1988). Impervious caliche layers are present at various depths in the Jornada Basin. Soil texture in depressions, waxes from shrub leaf litter, platy structure of surface soils, and hydrophobic cyanobacterial crusts on north-facing slopes of coppice dunes contribute to the low permeability of soils in the Jornada Basin (Kidron, unpublished data; Mabry et al., 1977; Verrecchia et al., 1995; Gutschick, in press). One underlying characteristic of arid regions that greatly affects runoff is the generally large percentage of bare soil (ranging from approximately 60% to over 90%). The infiltration rate of bare soil is much less than for similar vegetated soils; consequently, surface runoff is greater (Wainwright et al., 2000; Abrahams et al., in press). Some locations at the JER and other areas of the Southwest that have sand, loamy sand, or sandy loam soils exhibit high infiltration rates that negate overland flow despite high percentages of bare ground and being located on a sloping alluvial landform. Alluvial fans are formed at the outlet of mountain valley streams, with alluvium deposited as slope and stream velocity decrease. Fans coalesce over time with those from adjacent valleys into a broad and complex bajada or piedmont slope (Whitford, 2002). Infiltration rates are also increased in desert soils due to increased macroporosity associated with activities of burrow/tunnel-constructing invertebrates (Whitford, 2002).

2.4. Physiography

In many arid regions, the topography is dominated by rolling hills or outwash from mountain systems with steep land gradients and slopes commonly exceeding 50% (Renard, 1988). In these physiographic regions, the presence of bare soil and rocky slopes can produce a large amount of surface runoff near mountains. The amount can be significant because precipitation is increased in these same areas due to orographic lifting.

A weak relationship exists between drainage density and precipitation because of the more dominant effects of rock, soil type, and vegetation. Once these important surface features have redistributed precipitation, the resulting surface runoff is a more direct determinant of drainage density. Surface runoff often flows into rills and stream channels quickly. It is not unusual to observe flows as great as $8.5\,\mathrm{m^3\,s^{-1}}$ in ephemeral channels during summer thunderstorms in the Southwest. Furthermore, it is common for flows of this magnitude to be completely lost through infiltration in a reach of less than 15 km (Branson et al., 1981). Transmission losses in Jornada Basin hillslope rills vary from 23% to 51% (Parsons et al., 1999). Sediment yields are large in these arid regions, with a maximum occurring at about 300 mm of annual precipitation (Langbein and Schumm, 1958), placing the Jornada Basin near the peak in sediment production.

2.5. Vegetation

Associated with precipitation, evapotranspiration, soils, and physiography are various vegetation characteristics that influence the generation of runoff. Physical structure of vegetation influences surface water accumulation from stemflow and plant distribution influences overland flow paths. Vegetation type, canopy areal cover, and canopy structure all affect the amount of water that can be lost to the atmosphere through leaf stomata during various seasons. This vegetative loss influences moisture remaining in the soil, which subsequently influences infiltration rate and amount of surface runoff generated. Old vegetation root channels and other macropores can cause increased infiltration as they create large voids which transport water away from the soil surface more rapidly than normal infiltration/percolation processes (Branson et al., 1981).

Another vegetation process, hydraulic redistribution, can transport recently precipitated water from the surface to deeper, drier soil layers. This process is essentially the reverse of hydraulic lift, in which deeply rooted plants redistribute water from deeper, wetter soil layers to shallow, drier soil layers for use by the plant (Ryel et al., 2002; Hultine et al., 2003). Infiltration rates and surface runoff generation can be influenced by whether surface soil layers are gaining or losing water through hydraulic redistribution.

3. Islands of hydrologically enhanced productivity at different scales on the landscape

3.1. Plant scale

At the scale of individual plants, hydrological islands are closely aligned to resource islands because water is one of the resources concentrated beneath the plant canopy (Schlesinger et al., 1990; Reynolds et al., 1999). For an individual plant, interception of precipitation reduces raindrop impact energy and compaction of the soil surface and promotes throughfall and stemflow. When the intercepted water retained in the plant canopy evaporates, soil moisture is conserved because the energy consumed by evaporation reduces energy available to induce transpiration (Lee, 1980). Infiltration rates are greater under plant canopies, allowing more water to enter the soil. Evapotranspiration above plants is greater than above bare soil, which reduces the soil moisture reservoir beneath the plant canopy; however, the plant root system exploits available soil moisture in the plant interspaces (bare areas). At the individual plant scale, resource islands and hydrological islands co-occur and are complementary to each other.

At the JER, creosotebush (*Larrea tridentata*) is the dominant species in shrublands on bajada slopes. This plant is particularly adept at concentrating intercepted rainwater at its base where it is available for infiltration. This water is unusually rich in nutrients extracted from the leaves and wood of the plant and dryfall and microbial crusts on the shrub stems (Whitford et al., 1997). Dye-tracing studies indicate that some of this nutrient-rich water penetrates to considerable depths along root channels and macropores (Martinez-Mesa and Whitford, 1996). This deep storage is available to shrubs during drought (Nulsen et al., 1986; Reynolds et al., 1999), thereby affording them a distinct competitive advantage over shallow-rooted plants such as grasses that are unable to use this moisture source (Abrahams et al., in press).

In a series of experiments conducted at the JER by Tromble (1983, 1988), Wainwright et al. (1999), and Abrahams et al. (2003), it was determined that the average canopy storage on an individual creosotebush after a precipitation event is 4 mm.Average storage values for individual experiments ranged from 3.6 to 4.7 mm.Further, interception by the creosotebush canopy caused a significant decrease in drop size, fall velocity, and proportion of precipitation reaching the ground. Mean subcanopy rainfall intensity was reduced by 10% and mean kinetic energy by 30%. Canopy density controls these reductions and the enrichment of coincident hydrologically enhanced islands and resource islands. Enrichment results from (1) a slower rate of soil surface sealing below shrubs than in adjacent intershrub areas, and (2) a greater plant litter accumulation under shrubs. Both effects promote infiltration and enhance moisture status under the shrub canopy, while increased litter enriches the under-canopy nutrient level (Abrahams et al., in press).

At the plant scale, vegetation can act as a barrier to slow runoff and promote infiltration. This process can create small terraces, or terracettes, that form centered on grass clumps and small shrubs (Bergkamp, 1998; Whitford, 2002). Similarly, a stair-step structure with amplitudes of 2–5 cm was observed in the microtopography of grassland areas (Parsons et al., 1997).

3.2. *Medium-to-large patches*

At medium-to-large patch scales (patches and patch mosaics; see Peters and Havstad, 2006), it is necessary to consider how the plant-interspace patterns relate to runoff generation and vegetation production. Across the Jornada Basin, the maximum surface area covered by vegetation that we have observed with high resolution aerial photography is approximately 35–40%, except on very small areas experiencing run-on water. When precipitation intensity exceeds infiltration rate (both of which vary during a storm event), excess water initially fills surface depressions and then flows downslope over the soil surface. For the same precipitation intensity, more surface runoff is generated in bare interspaces than areas with shrub (or grass) cover. Thus, bare soil (60–90% of the total area) has increased runoff during a storm event compared to the 10–40% with vegetation. Abrahams et al. (in press) used rainfall simulators to examine the factors controlling surface runoff on the creosotebush bajada at the JER. Factors considered were canopy cover, litter cover, gravel cover, soil texture, soil porosity, soil crusting, and animal disturbance. Results of experiments conducted across the bajada indicated that the most important control of water yield is the proportion of the soil surface covered by plant matter (vegetation or litter; Abrahams et al., in press). More runoff is produced as vegetation interspaces or bare areas increase because their soils are susceptible to development of physical and biological crusts. When compared to grasslands, shrublands produce more frequent and larger runoff events. Mean runoff coefficients for grasslands and shrublands are 6% and 19%, respectively (Schlesinger et al., 2000; Abrahams et al., in press). The primary reason for greater runoff from shrublands is that two-thirds or more of a shrubland community may consist of barren intershrub areas with crusted surfaces and low infiltration rates. Grasslands have higher infiltration rates and a very different organization, with smaller and more regularly interspersed bare patches than shrublands. Additionally, litter is distributed more uniformly across the landscape in grasslands rather than being concentrated below individual plants as in shrublands.

At the JER, approximately 92% of the 783 km^2 experimental area is now dominated by shrubland (Gibbens et al., 2005). The three dominant shrubs on the JER are mesquite, creosotebush, and tarbush (*Flourensia cernua*). Although runoff percentages differ, the runoff generation processes active in each shrub community are similar and are dominant on the JER. Runoff produced becomes run-on for areas downslope. As is typical in deserts in the southwestern United States, runoff enters a rill system or stream channel and infiltration into the channel bed increases soil moisture, causing sparse riparian vegetation to grow along the channel. Attributes that slow down surface runoff (e.g. reduced slope) cause a hydrologic discontinuity that allows more time for infiltration to occur.

Vegetation is a common obstruction that slows runoff and increases time for infiltration, allowing nutrients, sediment, and litter transported in runoff to be deposited. This deposition results in a slight increase in elevation, enhancing development and persistence of the vegetation barrier. Over medium-scale areas, the vegetation barrier can consist of banded herbaceous and woody plants (Greene et al., 2001). This vegetation pattern is depicted in an aerial photograph of the Jornada Basin (Fig. 1), in which bright bands represent bare bands that generate surface runoff and dark bands denote vegetation bands where run-on infiltrates into the soil. Analysis of this polygon of banded vegetation (Fig. 1a) revealed 21% of the area was composed of bright "bare bands" and 79% was

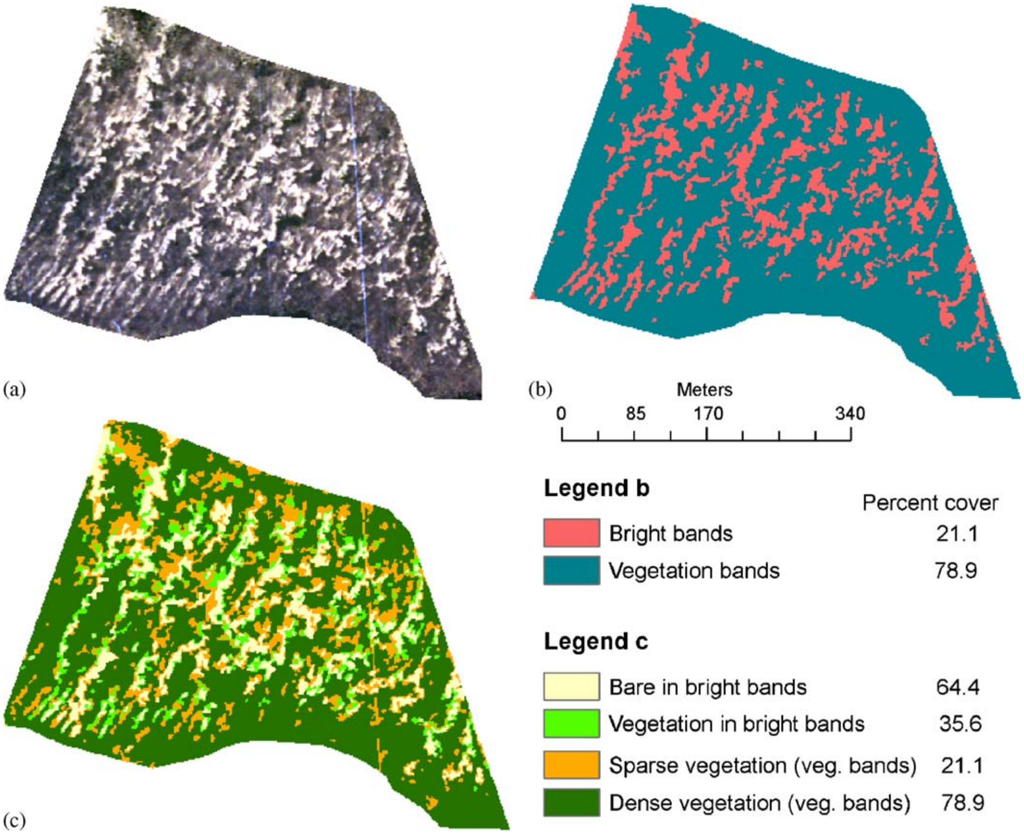

Fig. 1. Analysis of banded vegetation in the Jornada basin. (a) The original aerial photograph of a natural banded vegetation study area obtained from the United States Bureau of Land Management (October, 1980). (b) The areas covered by bare and vegetated bands. (c) The within band (bare or vegetated) percentages of bare soil, sparse vegetation, and dense vegetation cover.

dark "vegetation bands" (Fig. 1b). Within "bare bands," about 36% of the area actually contained some sparse vegetation cover (an intermediate signature between bare soil and dense vegetation), whereas the dark vegetation bands were composed of a mixture of dense and sparse vegetation cover (Fig. 1c). A discontinuity of vegetation and soil moisture occurs between runoff and run-on zones, with vegetated bands acting as islands of hydrologically enhanced biotic productivity. The vegetation barrier and resultant sediment deposition need not be extensive to be effective. Within the Chihuahuan Desert, bands are generally parallel to the contour lines (Cornet et al., 1988; Montana, 1992).

The occurrence of vegetation bands in water-limited environments can be interpreted as an evolutionary strategy for survival in areas normally lacking sufficient available soil water (Valentin et al., 2001). Vegetation bands accumulate water runoff from bare areas, and the biological systems within bands operate as if they were in an area of higher rainfall (Noy-Meir, 1973). Consequently, banded patterns act as natural water-harvesting systems (Valentin et al., 2001). Recent work regarding banded landscapes (Tongway et al., 2001) substantiated the theory of Noy-Meir (1973) that in environments with limited resources (e.g. water), vegetation productivity is greater if resources are concentrated into patches rather than being uniformly distributed over the landscape (Tongway and Ludwig, 2001; Valentin et al., 2001).

When surface runoff reaches small channels in the Jornada Basin, the water can discharge into small sinks in upland areas. These small playas, or playettes, can occur in clusters across the landscape (Doub and Colberg, 1996; Brostoff et al., 2001). Because of increased soil moisture in playettes, vegetative ground cover can be dense (comparable to vegetated bands). The dark spots on the landscape in Fig. 2 represent densely vegetated playettes. Their typical size is approximately 1.5 ha. Using QuickBird satellite image data, large differences in percentage of bare and vegetated area were detected within and outside playettes (Fig. 2). The average vegetation cover in playettes was 72% vs. 23% in the shrubland outside playettes (Rango and Laliberte, unpublished data).

3.3. *Catchment scale*

Although the Jornada Basin is a closed drainage, there are several features at the catchment scale (landscape and geomorphic units; see Peters and Havstad, 2006) related to hydrologic discontinuities. Ephemeral stream channels are organized hierarchically on the bajada slopes from the mountains to the valley bottoms. At the top of the bajada slope, runoff/run-on is due to precipitation in excess of infiltration and sand-bedded streams issuing onto the head of the bajada from the mountains. Smaller streams terminate near the top of the bajada, while larger ones reach the lower areas of the bajada. These larger streams have alternating single- and multi-channel reaches. At times, multi-channel reaches become reaches without clearly defined channelized flow termed beads because they are reminiscent of beads spaced on a necklace (Fig. 3). At the downstream end of a bead, flow coalesces into a single channel. Except for the uppermost bajada, these reaches have sandy beds (Abrahams et al., in press). It is unclear if the alternating sequences of beads and single channel reaches are coherent hydrological units. Beads appear to be important sinks for water within bajadas.

Because no water flow exits most of the Jornada Basin today, several playa lakes are present in the basin that fill when sufficient runoff travels through channels to the basin floor despite infiltration into channel beds. Playa filling usually occurs during large

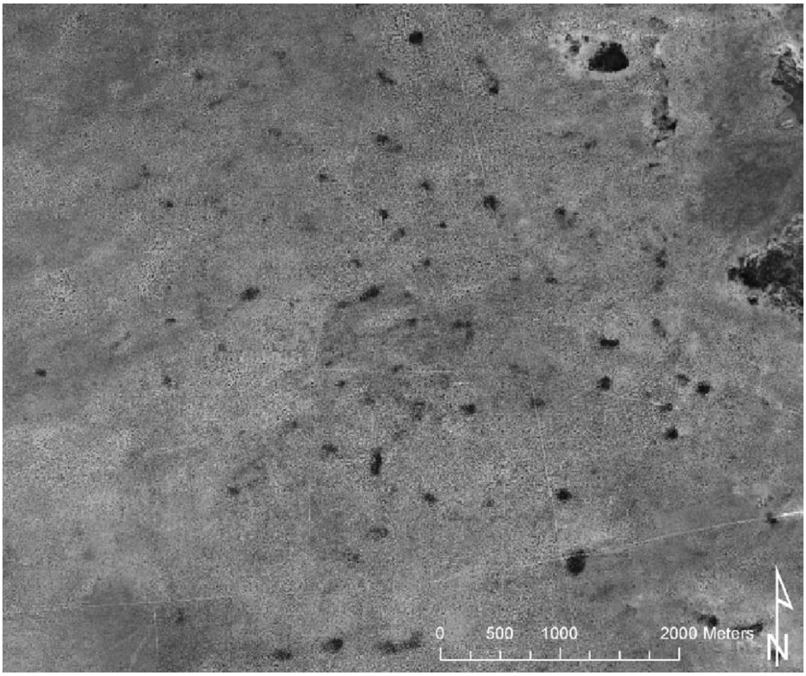

Fig. 2. Quickbird image (September, 2003) of an area of the Jornada Basin uplands pockmarked with natural low points or sinks in the topography containing more dense vegetation (dark areas), also called playettes.

precipitation events, principally during monsoonal rains. Vegetation growth in and around playas occurs after the lake water has evaporated or infiltrated the lake bed. Storms that fill playas are large-scale runoff events that can result from slow-moving, intense summer thunderstorms. Generally, less intense winter rains do not produce enough runoff to reach the larger playas on the basin floor. Small precipitation events that occur in close proximity to playas can cause partial filling (Van Vactor, 1989).

3.4. *Interactions across scales*

Islands of hydrologically enhanced biotic productivity occur at multiple scales, but interactions exist across scales that influence patterns of water redistribution. The size, number, arrangement, and connectivity of hydrologic sinks determine the storage of water upslope and availability of run-on water downslope (Puigdefabregas et al., 1999). For example, effective capture of water by banded vegetation upslope can reduce frequency and amount of water delivered to playas downslope. In arid and semi-arid landscapes, there is often a nonlinear negative relationship between runoff m^{-2} and catchment size due to the presence of hydrologic sinks within basins (Wilcox et al., 2003).

Water may be redistributed into several small sinks, such as discontinuous plant interspaces, or a few large sinks, e.g. playa lakes on the basin floor. It appears that limited variation in water inputs tends to create small islands, while large amplitude variation in inputs associated with large events, steep slopes, and high connectivity tends to create

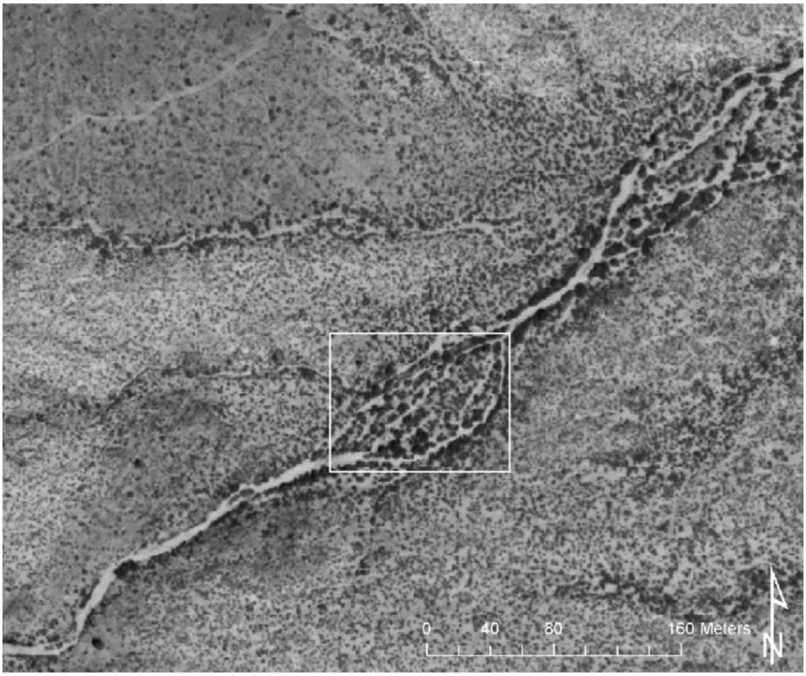

Fig. 3. Quickbird image (September, 2003) of channel and bead drainage networks on the Summerford Mountain bajada slope on the Chihuahuan Desert Rangeland Research Center in the Jornada Basin. One bead in the drainage network is enclosed in the white box.

larger islands. Temporal and spatial heterogeneity of water inputs and infiltration capacity promote the development of a diverse set of hydrologically enhanced islands at multiple scales. The cross-scale pattern of hydrologic sinks is broadly constrained by climate (especially precipitation pattern), geomorphology, soils, and historical legacies, but can be modified by ecohydrological feedbacks through vegetation.

Hydrologically enhanced islands are dynamic features of the landscape. Within-scale renewal of islands associated with migration of bands and beads or shifting mosaics of vegetation patches is likely. However, the accumulation of small changes or instability of positive feedbacks can alter the buffering capacity and outputs of hydrologic sinks, causing changes in islands at larger scales (Wu and Archer, 2005). Each scale is also subject to reorganization of the pattern of islands by larger scale impacts that overwhelm existing islands. Extreme events such as millennial downpours or climate change that increases storm intensity can shift dominant sinks to larger scales. Whether top-down (external) or bottom-up (internal) processes dominate, if the buffer capacity of the hydrologic sink is overwhelmed, a nonlinear threshold is crossed and the increased connectivity for water transport creates an opportunity for downstream or large scale islands to develop, potentially restructuring the size, distribution, and arrangement of islands of hydrologically enhanced biotic productivity.

Hydrologic discontinuities at multiple scales are an important source of habitat diversity, which supports related biological diversity. Degraded landscapes sometimes lose this cross-scale diversity of resource islands. For example, decreased upslope vegetation may increase runoff and water delivery to large playas while an invasive weed species upslope may capture more water and prevent large playas from filling. A landscape with a mixture of hydrologic sinks at multiple scales may be more effective in capturing the full range of variable precipitation patterns, more resistant to catastrophic floods or droughts, and more resilient to climate change or other disturbances (Van de Koppel and Rietkerk, 2004).

4. Remediation of degraded rangeland

As described for playettes, banded vegetation, and beaded drainage networks, natural processes can promote islands of hydrologically enhanced biotic productivity. A clearer understanding of the natural processes leading to hydrologic islands may improve our ability to successfully rehabilitate degraded rangelands by mimicking nature when water is a key remediation factor. For example, the concepts presented in Tongway et al. (2001) regarding banded vegetation led to an understanding that heterogeneous landscapes are more ecologically sensible and sustainable than homogeneous systems. These concepts led us to create management structures that favor trapping of runoff, sediments, and nutrients along the contour to establish vegetation patches (Valentin et al., 2001). Various types of structural features have been employed in the Jornada Basin to alter surface water flow, but only a few efforts have provided positive results.

4.1. Early attempts

During the 1930s and early 1940s, Civilian Conservation Corps labor was used to implement a variety of treatments on rangelands in the western United States to halt shrub encroachment and restore native grasslands. Several treatments were tested in the Jornada Basin. In one experiment, brush was cut and piled into low barriers roughly perpendicular to the direction of local overland flow and anchored to the ground with wire ties at 60–90 cm intervals. The purpose of these "brush spreaders" was to slow surface runoff and cause water to spread out behind the brush piles, infiltrate the soil, and promote grass growth. This treatment was compromised over time by water and wind eroding brush from the spreaders, causing gaps through which water easily flowed. Sections of the brush spreaders were visible for 35 years (Rango et al., 2002), but the gaps that developed early limited their effectiveness to 10–20 years. The ineffectiveness of brush spreaders was compounded by a lack of post-installation maintenance, structural weaknesses in various parts of the spreaders, and perhaps, animal disturbance.

Another treatment initiated in 1935 was the construction of contour terraces with a road grader to slow water flow down relatively steep slopes. On the New Mexico State University Chihuahuan Desert Rangeland Research Center (CDRRC) located adjacent to the JER, 21 contour terraces with a total length of approximately 24 km covering about 85 ha were constructed on a 3–5% slope. Rock weeps were installed in the terraces to release ponded water slowly and prevent breaches of the terraces. Today, little evidence of the terraces remains; no maintenance was regularly performed on these terraces, and little vegetation improvement could be attributed to them. The contour terraces remained until about 1972 (Rango et al., 2002) but were eventually eroded away by persistent water flow down the slope. No natural means for slowing water flow down bajada slopes as steep as 3–5% has been observed on a scale as large as attempted here.

Several types of contour furrows were also installed on the CDRRC in 1939. The furrow spacing in some areas was only 1 m. As with previous treatments, no maintenance was performed. These furrows were unprotected due to sparse vegetation cover, and water running off the bajada slopes washed them away by 1960 (Rango et al., 2002).

These failed treatments had several things in common. First, no maintenance was provided for these treatments and they quickly wore away in the Chihuahuan Desert environment. Second, the installations bore no resemblance to "natural" landscape features or patterns found in this area. Third, landscape-scale processes continuously occurring in this area (i.e. wind and water erosion, conversion to shrubland) simply overwhelmed these treatments. Later treatment attempts in the Jornada Basin more closely mimicked nature and were more successful despite a lack of maintenance.

4.2. Successful treatments

Water ponding (or retention) dikes have been used on arid and semi-arid rangelands to slow surface runoff, reduce soil erosion, increase soil moisture, and increase forage production. Historic experiments with water ponding dikes indicated that they are more effective on medium- and fine-textured soils than on coarse-textured soils in areas with annual precipitation exceeding 200 mm and sufficient rainfall intensity to generate significant overland flow (Bennett, 1939).

Earthen dikes built along the topographic contour on the JER were of a relatively simple construction and inexpensive to install. The water ponding dikes installed between 1975 and 1981 were three different heights: 7.5, 15, and 30 cm.Dike length ranged from 50 to 148 m and averaged 87 m. Additional details regarding these dikes appear in Table 1. The dikes were designed to be crescent shaped so that any excess water would flow around the ends. Without maintenance, however, breaches developed in the dikes and water flowed both through the breaches and around the dikes. In the mid-1980s, the dikes were unattended due to retirement of the principal investigator. It was not until the late 1990s that interest in the dikes was revived and analysis of historical aerial photographs and field measurements were initiated.

When measurements were terminated in the mid-1980s, some positive results were already evident for Taylor Well and Ace Tank dikes. Table 2 contains annual precipitation and forage production for the 7.5-cm water ponding dikes reported by Tromble (1984). The dikes resulted in a 3.9-fold average per year increase in forage production compared to the control area. The effectiveness of 7.5- and 15-cm water ponding dikes is illustrated in Fig. 4. At the end of July 1979, soil in the control area was uniformly dry down to 180 cm,

Table 1
Attributes of five sets of dikes/water spreaders established on the Jornada Experimental Range in southcentral New Mexico

Location	Date installed	Height	Number of dikes	Soil texture
Taylor Well	1975	7.5 cm	5	Fine
Ace Tank	1975	15 cm	5	Fine
Brown Tank	1978	15 cm	3	Fine
Doña Ana Exclosure	1981	30 cm	12	Medium–Coarse
Yarbrough Dam	1974	Variable	Variable	Medium

Table 2
Annual precipitation and forage production (kg ha^{-1}) for 7.5 cm water ponding dikes on the Jornada Experimental Range[a]

Year	Annual precipitation (cm)	Forage production (kg ha^{-1})		Factor of increase
		Control	7.5 cm dikes	
1980	18.3	1084	2935	2.7
1981	36.6	1613	3854	2.4
1982	23.4	215	976	4.5
1983	17.0	165	997	6.0
Mean	23.9	769	2190	3.9

[a] Adapted from Tromble (1984).

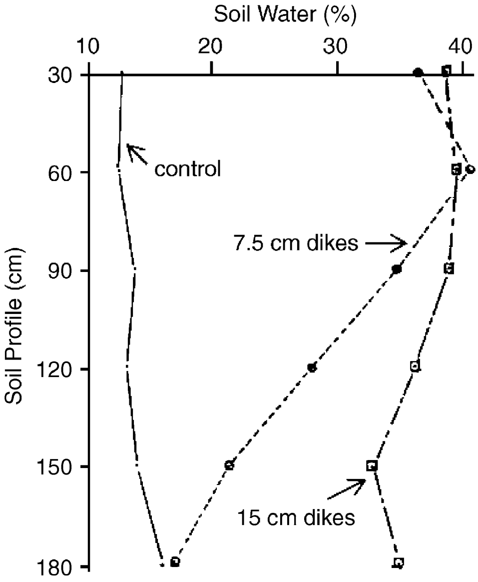

Fig. 4. Soil water profiles for control, 7.5-cm dikes, and 15-cm dikes on the Jornada Experimental Range (July, 1979; from Tromble, 1982).

whereas the 7.5-cm dikes contained greater soil water near the surface and gradually decreased down to 180 cm.The 15-cm dikes contained nearly uniformly greater soil water down to 180 cm (Tromble, 1982).

In 1997, measurements were reinitiated on these dikes (Walton et al., 2001). From a sequence of aerial photographs, it was apparent that significant growth had occurred behind and around the dikes, clearly exceeding nearby areas that were considered controls. Fig. 5 shows a 1994 aerial photograph of the Ace Tank dikes that illustrates a positive vegetation response to treatment. Additionally, the pattern of dike vegetation is similar to “naturally” occurring banded vegetation from which slight increases in elevation due to vegetation and sediment deposition cause runoff water to slow down and infiltrate.

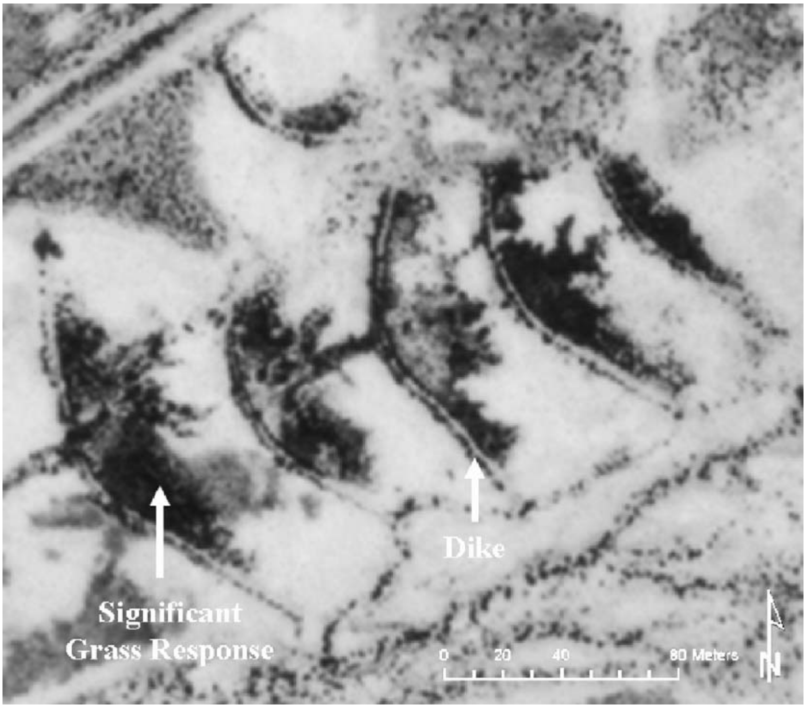

Fig. 5. Aerial photograph (1994) of water ponding dikes established in 1975 on the Jornada Experimental Range near Ace Tank, illustrating a positive response to treatment.

Significant rainfall events producing surface runoff are probably necessary to achieve a positive vegetation response. It may take several years/decades for these events to occur in arid environments (see Snyder and Tartowksi, 2006).

In 2004, soil moisture, soil texture, and vegetation measurements were collected from these dikes. These data for the Dona Ana dikes are shown in Fig. 6. Historic aerial photographs were used to select undisturbed reference or control areas adjacent to the Doña Ana dikes. Vegetation cover, species richness, and soil moisture (both upper and lower layers) were significantly greater behind the dikes than in similar unmodified areas (Fig. 6). These patterns occurred despite the fact that dikes were not maintained after installation in 1981 and were constructed in medium- to coarse-textured soils. Roads in arid and semi-arid regions that cut across the natural water-flow direction also serve as dikes or small dams and vegetation response is similar to that observed with water retention dikes.

Water spreaders, also tested on the JER, consist of a system of dikes, sometimes connected in a serpentine pattern, designed to automatically divert runoff from gullies or stream channels and spread water flow over adjacent floodplains, valley floors, and rangelands. The technique of water spreading is certainly not new as it was probably the first form of irrigation used by man (Houston, 1960). A water spreader was constructed in 1974 on the JER near the mountains in the course of an arroyo. The intent was to store water behind a manmade dam (Yarbrough Dam) from this watershed as well as from

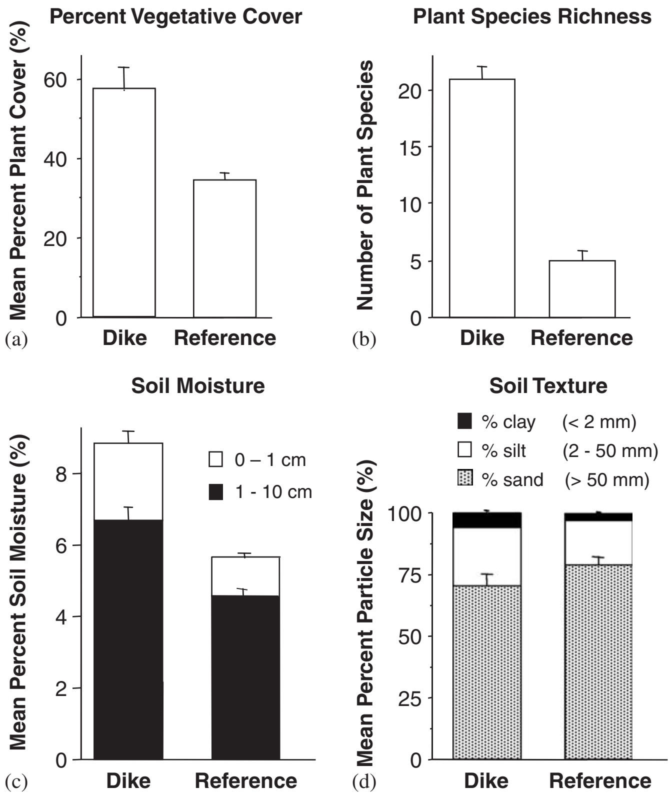

Fig. 6. Vegetation cover, species richness, soil moisture (0–1 cm and 1–10 cm), and soil texture data collected in 2004 at the Doña Ana dikes (constructed in 1981) and an adjacent reference area, indicating a persistent influence of dike construction.

adjacent diverted watersheds. Once a large volume of water was collected behind the dam, it could be released in a controlled discharge down the arroyo. The use of serpentine water-spreading dikes provided a longer length and time of flow than would occur if water were released directly down the arroyo. With the circuitous water route and highly pervious channel bottom, most of the water would be expected to infiltrate the soil before leaving the immediate area of the dam. A very strong vegetation response resulted from seeding with desired vegetation to capitalize on increased soil moisture along the spreader channel. Plant selection may be critical to the success of water spreading. Dikes and water spreaders are by far some of the most successful rangeland remediation treatments that have been attempted in the Jornada Basin.

5. Conclusions

In order to produce significant surface runoff in arid and semi-arid regions of the world, variability in atmospheric, landscape, surface, and subsurface variables and attributes is crucial. Generally, by slowing down surface runoff, water infiltration into soil is enhanced and vegetation productivity is increased. These areas of hydrologically enhanced biotic productivity occur at all hierarchical scales from the plant to the basin. At the plant scale, islands of fertility and islands of hydrologically enhanced biotic productivity coincide, particularly areas under shrubs. Vegetation bands (and bare bands) occurring at the medium-to-large patch scale have alternating areas of runoff production and infiltration. Larger catchments sometimes feature beaded drainage networks that create hydrologic discontinuities, as well as sinks for water accumulation such as playettes and playas. The principles described in this paper relate to all five key elements that connect landscapes at different scales (Peters and Havstad, 2006): transport processes, feedback mechanisms, historic legacies (e.g. historic treatments), spatial context, and resource redistribution. In order to rehabilitate rangelands, it is prudent to mimic the natural processes by providing time for surface runoff to infiltrate, thereby creating areas of potentially high vegetation productivity. The most successful treatments to date have been water ponding dikes and water spreaders. In order to design more successful remediation treatments, we need to better understand how hydrological islands of different sizes are distributed across the landscape and how they interact across scales.

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