Landscape Ecology vol. 11 no. 6 pp 351–362 (1996)
SPB Academic Publishing bv, Amsterdam

Relationships between landforms, geomorphic processes, and plant communities on a watershed in the northern Chihuahuan Desert

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Keywords: Erosion, deposition, limiting resources, runoff, water availability, ecotones, grazing, grassland, shrubland, desertification

Abstract

The close correlation of plant communities to landforms and geomorphic surfaces resulted from differences in the redistribution of water and organic matter between landforms in the northern Chihuahuan Desert. Biotic processes are limited by water and nitrogen, and the interactions between landforms, geomorphic processes, soils, and plant communities control the redistribution of these limiting resources within internally drained catchments. Geomorphic processes are regulated by the geologic structure and gross topographic relief of internally drained catchments over geological time scales. Land forming processes can be viewed as static at time scales of 10's to 100's of years, with individual landforms regulating geomorphic processes, namely erosion and deposition resulting from the horizontal redistribution of water within the catchment. The vegetation composition is a critical feedback, reinforcing the erosional or depositional geomorphic processes that dominate each landform.

The Jornada Long-Term Ecological Research site may be one of the simplest cases in which to decipher the relationship between landforms, geomorphic processes and plant communities. However, these geomorphic processes are common to all internally drained catchments throughout the Basin and Range Province, and result in the development of characteristic landforms and associated vegetation communities. Although the patterns may be modified by differences in parent material, watershed size, and land use history – erosional, depositional, and transportational landforms can still be identified.

The sharpness of ecotones between plant communities on individual landforms is related to the degree to which landforms are linked through the flow of water and sediment. Sharp ecotones occurred at the transition from depositional to erosional landforms where little material was transferred and steep environmental gradients are maintained. Gradual ecotones occurred at the transition from erosional to depositional landforms where large quantities of material were transferred leading to the development of a gradual environmental gradient.

The relationships between geomorphic processes and vegetation communities that we describe have important implications for understanding the desertification of grasslands throughout semi-arid regions of North America. Disturbances such as grazing and climate change alter the composition of plant communities, thereby affecting the feedbacks to geomorphic processes, eventually changing drainage patterns and the spatial patterns of plant communities supported within the landscape.

1. Introduction

Ecosystem studies in semi-arid and arid regions have shown that biotic processes, especially net primary production, are limited by the availability of water (Noy-Meir 1973; Szarek 1979; MacMahon and Schimpf 1981; Crawford and Gosz 1982; Ludwig *et al.* 1989). Further, strong relationships between plant communities and either soils or landforms have been shown by many studies in semi-

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arid regions. These studies suggest that the patterns of plant communities result from either the influence of soil properties on water availability or on the redistribution of water between landforms (Hunt 1966; Olsvig-Whittaker *et al.* 1983; Bowers and Lowe 1986; Mabbutt and Fanning 1987; Wondzell *et al.* 1987; Bowers 1988; Burke *et al.* 1989; Montana 1990; Schlesinger *et al.* 1990; Parker 1991; McAuliffe 1994; Ludwig and Tongway 1995; Wondzell and Ludwig 1995). Clearly, both primary productivity and the composition of plant communities in semi-arid and arid regions will be sensitive to the redistribution of water across the landscape (White 1971; Halvorson and Patten 1974; Yair and Danin 1980; Schlesinger and Jones 1984; Cornet *et al.* 1988; Schlesinger *et al.* 1989).

Much of the arid and semi-arid regions of North America lie within the Basin and Range Physiographic Province, which is dominated by internally drained basins where geomorphic processes operate in a predictable fashion (Peterson 1981). The combination of low plant cover and intense rain storms frequently generates runoff from landforms within the catchment. Internally drained catchments lack an outlet. Thus, runoff water runs onto depositional landforms lower in the basin. This horizontal redistribution of water and entrained sediment is regulated by interactions between landforms, geomorphic processes, soils, and plant communities. Over long periods of time, these interactions have resulted in the development of characteristic landforms and vegetation communities which repeat across the landscape.

We present a case study to illustrate these interactions. We first describe the landforms present along the original study transects at the Jornada Long-Term Ecological Research (LTER) site. We then describe how these landforms regulate geomorphic processes which, in turn, control the transport of water, sediment, and organic matter across the study site. Finally, we show how the redistribution of water explains the spatial pattern of plant communities at the Jornada LTER Site. Our work is based on previously published descriptions of the vegetation communities (Ludwig and Cornelius 1987; Cornelius *et al.* 1991), soils (Nash 1985; Wierenga *et al.* 1987), and geomorphic surfaces (Gile and Grossman 1979; Gile *et al.* 1981) at the Jornada LTER Site and the description and classification of basin and range landforms by Peterson (1981).

2. Study site

The study site is located in south-central New Mexico on the Jornada LTER Site (32°32'N, 106°47'W). This region lies within the Mexican Highland section of the Basin and Range province of North America (Fig. 1) and is characterized by north-south trending fault block mountains separated by broad linear valleys (Fenneman 1931; Hawley 1975). These valleys, which comprise at least 75% of the total surface area of this province (Blackwelder 1931), are most frequently closed basins with an ephemeral lake basin at the center (Peterson 1981). The landforms of the Basin and Range Province were classified by Peterson (1981).

The Jornada del Muerto is an internally drained basin, approximately 100 km long and 30 km wide that has resulted from faulting and warping relative to the bordering mountain ranges during the past 26 million years. Deposition of fluvial and alluvial sediment within this basin has exceed 1,000 m in depth over this period (Gile *et al.* 1981). Fluvial sediments were deposited by the ancestral Rio Grande river system (Strain 1966) whereas alluvial sediment was eroded from the bordering mountain ranges and deposited in extensive piedmont slopes along the mountain fronts (Gile *et al.* 1981). Fluvial deposition ended approximately 300,000 to 400,000 years BP when the Rio Grande incised its current river valley to the west.

The surface of the modern Jornada del Muerto basin is composed of a complex of smaller catchments. The original Jornada LTER research site was located within a 1,500 ha catchment draining the slopes of Mount Summerford, an isolated peak in the Dona Ana mountains which border the Jornada del Muerto basin to the southwest. Two major drainage networks are present within this catchment (Fig. 1). The original LTER transects are located between these two drainage systems on piedmont slopes which have been slightly dissected by localized runoff originating on the east flank of Mt. Summerford, or on the piedmont slope itself.

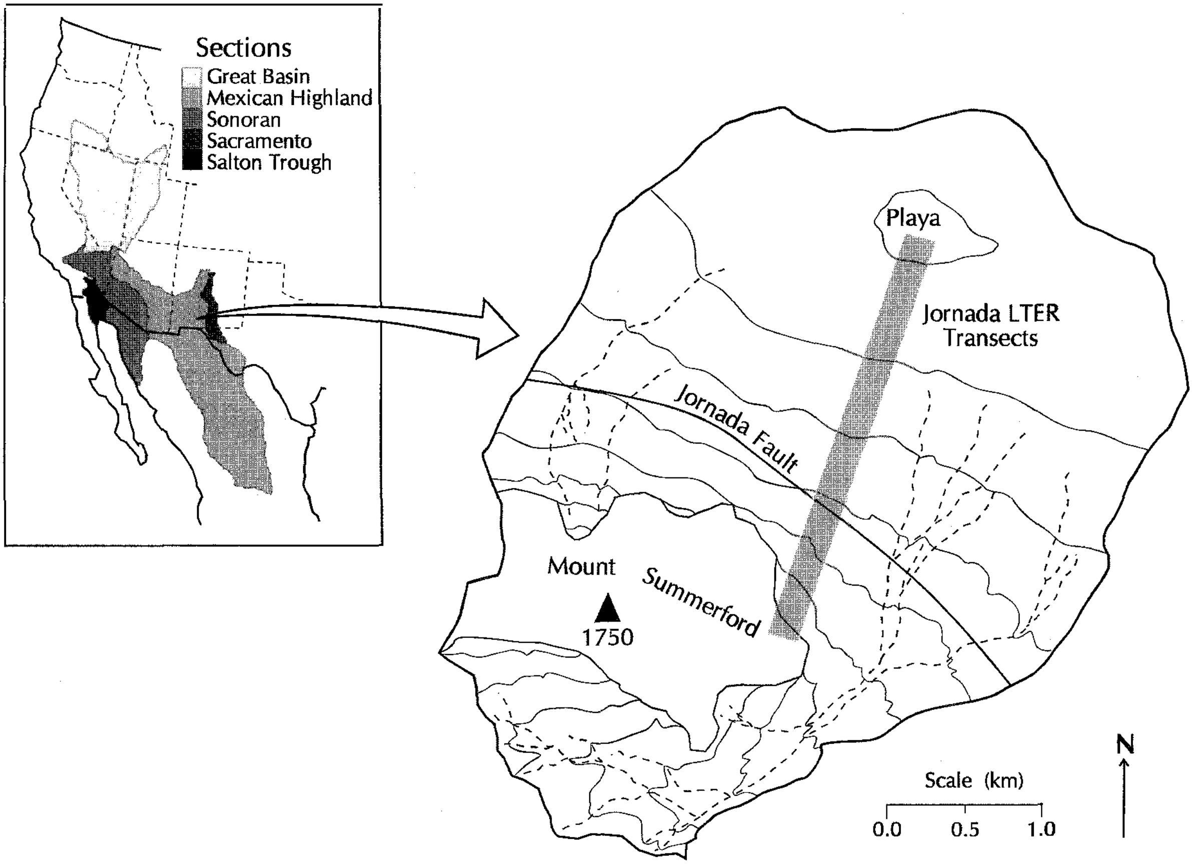


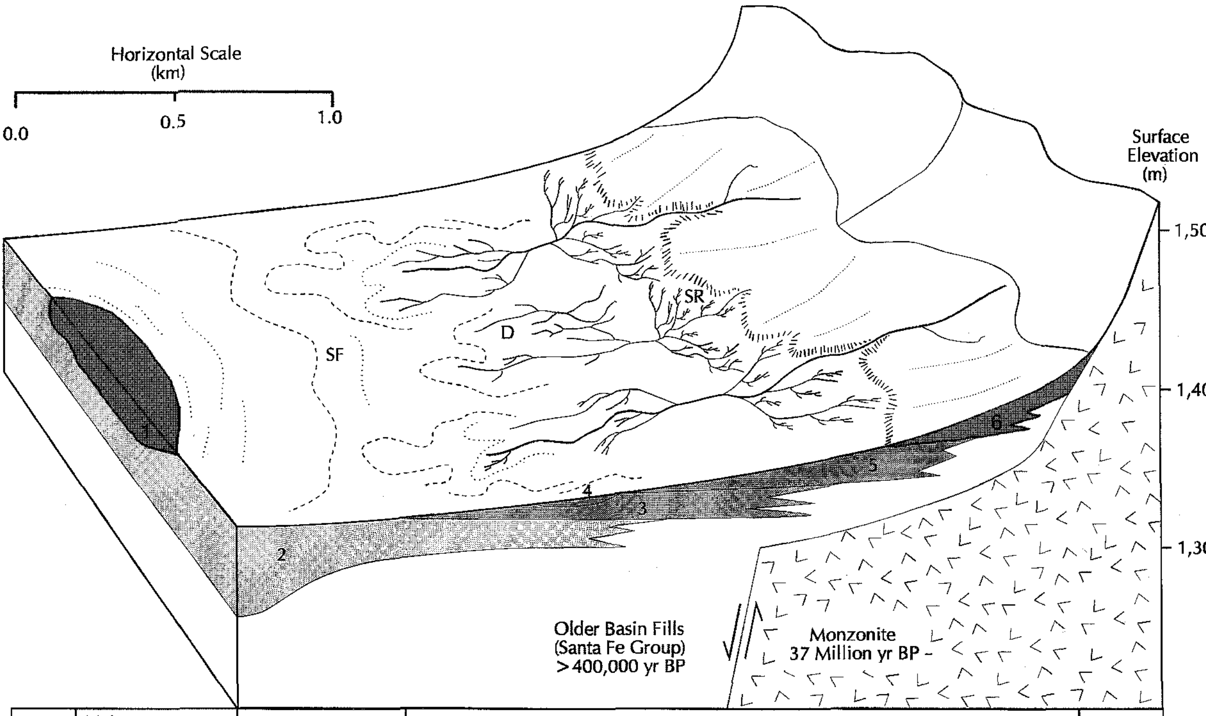
Fig. 1. Jornada LTER catchment showing location of the study transects, major drainage channels (dashed lines), and the location of the Jornada Fault. Contour interval is 15.5 m. Base elevation of the wathershed is 1310 m at the center of the playa. Inset shows the extent of the five sections of the Basin and Range Physiographic Province in the western United States and northern Mexico (adapted from Peterson 1981 and Ordonez 1936), and the location of the Jornada LTER Site.

3. Landforms of the Jornada LTER Site

The classification and terminology used to describe the landforms along the Jornada LTER transects follows Peterson (1981). The site is divided into three major physiographic parts at the broadest hierarchical level: mountain, piedmont slope, and basin floor (Fig. 2). The **mountain,** Mount Summerford, is the major source of runoff and the primary source of sediments within the catchment, but this small peak is poorly dissected, lacking deeply incised drainage networks.

The piedmont slope is a graded surface of alluvial deposits composed of sediment eroded from Mt. Summerford. There is a sharp break in slope marking the transition from the mountain to the adjacent piedmont slope (Fig. 2). The upper part of the piedmont slope is a thickly mantled, stone free, granitic pediment which extends from the toe of the mountain to the buried Jornada fault which is located at approximately mid slope. The erosional bedrock base of the pediment gives the catchment a concave longitudinal profile which decreasing gradients down slope, and a minimum of transverse relief. Although the pediment does determine the gross topographic relief of the piedmont slope, it is unaffected by modern pedogenic processes and is buried deeper than either the rooting zone of plants or water infiltration depths and thus does not directly affect present-day surface processes. The landforms which have developed in the sediment mantle do affect surface processes, and subsequent discussion will emphasize them.

The landforms and geomorphic surfaces on the piedmont slope have developed in distinct bands that increase in age with distance from Mount



LANDFORM	Major Physiographic Part	Basin Floor			Piedmont Slope							Mountain
	Major Landform	Playa	Alluvial Plain		Fan Piedmont					Alluvial Fan		
	Component Landform				Non-buried Fan Remnant		Alluvial Fan Apron		Erosional Fan Remnant	Fan Collar		
GEOMORPHIC SURFACE		1 Lake Tank	2 Jornada I		3 Jornada II		4 Isaacks' Ranch	5 Organ I		6 Organ II		
VEG.	Perennial	Playa	PF	Mixed Basin Slope					Creosote Shrubland	Lower Grass	Upper Grass	
	Annual			Lower		Middle		Upper				

Fig. 2. Block diagram showing key surface features of the central part of the Jornada LTER catchment traversed by the study transects shown in Fig. 1. (SR = Sheet Rill; D = Distributaries; and SF = Sheet Flow). Numbers 1 through 6 designate geomorphic surfaces aged at: (1) Lake Tank – present to 100,000 yr BP; (2) Jornada I – 250,000 to 400,000 yr BP; (3) Jornada II – 25,000 to 75,000 yr BP; (4) Isaacks' Ranch 8,000 to 15,000 yr BP; *(5)* Organ I – 2,200–7,000 yr BP; (6) Organ II – 1,100–2,100 yr BP. The longitudinal profile of the surface is drawn to scale, but the width of the block diagram, and the thickness and depths of contact between geomorphic surfaces shown in cross section, have been exaggerated for purposes of illustration. Classification of landforms follows Peterson (1981), geomorphic surfaces were described and dated by Gile and Grossman (1979), vegetation was described by Ludwig and Cornelius (1987) and also in Wierenga *et al.* (1987), and Cornelius *et al.* (1991).

Summerford. The **fan collar** is a superficial apron of coarse sediment, immediately adjacent to Mount Summerford, which has been deposited from both sheet wash and channelized flow originating on the mountain slope (Fig. 2). The fan piedmont, located down slope from the fan collar, results from lateral transport, mixing, and deposition of sediment which blurs the distinction between individual alluvial fans. This landform can be subdivided into three components which are present along the LTER transects. The **erosional fan remnant** comprises the upper portion of the fan piedmont which has been eroded, leaving remnants of the original constructional surface. The **alluvial fan apron** is located at mid slope where sediment from upslope landforms is deposited because longitudinal gradients decrease and drainage channels debouch onto the piedmont slope. The **non-buried fan remnant** comprises the lower portion of the piedmont slope where water cannot effectively dissect the surface because longitudinal gradients are too shallow, and where the original constructive surface is extensively preserved because the bulk of the deposition occurs up slope.

At their lower limit, piedmont slopes grade into the basin floor, which can be subdivided into two major landforms – alluvial plain and playa. The **alluvial plain** is a relic floodplain of the ancestral Rio Grande River which has not been buried with alluvial sediment, nor eroded. The **playa** is a local depression in the basin floor which is occasionally flooded, and contains thick accumulations of lacustrine deposits.

The individual landforms described above did not develop continuously throughout the Pleistocene and Holocene. Rather, these landforms resulted from recurrent cycles of landscape stability and instability associated with climatic changes during glacial and inter-glacial periods (Gile *et al.* 1981). Pleistocene pluvials coincided with periods of general lanscape stability (Hunt 1966). Plant cover increased on both mountain and piedmont slopes, rates of weathering of bedrock and sediments increased as did rates of soil formation (Peterson 1981). The transition to the dry periods which followed each pluvial coincided with periods of general landscape instability (Hunt 1966). Regolith weathered from bedrock during the pluvials was eroded from mountains and deposited in fan piedmonts, while finer sediments were transported across piedmont slopes and gradually filled basin floors (Peterson 1981).

These recurrent cycles of landscape stability and instability have formed a series of differently aged surfaces known as geomorphic surfaces, which have been described in detail by Gile and Grossman (1979) and Gile *et al.* (1981). Throughout the Jornada del Muerto, a single geomorphic surface may be represented by several landforms including both erosional and depositional forms. However, due to the characteristics of this portion of the catchment, these surfaces are ordered sequentially and tend to be associated with a single landform along the study transects (Fig. 2).

4. Geomorphic processes on each landform

We characterized the runoff patterns and associated sediment loads for each landform based on the development of the drainage network, and present-day evidence of erosion or deposition (Table 1). We also predicted a flow threshold – a combination of the intensity and duration of a storm necessary to generate runoff from each landform.

Mount Summerford is a major source of runoff and the primary source for sediments within the catchment. The steep slopes are mantled with boulders resting on bedrock forming small dams holding deposits of gravel and finer sediment. This landform should have a low to intermediate flow threshold because runoff from exposed bedrock occurs almost immediately following the beginning of a storm. Runoff is collected in sediment dams during small, low intensity storms. Larger storms produce runoff and the total volume of runoff increases proportionally to precipitation intensity.

The flow threshold of the **fan collar** must be higher than that of the mountain slope because the soils of the fan collar are coarse, with a high volume of fine gravel, and because 66% of the surface area is vegetated (perennial grasses comprise over half of the cover). There is a range of storm intensities which will generate runoff from the mountain slopes without exceeding the infiltration capacity of the fan collar. During these storms, runoff from the mountain slopes will infiltrate into the fan collar and entrained sediment will be deposited. Storms large enough to exceed the infiltration capacity of the fan collar must be rare since there is little evidence of surface erosion near the mountain front. Thus, the fan collar is dominated by depositional processes, receiving runon water and associated sediment eroded from Mount Summerford (Table 1). However, rare storms must generate runoff and erosion because most arroyos have their heardward limits on the lower portion of this landform.

The **erosional fan remnant** has perennial plant cover of 39%, two thirds of which is the desert shrub *Larrea tridentata*. The combination of fine soil texture and shallow depth to the indurated calcic horizon should limit the infiltration capacity of soils on this landform. Relatively low storm intensities exceed the infiltration capacity, generating runoff and erosion (personal observation). Today the surface of this landform is dissected by a network of rills and small channels and the root crowns of shrubs are pedestaled, standing 10 to 30 cm above the current soil surface. The erosional

Table 1. Summary of geomorphic processes dominant on each landform.

Landform	Ecotone	Slope (%)	Erosion / deposition	Flow threshold	Geomorphic process
Mountain		>33	Erosion sediment source	Low to intermediate	
	Sharp				
Fan collar		7–10	Deposition (rare erosion)	Intermediate to high	Headward extent of channels
	Sharp				
Erosional fan remnant		4	Erosion	Very low	Sheet rill / active channels
	Gradual				
Alluvial fan apron		2–3	Deposition	Intermediate	Sheet flow / loss of distinct channels
	Gradual				
Nonburied fan remnant		2	Transport	Intermediate	Sheet flow
	Gradual				
Alluvial plain		2	Transport	Intermediate	Sheet flow
	Sharp				
Playa		0	Deposition	Never	Flooding / lacustrine deposition

fan remnant cannot receive runon water, since runoff generated higher on the catchment is channeled into arroyos by the time it reaches this landform. Further, any storm that produces runoff from the fan collar would also exceed the infiltration capacity of the erosional fan remnant. Consequently, water is lost to runoff and sheet rill erodes sediment from inter-shrub spaces (Table 1).

Longitudinal gradients of the catchment continue to decrease with distance from the mountain front. Eventually, a point is reached at which the slope is insufficient for runoff to maintain a distinct channel. Here, channels disintegrate into a braided network of distributaries and runoff spreads laterally across the catchment. Most of the bedload and the coarser fraction of the suspended load of sediment are deposited, creating the **fan apron** landform. Both infiltration capacity and the flow threshold are high due to the coarser texture of the soils. Therefore, this landform absorbs all runoff originating on the erosional fan remnant during low intensity storms and should be dominated by depositional processes (Table 1). Of course, runoff from upslope landforms will be transported across the fan apron when storm intensity exceed the infiltration capacity of the fan apron, but most of the coarser sediment will still be deposited because it cannot be transported in sheet flow.

Neither the **nonburied fan remnant** nor the adjacent **alluvial plain,** have been actively eroded or buried. Sheet flow predominates below the alluvial fan apron because longitudinal gradients are shallow. Running water cannot dissect the surface and deposition does not occur because the bulk of the sediment is been deposited upslope. Infiltration rates and flow thresholds of these two landforms are roughly similar to those of the aluvial fan apron (Table 1). Therefore, storms of the same intensity exceed the infiltration capacity of all three of these landforms. Runoff originating higher on the catchment during these storms is transported as sheet flow across the nonburied fan remnant and alluvial plain into the playa. Because neither erosional or depositional processes predominate on these landforms, we characterize them as transportational landforms.

The catchment lacks an outlet for through-drainage. Runoff originating on the entire catchment during rare, high intensity storms occasionally floods the **playa** (Fig. 2), depositing clays eroded higher in the catchment.

5. Plant communities

The plant communities present on the study site were described by Ludwig and Cornelius (1987), Wierenga *et al.* (1987), Cornelius *et al.* (1991). The slopes of Mount Summerford supported a high diversity of vegetation, including species normally found under much wetter climatic conditions, such as *Juniperus* spp., because of horizontal redistribution of water between microsites on the **mountain** slope. Rain falling on bare rock runs into local depressions behind barricades of boulders, which also hold sediments and organic debris deposited during larger events creating mesic microsites. These microsites support a mixture of perennial grasses, shurbs, and some small trees.

Two grassland types have been identified on the **fan collar** (Fig. 2). Grasslands at the head of the fan collar had high cover of perennials (Table 2), and were dominated by *Bouteloua eriopodu.* The high cover of perennial grasses appears to stem from several factors. First, precipitation is effective on these loamy skeletal soils because runoff and evaporational losses are low (Noy-Meir 1973). Secondly, runon from the mountain slopes appears to supply additional water to the head of the fan collar. Lastly, nutrients appear to be retained and cycled within this plant community because organic matter is not lost to surface erosion (Schlesinger *et al.* 1990). Grasslands on the lower portion of the fan collar had lower total plant cover. The cover of perennials, especially grasses, was reduced and the cover of woody species was higher (Table 2). *B. eriopodu* was codominant, and many other species of perennial grasses and subshrubs were present. Runoff and erosion occur in this portion of the fan collar as indicated by the headward limit of arroyo channels. Apparently, the greater relative importance of erosion and the removal of some organic matter, combined with the lack of additional runon water leads to a reduction in the plant cover and the increased dominance by woody species.

The **erosional fan remnant** had low plant cover (Table 2) because the landform is dominated by erosional processes and runoff reduces the moisture available for plant growth. The plant community was dominated by the drought resistant desert shrub, *Lurrea tridentuta,* which comprised two-thirds of the plant cover. This shrub community has probably been present since pre-settlement times (Stein and Ludwig 1979). The soils of the erosional fan remnant are low in nitrogen (Table 2), and unlike the soils of the adjacent grassland, the nitrogen is heterogeneously distributed. Leaves dropped from the shrubs build up around the root crown of the plants, where the soil surface is protected from the impact of raindrops, creating “islands of fertility” (Garcia-Moya and McKell 1970). Sheet rill removes litter from the soil surface in the intershrub spaces, which are nutrient poor and tend to remain bare of vegetation, even in wet years.

Table 2. The cover of perennial and annual species during the fall of 1986, and the mean inorganic nitrogen concentration in the surface soil averaged for 9 sampling dates between 1983 and 1986.

Landform	Perennial cover (%)	Annual cover (%)	Inorganic nitrogen (mg kg^{-1})
Mountain	65.6	0.0	3.3
Fan collar			
depositional	76.8	5.0	5.5
erosional	55.3	10.9	2.6
Erosional fan remnant	39.0	1.4	2.7
Alluvial fan apron	35.0	40.2	4.0
Nonburied fan remnant	47.5	18.7	4.2
Alluvial plain	46.4	15.6	3.4
Playa	91.7	19.3	10.5

Larrea tridentata extends from the erosional fan remnant into the **fan apron** along the braided network of shallow distributory channels. However, it appears that the deposition of organic matter and the addition of runon water maintain a mixed community of perennial grasses, forbs, and subshrubs between these channels. Ephemeral species attain maximal cover (Table 2) and species richness on the fan apron. Since the storm intensities necessary to produce large volumes of runoff from upslope landforms are relatively rare, there should be a great inter-annual variability in the supply of resources. These conditions favor the development of a rich annual flora.

Both the **nonburied fan remnant** and the **alluvial plain** landforms support mixed communities of perennial grasses, forbs and subshrubs, though perennial cover is higher and annual cover is much lower than on the fan apron (Table 2). These transportational landforms are geomorphically stable and disturbance since settlement does not appear to have altered the distribution of resources within this portion of the catchment. Therefore, these areas have maintained a semblance of the primeval desert grassland even without additional organic matter or water supplied through runon.

The **playa** is the ultimate sink for nutrients and organic matter within the catchment. The heavy clay soils have the highest nitrogen content and support the highest perennial cover of any landform in the catchment (Table 2).

6. Discussion

6.1. Beyond the case study

The Jornada Long-Term Ecological Research site may represent the simplest case in which to decipher the relationships between landforms, geomorphic processes and plant communities. Mount Summerford lacks deeply incised catchments so landforms and geomorphic surfaces have development perpendicular to the mountain front. Mountain ranges with deeply incised catchments of varying sizes have multiple point sources for water and sediment where channels issue from the mountain front. Because large catchments may be adjacent to smaller catchments, erosional and depositional landforms may develop at varying distances from the mountain. Further, younger surfaces may be inset below and on top of older surfaces due to differences in size, topography, climate and the quantity of sediment produced. Finally, depositional landforms may be uncommon and erosional and remnant (inactive) landforms more common in catchments open to through-drainage. Despite these differences, erosional, depositional and transportational landforms with characteristic vegetation communities can still be identified (Peterson 1981).

The effect of geomorphic processes on plant communities also depends on the prevailing climate. Decreased soil moisture availability due to runoff leads to dominance by desert shrubs whereas increased availability of soil moisture leads to dominance by perennial grasses at the Jornada LTER Site. The horizontal redistribution of water in more arid sites may either influence the species composition between different shrub communities (Hunt 1966), or simply determine the biomass and density of desert shrubs rather than changing the lifeform (shrub *vs.* grass) of the dominant species within the community (Schlesinger and Jones 1984).

6.2. Geomorphic transitions and vegetation ecotones

The sharpness of ecotones appears to be related to the degree to which landforms are linked through the flow of water and sediment. The transition zones between erosional and depositional landforms range in width from less than 5 meters to over 100 meters, with associated vegetation ecotones that range from sharp to gradual, respectively. Sharp ecotones should be located at the transition from a depositional to an erosional landform where little material is transferred. The ecotone was only 10 to 20 m wide between the grasslands of the fan collar and the shrub dominated erosional fan remnant. The alluvial fan collar rarely produces runoff and therefore, only small amounts of material are transported across the ecotone. Occasional runoff from the fan collar during high intensity storms is channelled into arroyos. The effect on the ecotone between the fan collar and the erosional fan remnant is negligible because the transport of water and sediment is spatially restricted to the immediate arroyo channel. This rapid transition between depositional and erosional processes maintains a sharp ecotone between the plant communities on these two landforms.

Gradual ecotones should occur at the transition from an erosional to a depositional landform because large quantities of material are transferred across this ecotone. The ecotone between the shrub community on the erosional fan remnant and mixed plant community on the alluvial fan apron is gradual, with shrubs extending into the fan apron along distributary channels. Runoff from the erosional fan remnant transports sediment and organic matter to the alluvial fan apron where it is deposited in a wide band parallel to the contour of the slope. However, large channels extend much further down slope whereas small channels give way to sheet flow much sooner. The difference in size among distributary channels, variation in storm duration and intensity, and the large quantity of sediment deposited within this ecotone, lead to increased spatial heterogeneity in sediment deposition and a gradual transition from erosional to depositional processes. The ecotone between plant communities on these two landforms is correspondingly gradual.

Sharp ecotones between the plant communities are also present at the base of Mount Summerford and around the playa lakebed, even though large quantities of material are transported across these ecotones. Here, the environmental conditions of each landform are fixed by the topographic structure of the catchment and the transport of materials across these transition zones cannot lead to the development of a gradual environmental gradients. For example, the transition between the steep, exposed bedrock slopes of Mount Summerford and the alluvial fan collar, or the high water limit following occasional flooding of the playa lakebed (Wondzell *et al.* 1990) create steep environmental gradients that cannot be smoothed by transport and deposition of sediment. Consequently, vegetation ecotones remain sharp between these landforms.

6.3. Landscape structure

The landscapes of the Basin and Range province are structured by the underlying geology creating clearly defined erosional, transport, and depositional landforms, even though differences in slope or soil texture between landforms may be subtle. Although other authors have linked vegetation patterns to geomorphic processes in semi-arid environments, they have not necessarily linked the location and extent of erosional, transport, and depositional zones to the underlying geologic / geomorphologic structure of the landscape. Pickup (1985) described central Australian rangelands as a mosaic of erosion cells resulting from natural or grazing-induced disturbances that initiate erosion. Ludwig and Tongway (1995) describe vegetation patterns in central Australia as a mosaic of groves and intergroves resulting from the establishment and coalition of vegetation patches that initiate deposition of sediment. These two views are clearly applicable to areas of low topographic relief in central Australia, or large alluvial plain landforms of the Basin and Range Province in North America. Pickup (1985) also applied his model at a larger scale so as to include hillslopes (source) and alluvial plain (sink) landforms. Similarly, Ludwig and Tongway (1995) explained differences in vegetation patterns between low ridges (source) and swales (sink) on the basis of the redistribution of limiting resources. Our view differs only in that it is explicitly based on the underlying geology and geomorphology of internally drained catchments.

We choose not to describe the erosional fan remnant and alluvial fan apron landforms in the central portion of our study site (Fig. 2) as a mosaic of smaller erosion cells as suggested by Pickup (1985). We believe that landforms must be described within the context of the entire landscape wherever possible, regardless of terminology, because it provides a causal mechanism to account for the location of erosional and depositional surfaces within the catchment. We stress that these views are not incompatible. First, erosion cells and related vegetation patterns may be the dominant organizational feature at the landscape scale in regions of very low topographic relief. Secondly, erosion cells exist at the scale of individual landforms within internally drained catchments. For example, vegetation patterns on adjacent alluvial plain landforms (personal observation) suggest that smaller scale erosion cells redistribute water, forming vegetation bands such as those described by Comet *et al.* (1988) for the Chihuahuan desert or Ludwig and Tongway (1995) for central Australia. Thus, even though landforms are the dominant organizational feature in internally drained basins where topographic relief is much greater, the erosion cell concept remains important. Finally, we join with Pickup (1985), Ludwig *et al.* (1994) and Ludwig and Tongway (1995) in stressing that (1) conceptual models of landscape dynamics must include deposition zones along with erosion zones; (2) disturbance can change the location and extent of both erosion and deposition; and (3) the redistribution of limiting resources is a critical factor determining the spatial organization of vegetation communities and their productivity in semi-arid environments.

6.4. Landscape structure and vegetation dynamics

The relationships between geomorphic processes and vegetation communities have important implications for understanding the desertification of grasslands throughout semi-arid regions in North America. Many studies have described the replacement of extensive desert grasslands by shrubs, especially *Larrea tridentata* and *Prosopis* spp. (Griffiths 1901 and 1910; Leopold 1924; Gardner 1951; Buffington and Herbel 1965; Hastings and Turner 1965; York and Dick-Peddie 1969; Stein and Ludwig 1979; Gibbens *et al.* 1983; Hennessy *et al.* 1983; Neilson 1986; Gibbens and Beck 1988; Grover and Musick 1990; Gibbens *et al.* 1992; Bahre and Shelton 1993). The changes in vegetation composition have usually been accompanied by accelerated erosion and the cutting of arroyo channels. Several causal mechanisms have been proposed, most notably the grazing of domestic livestock and climatic change. However, these studies have usually lacked an understanding of the relationships between landforms and plant communities within the landscape, and failed to account for the interactive effects of geomorphic processes.

Pickup (1985) proposed the erosion-cell model to link sediment source zones, transfer zones and sediment sinks within the landscape and to show how grazing and climate change affect the size and location of these cells. We apply this concept to entire drainage basins in the Basin and Range physiographic province. The horizontal redistribution of water and sediment within closed basins leads to the development of characteristic landforms, geomorphic processes, soils, and plant communities over thousands of years (Bull 1991). Interactions between these factors are complex. Geology determines the size and topographic relief of each catchment. Parent material determines the rate of weathering (Bull 1991; McAuliffe 1994), and therefore, both the rate at which sediment is supplied and the size fraction of sediment available for transport. Climate and catchment topography, in turn, determine the locations at which erosional, depositional, or transport processes will dominate within the catchment. Over long periods of time, these factors have worked in concert to determine the size and position of landforms within the catchment and the characteristics of the soils on these landforms. Over shorter periods, the redistribution of precipitation between landforms, and the influence of the soil type on soil moisture availability, have constrained the development of plant communities on each landform.

Increased moisture availability would tend to favor grass dominance whereas decreased moisture would favor shrub dominance. Thus depositional landforms which receive additional water via run-on, may support relatively high covers of perennial grasses, which in turn, stabilize the soil surface, increase the infiltration capacity and further reduce runoff. In contrast, erosional landforms loose water via runoff, and support desert shrub communities. Plant cover is low, and erosion rapidly develops a network of channels which further enhances runoff and erosion from these landforms. Vegetation communities may also dampen the effects of extreme climatic events. During very intense storms, all landforms should generate runoff. However, high grass cover on depositional landforms such as the fan collar or alluvial fan apron may reduce erosion, thereby limiting the development of channel networks which could dramatically alter the patterns of erosion and deposition within the landscape.

The vegetation composition is a critical control, reinforcing the erosional or depositional geomorphic processes that dominate each landform. The prevailing climatic conditions in desert grasslands appear to support stable vegetation communities dominated by either shrub or grasses. Small increases in moisture availability favor grass dominance whereas small decreases in moisture availability favor shrub dominance. Disturbance induced by either grazing or climate change could alter vegetative cover and the composition of plant communities, affecting rates and locations of erosion and deposition within landscapes. The loss of grass cover would lead to accelerated erosion and extend channel networks into formerly stable landforms. The quantity of water lost to runoff would increase as the density of drainage networks increases, reducing the water available for plant growth. At this point, grasslands would no longer be maintained, and could be replaced by shrubs.

Acknowledgments

We thank Laura Huenneke, David Tongway, and Steven VanVactor for critical reviews of this manuscript. This study was partially funded by N.S.F. grant BSR-8114466 to the Jornada Long Term Ecological Research Site.

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