A Hierarchical Classification of Landforms: Some Implications for Understanding Local and Regional Vegetation Dynamics[1]

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Abstract. Analyses of soils and vegetation on the Jornada / Long-Term Ecological Research site have shown strong relationships between vegetative communities and landforms. Observations indicate that similar vegetative patterns exist throughout the Mexican Highland division of the Basin and Range Province. A generalized landscape-level model is presented which attempts to explain the desertification trends producing the shrub - grassland vegetational mosaic found today in southern New Mexico.

INTRODUCTION

Over geological time scales, geomorphologic processes have formed the representative landforms of the Basin and Range physiographic province (Mabbutt 1977). Over periods of 10's to 100's of years, these processes can be viewed as static because of the low rate of landforming events (Allen and Star 1981, O'Neill et al. 1984). At this temporal scale, individual landforms regulate the rates of geomorphic processes, and thereby control the rates at which energy and materials (water, sediment, organic mater, propagules, and organisms) are transported within the landscape (Swanson et al. 1987).

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, Crawford and Gosz 1982) and nitrogen (Pauli 1964, Cline and Rickard 1973). This paper attempts to expand on these studies by developing a framework for understanding how landscape elements influence the distribution of limiting resources within and between ecosystems. Our working hypothesis is that vegetative communities in semi-arid and arid regions should reflect differences in the horizontal redistribution of both water and organic matter between landform elements. The first objective of this paper, then, is to identify the landform elements of the Jornada Long Term Ecological Research site (LTER/Jornada); to demonstrate how these landform elements can regulate geomorphic processes that control the transport of water, sediments, and organic matter across the landscape; and to use the relationships between landform elements and geomorphic processes to attempt to explain the spatial patterns observed in vegetative communities.

Numerous studies describe the primeval vegetation of the semi-arid regions of North America as extensive grasslands with interspersed shrubs. These grasslands have been replaced by *Larrea tridentata*, *Flourensia cernua*, and *Prosopis* spp. throughout much of their former extent. These changes have often been accompanied by extensive sheet and wind erosion, and cutting of arroyo channels (Gardner 1951, Buffington and Herbel 1965, York and Dick-Peddie 1969, Stein and Ludwig 1979, Gibbens et al. 1983, Hennessy et al. 1983, Wondzell 1984, Gibbens and Beck 1987).

Several causal mechanisms have been proposed, most notably the grazing of domestic livestock (York and Dick-Peddie 1969) and climatic change (Buffington and Herbel 1965, VanDevender and Spaulding 1979, Neilson 1986); these mechanisms do act directly on vegetative communities. However, these studies usually did not consider the spatial relationships between the communities within the landscape and did not account for the interactive effects of landscape level processes.

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Landforms regulate geomorphic processes which are modified by the vegetation supported by individual landforms. Over long time periods entire landscapes converge to metastable states (Forman and Godron 1986, p. 436) at which the interactive effects of landforms, geomorphic processes, and vegetation are balanced. Our working hypothesis is that an exogenous disturbance, such as grazing or climatic change, that affects vegetation can overcome the inertia of a metastable state, leading to changes in the horizontal redistribution of water and organic matter between landform elements. The second objective of this paper, then, is to develop a generalized model which incorporates our understanding of geomorphic processes to explain the post-settlement vegetative dynamics from which the desert scrub/desert grassland vegetational mosaic of southern New Mexico resulted.

LANDFORMS, GEOMORPHIC PROCESSES, AND VEGETATION

General Setting

Landscapes within the Mexican Highland section of the Basin and Range province of North America (fig. 1) are characterized by north-south trending fault block mountains separated by broad linear valleys (Fenneman 1931, Hawley 1975).

Figure 1. Basin and Range Physiographic Province (adapted from Peterson 1981 and Ordonez 1936).

The Jornada del Muerto, which is approximately 100 km long and 30 km wide (fig. 2a & b), is a structural and topographic basin in south central New Mexico. The tectonic evolution of this basin has been accompanied by deposition of fluvial and alluvial sediments which exceed 1,000 m in depth (Gile et al. 1981). Fluvial sediments were deposited by the ancestral Rio Grande river system (Strain 1966) while concurrent erosion of the adjoining ranges resulted in deposition of alluvial sediments in extensive piedmont slopes along the mountain fronts (Gile et al. 1981).

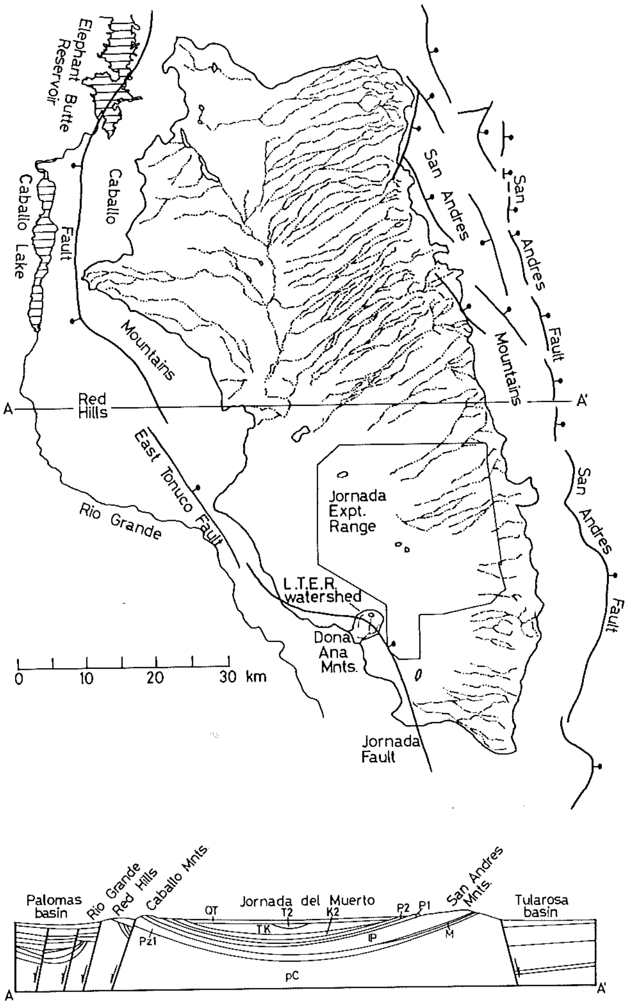


Figure 2. Jornada del Muerto. A. Structural basin bounded by faults (down thrown sides marked) and topographic basin outlined (with arroyo channels and playa lake beds shown). B. Geologic cross section showing bounding faults (adapted from New Mexico Highway Geologic Map, see for explanation of geologic symbols).

The surface of the Jornada del Muerto basin is a complex of smaller watersheds which vary in size from 1,000 to 50,000 ha. The LTER/Jornada research site traverses a 1,500 ha watershed draining the slopes of Mount Summerford, an isolated peak in the Dona Ana mountains which border the Jornada del Muerto basin on the southwest. Two major drainage systems are present within this watershed. The LTER transects are located between these 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 3).

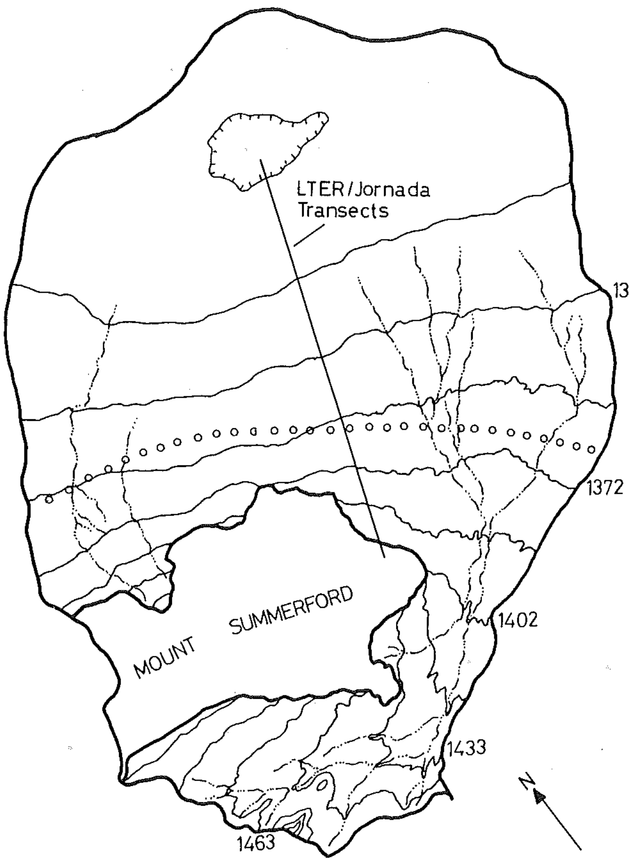


Figure 3. LTER/Jornada watershed showing location of study transects, elevations (contours in meters), and major drainages. Line of open circles represents the buried Jornada fault.

Mountain

Following Peterson's (1981) hierarchical classification, this watershed can be divided into three major physiographic parts (fig. 4), the first of which is **Mount Summerford**. It is the major source of run-off and the source of sediments within the watershed. A vertical projection of the east slope of Mount Summerford shows that precipitation is spread over a 25% greater actual surface area than would occur on a level plain. This effect, combined with the damming effect caused by the high surface roughness of bouldery slopes, allows the retention of precipitation throughout a range of low to intermediate storm intensities (fig. 5).

There is great horizontal redistribution of water between microsites on the mountain slope in all but the smallest storms. Rain falling on bare rock runs into local depressions behind barricades of boulders, which also hold sediments and organic debris deposited during larger events. These mesic microsites support a high diversity of vegetation, including species normally found under much wetter climatic conditions.

The total volume and energy of runoff increase proportionally to precipitation intensity once the flow threshold is surpassed. This is accompanied by increases in both the total sediment load and the size of sediments eroded from the mountain slope (fig. 5).

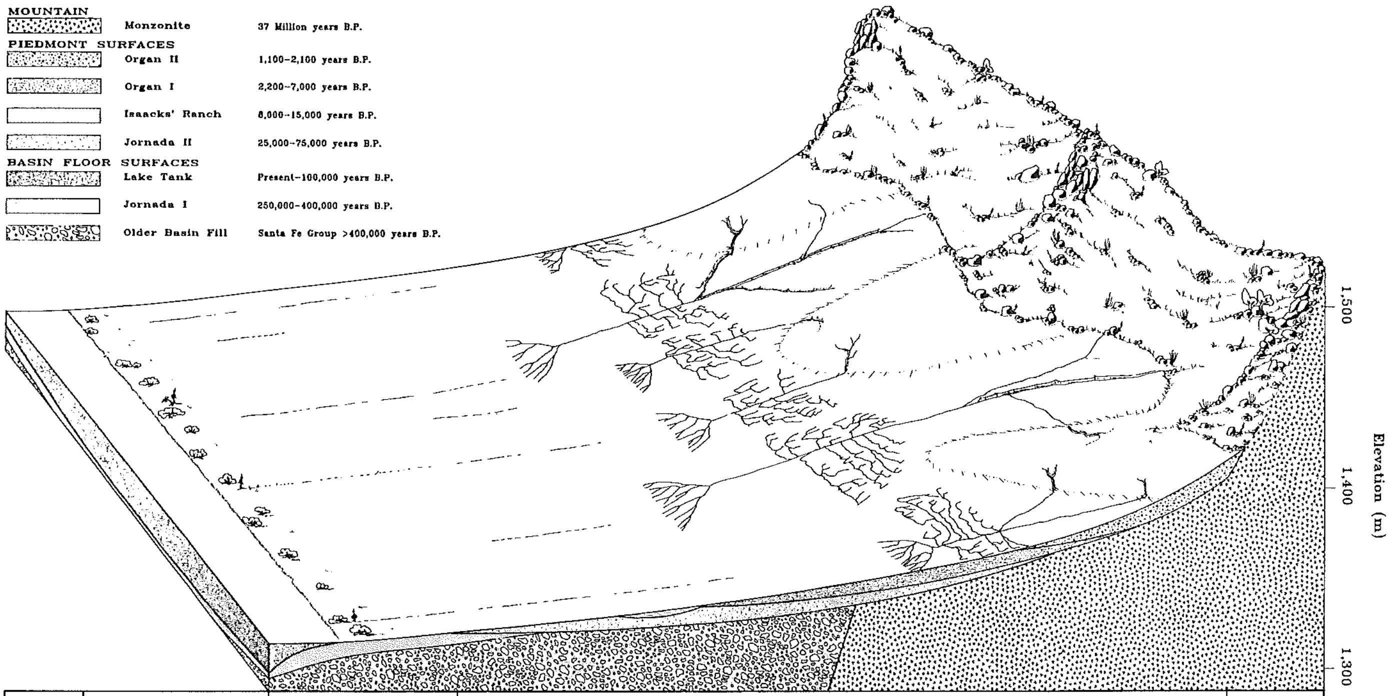
Piedmont Slope

The sediments eroded from Mt. Summerford have been deposited in a graded surface extending from the piedmont junction to the nearly level basin floor which comprises the second major physiographic part - the **piedmont slope**. The upper part of this slope is a thickly mantled, granitic **pediment** which extends from the **piedmont junction** to the buried Jornada fault, located at approximately mid-slope (fig. 4)(the structural Jornada basin lies beyond the fault). The pediment, which is unaffected by pedogenic processes and is buried deeper than either the rooting zone of most plant species or water infiltration depths, does little to affect surface processes within the watershed other than determining the gross topographic relief of the piedmont slope. In contrast, the landforms that have developed in the thick sediment mantle, resembling an alluvial fan - fan piedmont continuum, do affect surface processes. Therefore, subsequent discussion will emphasize these surface landforms.

Alluvial Fan

Fan Collar. Immediately adjacent to Mount Summerford, there is a superficial apron of loose unconsolidated sediments, known as a **fan collar** (fig. 4). The flow threshold of the fan collar should be higher than that of the mountain slope (fig. 5) due to a combination of two factors. First, the gravelly sediments have a high infiltration rate; and second, 73% of the surface area is vegetated (Table 1) (perennial grasses contribute over half of the cover). Therefore, there is a range of storm intensities which will cause runoff from the mountain without exceeding the infiltration rate of the fan collar. This runoff has developed a network of small rills that spreads the runoff across the head of the fan collar, where it infiltrates into the gravelly sediments, depositing its entire sediment load (fig. 5).

Within a few hundred meters of the mountain front the relative importance of erosional processes increases, forming small gullies.



LANDFORMS	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	Alluvial Fan Collar			
GEOMORPHIC SURFACE		Lake Tank	Jornada I	Jornada II	Isaacks' Ranch	Organ I	Organ II			
SOILS		Dalby	Head Quarter	Bucklebar	Berino	Onite	Dona Ana	Aladdin		
VEGETATION	Type (perennial)	Playa	Fringe	Mixed Basin Slope	Creosote Shrubland	Lower Grass Land	Upper Grass Land	Rock Land		
	Sub-type (annual)			Lower	Middle	Upper				
SLOPE (%)		0.1	2.1	3.3	4.2	6.9	9.8	33.0 +		
DISTANCE (m)		300	600	900	1200	1500	1800	2100	2400	2700

Figure 4. Block diagram of the central part of the LTER/Jornada watershed that is traversed by the study transects. Classification of landforms follows Peterson (1981), geomorphic surfaces are from Gile et al. (1981), soils from Wierenga et al. (1987), vegetation is from Ludwig and Cornelius (1987), and percent slope from unpublished data (LTER/Jornada).

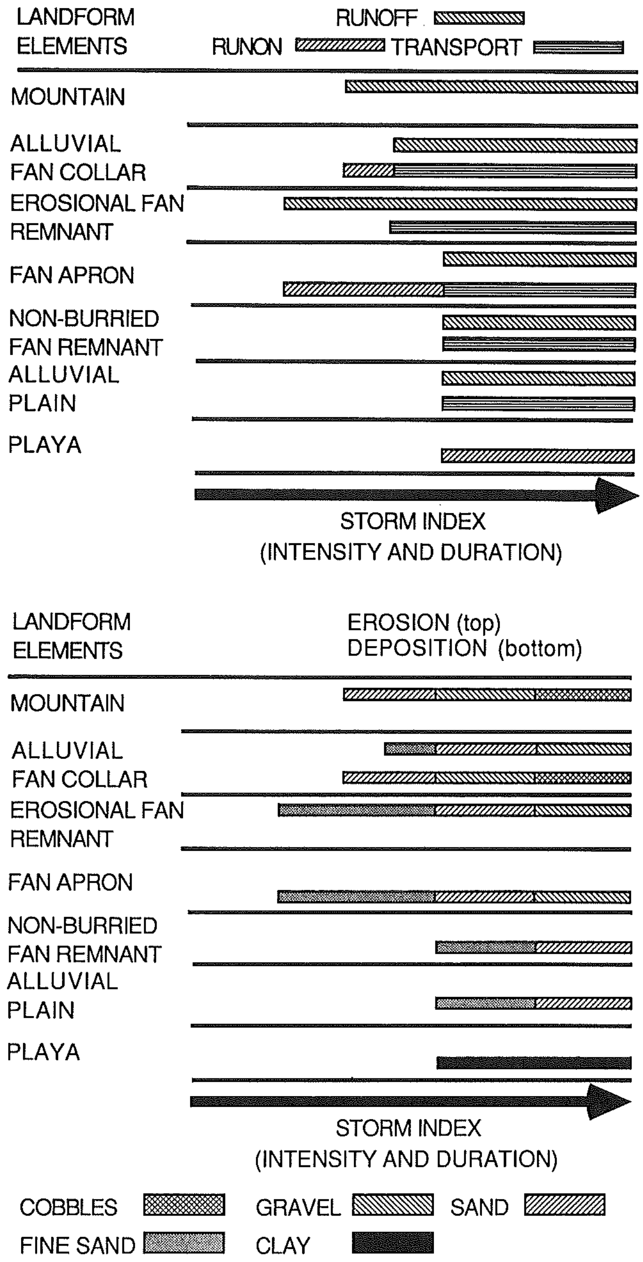


Figure 5. Hypothetical horizontal redistribution of water (A) and sediments (B) between landform elements on the LTER/Jornada watershed during storms of varying intensity.

When the precipitation intensity finally exceeds the infiltration capacity of the fan collar, runoff begins, combining with discharge from the mountain slope, and is transported out of the fan collar. However, since longitudinal gradients average only 8%, the velocity of runoff on the fan collar decreases, reducing the energy available to carry sediments. This rapid drop in energy results in the deposition of the coarse sediment fraction eroded from the mountain during these high intensity storms, even though they produce runoff from the fan collar (fig. 5).

Table 1. Percent cover of all perennial and all annual species during the fall of 1986 for each landform on the LTER/Jornada watershed.

LANDFORM	PERENNIALS	ANNUALS
MOUNTAIN	65.6	0.0
ALLUVIAL FAN COLLAR (deposit)	76.8	5.0
ALLUVIAL FAN COLLAR (erosion)	55.3	10.9
EROSIONAL FAN REMNANT	39.0	1.4
ALLUVIAL FAN APRON	35.0	40.2
NONBURIED FAN REMNANT	47.5	18.7
ALLUVIAL PLAIN	46.4	15.6
PLAYA	91.7	19.3

The fan collar supports two grassland communities (Table 1). Grasslands at the head of the fan collar are dominated by Bouteloua eriopoda - the primeval desert grassland dominant in southern New Mexico. The stability of this grassland appears to stem from several factors. First, precipitation is highly effective on these loamy skeletal soils due to the inverse textural effect (Noy-Meir 1973). Secondly, runoff from the mountain slopes frequently supplies additional water and nutrients. Lastly, nutrients appear to be retained and cycled within this vegetative community due to low surface erosion. Resulting soils have some of the highest nitrogen contents on the site (Table 2).

Table 2. Total inorganic nitrogen for each landform on the LTER/Jornada watershed (in mg kg^{-1} dry soil). Data (Fisher pers. comm.) are averaged for 9 sampling dates between 1983 and 1986.

LANDFORM	NITROGEN
MOUNTAIN	3.3
ALLUVIAL FAN COLLAR (deposit)	5.5
ALLUVIAL FAN COLLAR (erosion)	2.6
EROSIONAL FAN REMNANT	2.7
ALLUVIAL FAN APRON	4.0
NONBURIED FAN REMNANT	4.2
ALLUVIAL PLAIN	3.4
PLAYA	10.5

B. eriopoda is also important in the lower and more highly gullied portion of the fan collar, but codominates with other perennial grasses and subshrubs. Apparently, the greater relative importance of erosion and the removal of some organic matter, combined with the lack of additional runon water, sufficiently alter conditions so that pure swards of B. eriopoda cannot be supported.

Fan Piedmont

Down slope from the fan collar, lateral transport, mixing, and deposition of sediments form a **fan piedmont** (fig. 4) which can be subdivided into three component landforms **erosional fan remnant, alluvial fan apron**, and a **non-buried fan remnant.**

Erosional Fan Remnant. Finer textured sediments formerly deposited along the piedmont slope have been erosionally dissected leaving remnants of the original constructional surface known as an **erosional fan remnant** (fig. 4). This landform, with a longitudinal gradient of 4.2%, has the lowest flow threshold (fig. 5). First, finer soil textures and shallow depths to caliche (which plugs the soil horizon) reduce the infiltration rate. Secondly, vegetation covers only 34% of the surface area and two thirds of this (22%) is *Larrea tridentata*. Therefore, relatively low storm intensities would exceed the infiltration capacity of this landform and initiate runoff. Since longitudinal gradients are too high for sheet flow to predominate, but too low for extensive gullying, this runoff has produced a network of small rills, known as sheet rill. The few arroyo channels present in this landform head higher on the slope, and primarily transport runoff from either Mount Summerford or the fan collar through this landform (fig. 4).

This *Larrea tridentata* - dominated community has probably been present since pre-settlement times (Stein and Ludwig 1979). Apparently, the overall characteristics of the watershed lead to a dominance of erosional processes (fig. 5) which maintain the shrub community. Leaves dropped from the shrubs build up around the rootcrown of the plants, where the soil surface is protected from the impact of raindrops. In the intershrub spaces, sheet rill removes litter from the soil surface. Overall, these soils are low in nitrogen (Table 2); however, what little nitrogen is present is distributed heterogeneously. Soils under the canopies of the shrubs are considered "islands of fertility" (Garcia-Moya and McKell 1970); intershrub spaces are nutrient poor and seldom colonized, even by annuals, and tend to remain bare even in wet years (Table 1) (also see Cornelius and Cunningham, this volume).

Alluvial Fan Apron. Longitudinal gradients of the watershed continue to decrease away from the mountain front and as elevation approaches the watershed base level. Eventually, a point is reached where the slope is insufficient for runoff to maintain distinct channels. Instead each channel gives way to a braided network which eventually disintegrates as runoff begins to move as sheet flow.

Within this transitional zone runoff rapidly decreases in energy as it spreads laterally across the watershed. Correspondingly, most of the bedload, and the coarser fraction of the suspended load, must be deposited (fig. 5), forming the **alluvial fan apron** landform (fig. 4). The coarser texture of the soil surface on the fan apron increases its infiltration capacity and results in a relatively high flow threshold. Therefore, this landform absorbs all runoff originating from the erosional fan remnant in low intensity storms, or from all upslope landforms in greater intensity storms. Sediments and organic matter carried in this runoff are also deposited (fig. 5); coarsest sediments are deposited near the head of the fan apron and progressively finer sediments are carried further down slope with low density organic matter deposited last. When storm intensity exceeds the infiltration capacity, runoff from upslope landforms will be transported across the fan apron.

Larrea tridentata extends from the erosional fan remnant into the fan apron along the braided network of arroyo 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 sub-shrubs in the areas between arroyo channels. Also, ephemeral species attain maximal cover (Table 1) and species richness on the fan apron. Since the storm intensities necessary to produce large volumes of runoff from upslope landforms are relatively rare (see Reynolds et al., this volume) there should be a great inter-annual variability in the supply of additional resources. Apparently, these conditions favor the development of a rich ephemeral flora.

Nonburied fan remnant. The watershed below the fan apron, with longitudinal gradients of only 2.1%, is dominated by sheet flow. Here, water movement cannot dissect the surface through gullying or sheet rill as occurs higher on the slope, nor does deposition occur, since the bulk of the sediment load was dropped on the fan apron. Therefore, the original aggradational surface is preserved in a component landform called the **nonburied fan remnant** (fig. 4). However, sheet wash does move some surface sediments during large runoff events. The resulting soil surfaces on both the nonburied fan remnant and the alluvial plain (described below) are similar, so they are discussed together.

Basin Floor

The piedmont slope grades into the **basin floor** - the third major physiographic part - which is an essentially level alluvial or lacustrine plain. This area can be subdivided into two major landforms - **alluvial plain** and **playa** (fig. 4).

Alluvial Plain

The **alluvial plain** is the relictual floodplain of the ancestral Rio Grande River which has not been buried with alluvial sediments, nor eroded. Instead, the soil developed in these fluvial sediments has been preserved relatively intact along the edges of the playa (fig. 4).

Infiltration rates and flow thresholds of the nonburied fan remnant and the alluvial plain are roughly similar to the alluvial fan ~~collar~~ apron (fig. 5). Therefore, storms of the same intensity exceed the infiltration capacity of all three of these landforms. Runoff originating higher on the watershed during these storms is simply transported across the nonburied fan remnant and alluvial plain into the playa. Both of these landforms support mixed communities of perennial grasses, forbs and subshrubs, as does the alluvial fan apron, though perennial cover is higher and annual cover is much lower than on the fan apron (Table 1). 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 watershed. Therefore, these areas have maintained a semblance of the primeval desert grassland even without additional organic matter or water supplied through runon.

Playa

The LTER/Jornada watershed lacks an outlet for through flow; therefore, runoff originating on the entire watershed (fig. 3) during rare, high intensity storms occasionally floods the lowest portion of the watershed known as the **playa** landform (fig. 4). Each flooding event deposits lacustrine sediments, which have accumulated, burying the fluvial sediments of the ancestral Rio Grande River (fig. 5).

This landform is the ultimate sink for nutrients and organic matter within the watershed. The heavy clay soils have the highest nitrogen content (Table 2) and support the highest perennial cover of any landform in the watershed (Table 1).

Conclusions

The preceding section developed a hypothesis demonstrating how distribution of limiting resources may be controlled by geomorphic processes, which would explain the correlation of vegetative communities and landforms on the LTER/Jornada site. However, this hypothesis is site specific. We would now like to develop a general hypothesis, that could include temporal vegetation dynamics at a landscape scale (desertification), and that could apply to a broader region.

GEOMORPHIC PROCESS / VEGETATIONAL MOSAIC MODEL

Drainage basins, the fundamental unit of geomorphology (Chorley 1969), are usually internally drained in the Basin and Range Physiographic Province. Landforms, soils, and vegetation develop simultaneously within these basins under a given suite of environmental and geomorphic conditions. Over 100's of years, the interactive effects of landscape level processes create a metastable state (Forman and Godron 1986, p. 436) which tends to be self-maintaining even under a fairly wide range of exogenous disturbances.

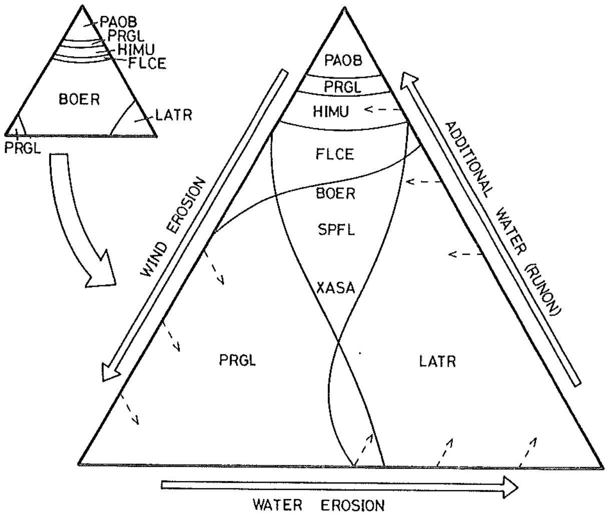


Figure 6. Generalized geomorphic process / vegetational mosaic model. Small triangle in upper left corner represents primeval vegetation mosaic. Large arrow between triangles represents a post-settlement disturbance regime. Large triangle represents current vegetational mosaic. Axes represent increasing levels of wind or water erosion and runon (axes are read parallel to the small dashed arrows). (PAOB - *Panicum obtusum*; PRGL - *Prosopis glandulosa*; HIMU - *Hilaria mutica*; FLCE - *Flourensia cernua*; LATR - *Larrea tridentata*; XASA - *Xanthocephalum sarothrae*; SPFL - *Sporobolus flexuosa*; and BOER - *Bouteloua eriopoda*)

This was the situation in southern New Mexico prior to settlement (Fig. 6). The primeval desert grasslands were a mosaic of vegetation types. The low points of internally drained basins, that were occasionally flooded, but little affected by wind or water erosion, supported playa communities dominated by the grass *Panicum obtusum*. These temporary lakes were surrounded by a gallery forest of *Prosopis glandulosa*, which also bordered major drainage channels. Depositional areas with heavy clay soils and exposed to overland sheet flow (but not holding standing water) were dominated by the grasses *Hilaria mutica* and *Scleropogon brevifolia* with occasional *Flourensia cernua* shrubs. Areas dominated by aeolian erosion, mostly restricted to blow outs along the valley border, were dominated by shrubby forms of *Prosopis glandulosa*. Areas dominated by fluvial erosion, mostly restricted to mid-piedmont slopes and the tops of small hills and ridges, were dominated by *Larrea tridentata*. Extensive grasslands, dominated by *Bouteloua eriopoda*, occupied the remaining area (perhaps as much as 90% of the total surface area)(Buffington and Herbel 1965) and were maintained by relatively homogeneous redistribution of water and vigorous internal cycling of limiting nutrients. These areas included a wide variety of soil types from deep sand to shallow calcareous gravel, and were subject to widely different levels of potential water and wind erosion (Gardner 1951, York and Dick-Peddie 1969, and Stein and Ludwig 1979).

The conversion of these primeval grasslands in southern New Mexico to a heterogenous matrix, dominated by desert shrub species with scattered remnants of the original grassland (fig. 6), has been well documented. The combined effects of several types of disturbance - including drought, overgazing, and trampling - fragmented the once extensive grasslands, forcing the landscape into an unstable state. The rate and extent of erosion, formerly limited by grass cover, increased dramatically (represented by an extension of the two erosion axes in the large triangle, fig. 6). Increased erosion led to increased runoff from some landforms (and increases in runon to other landforms) and eventually to heterogeneous horizontal redistribution of limiting resources within the landscape (represented by an extension of the runon axis, fig. 6).

Changes in the rate or level of the underlying geomorphic processes within the drainage basin led to these heterogeneous patterns of horizontal redistribution of limiting resources. These changes were most likely to occur at the transitions between erosional landforms and stable or aggrading landforms. Using the LTER/Jornada watershed as an example, the transitions between the fan collar (depositional) and the erosional fan remnant or between the erosional fan remnant and the alluvial fan apron (depositional) are most likely to exhibit instability. The current patterns of vegetation communities support this premise.

The lower portion of the fan collar is characterized by a mixture of perennial grasses with abundant subshrubs and is cut by active gullies which indicate accelerated erosion. Though this grassland community does appear degraded, its sharp boundary with the L. tridentata community occurring immediately down slope, indicates that L. tridentata is not extending into this grassland. Geomorphic processes on this degrading grassland appear relatively stable. The grassland is located near the head of the watershed and immediately below the aggradational upper portion of the fan collar which limits the headward cutting channels.

In contrast, the boundary between the erosional fan remnant and the alluvial fan collar (and their associated vegetation communities) is quite gradual. The effects of slightly accelerated erosion upslope of the fan collar become concentrated in the converging drainage network, allowing individual channels to extend down slope, isolating portions of the once depositional surface in their interfluves. Once isolated, these interfluve areas no longer receive additional water or organic matter. Instead they begin to be dissected with sheet rill and colonized by L. tridentata.

The distance that channels can extend down slope is determined by characteristics of the drainage basin, namely the ratio of basin relief to basin length and the catchment size. As the relief:length ratio increases the kinetic energy of runoff increases with a corresponding increase in the effect of water erosion. Similarly, as catchment size increases, a greater volume of runoff can be produced by the watershed, resulting in greater erosion down slope.

The classification of arid rangelands using a hierarchical combination of landforms and the extant vegetation permits the identification of the major processes, such as erosion, deposition, and material redistribution, contributing to vegetation dynamics. There is great potential for this type of dynamic, landscape oriented classification to assist in our attempts to improve management of arid rangelands. For example, it should make it possible to evaluate management decisions in pastures located in upland catchments or in erosional zones of piedmont slopes in light of their probable effects on adjacent landforms. Likewise, this approach will aid in the identification of desertified grassland areas occurring on stable or aggradational landforms that have a high probability for recovery. These are the areas that should receive our greatest efforts and resouces in attempts to reverse desertification trends.

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