Rapid Evaluation of Arid Lands (REAL):
A Methodology

Daniel P. Dugas, New Mexico State University, USA
Michael N. DeMers, New Mexico State University, USA
Janet C. Greenlee, New Mexico State University, USA
Walter G. Whitford, New Mexico State University, USA
Anna Klimaszewski-Patterson, New Mexico State University, USA

ABSTRACT

Management of desert grasslands requires rapid, low technology, coarse assessment methods that provide a triage-like prioritization for the manager. Such approaches necessitate the ability to quickly and effectively identify coarse-scale plant communities that provide guidance for this prioritization. Complex, computer intensive digital image classification of Landsat TM data, while marginally successful, requires time, equipment, and expertise not always available in such environments. This study identifies landform boundaries in the Armendaris Ranch, New Mexico by visual inspection of Landsat-7 Enhanced Thematic Mapper imagery and topographic maps using traditional photoreconnaissance techniques. Employing predetermined hierarchical landform classifications, it was possible to map plant communities using ecological relationships that exist between the general physiographic and vegetation settings in the area and representative geomorphic landform-mapping units. The authors' field verified the plant community map using a random walk approach and visual inspection. This synthetic expert opinion-based approach proved successful and is repeatable in other arid rangeland settings.

Key words: *Arid Land Management, Chihuahuan Desert, Ecoregions, Land Assessment, Landforms*

INTRODUCTION

Worldwide, desert grasslands are undergoing change from a relatively uniform, non-fragmented structure to a more patch-dominated pattern (Schlesinger et al., 1990). This fragmentation results both in negative economic conditions where livestock forage is limited, and in substantial ecological consequences such as more heterogeneous concentrations of nutrients, moisture, and biomass, along with attendant changes in species composition (Whitford, 2002). Many believe that overgrazing accounts for substantial desert landscape modification, although climate change, fire history, and

DOI: 10.4018/jagr.2011070103

anthropogenic activity are also seen as partial causes of such changes (Buffington & Herbel, 1965; Grover & Musick, 1990; Whitford, 2002; Zonn, 1988). There is also increasing evidence that geomorphometric terrain variables (Franklin, 1987), especially reflected in soil and sediment properties, greatly modify the degree to which these factors influence desert vegetation (Schlesinger et al., 1990).

The concept that geomorphic landforms can have a significant effect on natural desert vegetation cover has been proposed and demonstrated by several workers including Buffington and Herbel (1965), Cole and Brown (1976), McAuliffe (1994, 1995), Montaña and Greig-Smith (1990), Parker (1991, 1995), Schlesinger et al. (1990), Sharma (1993), Valverde et al. (1996), Wondzell, Cunningham and Brachelet (1987, 1996), and Zimmerman (1969). Parker and Bendix (1996) provided a comprehensive review of geomorphic influences on vegetation pattern, or what has been called "physiographic plant geography" (Zimmerman & Thom, 1982). Most studies emphasized either spatial patterns (Satterwhite & Ehlen, 1982; Smith, Adams, & Gillespie, 1990), or the underlying processes creating those patterns (Glaser, Janssens, & Siegel, 1990; Malanson, 1993; Swanson, Caine, & Woodmansee, 1988).

Distribution of sediments across the landscape, as a result of geomorphic processes, affects physical and chemical surface properties, pedogenesis, and the movement of water and nutrients (Birkeland, 1990; Bowers & Lowe, 1986; Gile & Grossman, 1979; Graf, 1988; Key, Thompson, & Van Hoogenstyn, 1984; Malanson, 1993; McAuliffe, 1994; Parker, 1995; Shreve, 1964; Philips & MacMahon, 1978; Yang & Lowe 1956). The contributions of varying geologic parent material into the sediment budget also affect the types of sediments produced by weathering (McAuliffe, 1994; Parker, 1995; Shreve, 1964). With geomorphic landforms, therefore, comes a suite of related attributes in addition to such basic characteristics as topographic position, elevation, slope angle, and aspect (Davis & Goetz, 1990; Franklin, 1987; Satterwhite, Rice, & Shipman, 1984; Shasby & Carneggie, 1987; Zevenbergen & Thorne, 1987). All of these attributes, in turn, affect microclimate and hydrologic processes that profoundly influence plant distribution (Parker & Bendix, 1996; Swanson, Caine, & Woodmansee, 1988). This complexity, particularly in the context of arid and semi-arid alluvial fans, has been noted by several workers in North American hot deserts (Burk & Dick-Peddie, 1973; Cunningham & Burk, 1973; Denny, 1965; Dorn, 1988; Graf, 1988; Harvey & Wells, 1994; Mabbutt, 1977; McAuliffe, 1994; McFadden, Ritter, & Wells, 1989; Parker, 1995; Rachocki, 1981; Stein & Ludwig, 1979; Wierenga et al., 1987).

Buffington and Herbel (1965) and Wondzell, Cunningham, and Bachelet (1987, 1996) offer theoretical and empirical examples of geomorphology-vegetation relationships in the Chihuahuan Desert of New Mexico. Field research involving the use of transects of soils, vegetation, and geomorphological position in the Chihuahuan and Sonoran deserts also provides support for presuming such relationships (Wierenga et al., 1987; Cornelius et al., 1991). While these approaches are invaluable for the insights they provide, transects and point sampling techniques are limited in spatial extent, preventing the direct transference of results to larger regions for impact analysis, prediction, and remediation. Without a synoptic view it is difficult to develop spatially explicit, testable hypotheses from which range management plans can be developed within desert grassland environments.

Recent advances in remote sensing techniques have provided some degree of success for monitoring and identifying desert landscape use and natural processes at the regional scale. Okin and Roberts (2001) discuss the challenges and limitations of direct vegetation mapping using remote sensing in arid areas and review several methods that have been attempted, although none with overwhelming success. Several difficulties arise when attempting to ascertain the type, quantity, or quality of vegetation cover in arid environments, such as the presence of common spectrally indeterminate vegetation types

(Okin et al., 2001), and to the large radiation signal supplied to satellite receivers by bare soil, sediments, and rock, which overwhelms the lesser signal returned by the typically sparse vegetation cover of deserts (Becker & Choudhury, 1988; Duncan et al., 1993; Dwivedi et al., 1993; Huete & Jackson, 1987; Okin & Roberts, 2001, Okin et al., 2001). Omuto et al. (2010) found some success identifying vegetative loss using mixed-effects modeling of NDVI-rainfall relationships. Still other high-end image processing techniques such as spectral unmixing (Byambakhuu et al., 2010), combining remote sensing and GIS (Hadeel et al., 2010; Emadi et al., 2010), and image segmentation techniques (Karl & Maurer, 2010) among others have been applied with varying degrees of success.

In the Chihuahuan Desert region of the study area, investigations into satellite-based mapping have been conducted with some success in identifying general vegetation types, structure, and condition, although none have reached the level of accurately identifying individual plant community types. For example, Duncan et al. (1993) used spectral vegetation indices and were able to distinguish shrub types and shrubs from grasses with varied success. A phenological time-series approach using a sequence of Advanced Very High Resolution Radiometer (AVHRR) images in conjunction with normalized difference vegetation indices (NDVI) was able to distinguish shrubland, grassland, and mixed shrub and grass areas (Peters et al., 1997). AVHRR imagery and NDVI were also used by Eve, Whitford and Havstadt (1999) to provide a triage assessment of rangeland degradation conditions based on changes in desert grassland versus shrubland cover.

As an alternative to focusing on direct satellite-based vegetation mapping, the prospect for remotely sensed mapping of the geomorphic terrain across arid regions is promising *because* of the sparse vegetation cover (Argialas & Miliaresis, 2001; Clark, 1999; Dwivedi et al., 1993; Stephens, Butler, & Malansan, 1998; Verstappen, 1977). Remote sensing-based predictive vegetation mapping (Franklin, 1995; Haines-Young, 1991) is premised on ecological niche theory (Austin, 1985) and physiographic ecology (Strahler 1981) with the understanding that the spatial distribution of environmental variables, such as the geomorphological landforms, correlate with or control plant community distributions (Collins, Glenn, & Roberts, 1993). Plant communities are geographic entities and therefore can be mapped predictably (Franklin, 1995). Given known geomorphology and plant community spatial correlations in the northern Chihuahuan desert, we hypothesized that the boundaries of potential plant communities were predictable based on the pattern of landforms determined from satellite images, topography, and field analysis. The methodology, called the rapid evaluation of arid lands (REAL) is integrative and qualitative rather than focused and quantitative. It shares some of the attributes of applying expert opinion for monitoring grazing-induced degredation in Semi-Arid Environments (Thompson et al., 2009), but examines more arid regions and does not rely on NDVI calculations that have proven to have limited success in arid land studies (Peters et al. 1997). Much like the well established broad-scale approaches to ecoregionalization (Bailey, 1983) REAL is designed to provide a readily accessible tool for planning, based on simple, low-tech methods and relying on expert opinion.

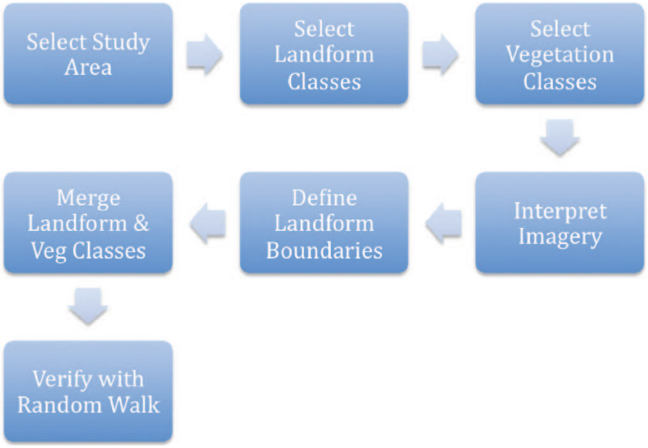
METHODS

The REAL model is a simple, effective, reconnaissance-based approach that involves the following steps (Figure 1). Although the diagram indicates that these steps are linear, they are often performed simultaneously. The following text details each step.

STUDY SITE

For this investigation, a study area was chosen which provided a vegetation cover that had experienced minimal historical or recent grazing, and which offered the opportunity for mapping several landform types typical of this desert region (Peterson, 1981; Wondzell, Cunning-

Figure 1. Flowchart of the REAL methodology. Although represented as a linear model the steps can, and often are performed in tandem to increase speed and efficiency.

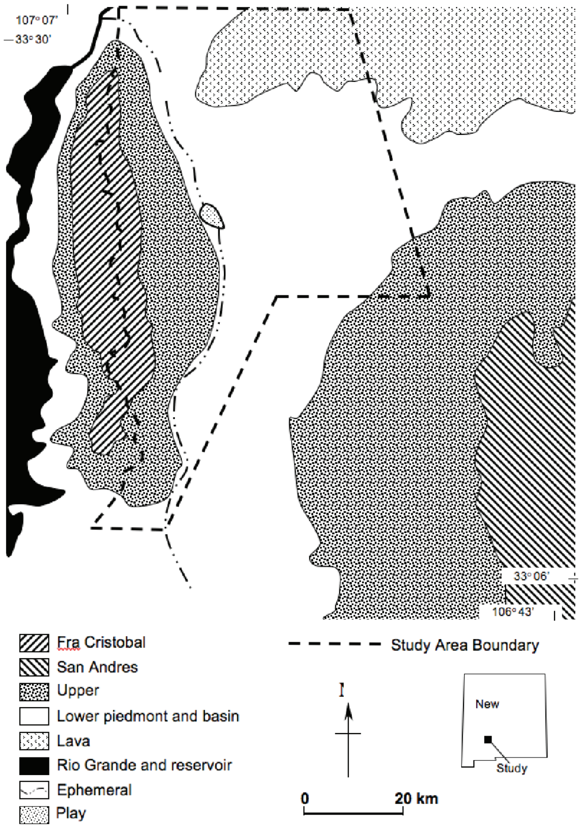


ham, & Bachelet, 1987, 1996). The Armendaris Ranch, located 120 km north of Las Cruces, New Mexico, fit these requirements (Figure 2) and had not been the subject of either detailed geomorphological or vegetation mapping prior to the current effort.

Physiographically, the Armendaris Ranch lies in the Rio Grande rift zone, characterized by basin and range topography with isolated mountain blocks, separated by either hydrographically open or closed basins. The study area occupies a broad basin bounded by the Fra Cristobal and San Andres ranges to the west and east, respectively (Figure 2). Both of these ranges are predominantly composed of Pennsylvanian-age marine sediments of limestone, sandstone, and shale, with some Pre-Cambrian granites, and isolated, Tertiary-to-Holocene age basalts (Dane & Buchman, 1965; Seager et al., 1975; Thompson, 1992). The study area was limited on the north by a large Holocene-age basaltic lava field and to the south by the ranch property boundary. External drainage from the basin is ephemeral (northward through Lava Gate and southward through Jornada Draw), and the area is essentially a hydrologically closed basin much of the time.

Vegetation cover in the study area is a sequence of desert grassland and Chihuahuan desert scrub communities; essentially equivalent to types described by Buffington and Herbel (1965), Dick-Peddie (1993), Brown (1994), and Stubbendieck, Hatch and Butterfield (1997). The plant communities transition down slope from the mountains to the basin floor. There are combinations of creosotebush *Larrea tridentata* and ocotillo *Fouquieria splendens* among black-grama *Bouteloua eriopoda* grassland in the rocky uplands; with creosotebush with black grama, three awn *Aristida* sp. and bush muhly *Muhlenbergia porteri* on steep rocky piedmont slopes. Black grama desert grassland with blue grama *Bouteloua gracilis* and hairy grama *Bouteloua hirsuta* occur on gentler piedmont slopes. Black grama grassland with Soaptree yucca *Yucca elata* occupy sandy rolling piedmont surfaces. Creosotebush and tarbush *Flourrensia cernua* within a tobosa grass *Pleuraphis mutica* and burrograss *Scleropogon brevifolius* matrix in low-lying, swales. Alkali sacaton *Sporobolis airoides* and burrograss mixes appear around gypsic basins. The presence of grasses such as black grama *Bouteloua eriopoda*, blue grama *Bouteloua gracilis*, bush muhly *Muhlenbergia porteri*, tobosa *Hilaria mutica*, and burrograss *Scleropogon brevifolius* are diagnostic of climax desert grassland communities rather than

Figure 2. Location of Armendaris Ranch Study Area



disturbed desert grassland associations (Dick-Peddie, 1993).

Significantly, intensity of livestock grazing in the area has been relatively low since the arrival of Europeans, especially compared to other areas such as the Jornada del Muerto basin to the south, which experienced significant overgrazing in the late 1800s and early 1900s (Whitford, 2002). The minor grazing in the Armendaris area is due in part to its history as a Spanish land grant and the relatively small number of wells drilled on the property. Currently, grazing in the area is limited to a small herd of Bison (*Bison bison*). The plant communities in the study area essentially represent those of pre-cattle grazing conditions in the northern Chihuahuan desert region over the past one hundred and fifty years, and provided a straightforward view of the relationship between geomorphological factors and "potential" (*sensu*) (Kuchler, 1988) plant communities.

POLYGON MAPPING

Landform Delineation

Designation of landform boundaries, whether identified on remotely sensed imagery, topographic maps, or in the field, is to a large degree a matter of background knowledge and experience (Verstappen, 1977). A pre-determined classification, however, is indispensable for achieving consistent, reproducible results. The geomorphological units for this study were modeled after the desert basin and range landform classifications of Peterson (1981), Montaña and Greig-Smith (1990), Valverde et al. (1996), Wondzell, Cunningham and Bachelet (1987, 1996), and Argialas and Miliaresis (2001). Peterson's (1981) classification, in particular, based on a hierarchical scheme designed specifically for mapping soils, fit particularly well with our objectives. Specific types of landforms, as noted by Peterson (1981) are three dimensional parts of the land surface formed of soil, sediment, or rock that repeat across various landscapes, are distinctive because of their shape, and have fairly consistent positions relative to surrounding landforms. The consistency of position, in terms of their relative sequences down-slope, relative elevations, and their adjacency make the mapping of these landforms quite predictable. The landform units shown in Table 1 include only those types found and mapped in the study area. The mapping of geomorphic units in any particular study area requires that the researcher acquire an understanding of the landform features that could potentially occur there and whether any previously defined classification scheme(s) are applicable.

Originally, a more extensive list of landform types was compiled based on the sources cited above. This list was consulted during the mapping process to avoid overlooking potential identifications and to maintain consistent terminology. Some landforms from the list were not mapped because they were either too small to be recognized on the satellite image or they proved to not be identifiable because of insufficient knowledge of the landform itself (i.e. detailed soil characteristics). Geomorphic map unit boundaries were defined using a combination of visual appearance, topographic character and relationships, and the expectation that specific landform types occur in predictable locations with logical spatial distributions.

Table 1. Selected geomorphic landforms found in Armendaris Study Area (Definitions after-Peterson 1981)

LF2 - mountain slope - colluvial slope of bedrock areas.

LF4 - fan piedmont - extensive landform of piedmont slopes, formed by lateral coalescence of mountain-front alluvial fans into a single, generally smooth slope.

LF5 - alluvial fan - semi-conical, deltoid, constructional landform on the upper margin of the piedmont, build of alluvium and debris-flow deposits, debouching from mountain valleys into the basin.

LF8 - fan skirt - landform comprised of laterally coalescing, alluvial fans that issue from extensions of inset fans and that merge along their toeslopes with the basin floor.

LF9 - lake plain - nearly level area of fine textured, stratified sediments deposited in low-lying ephemeral lakes.

LF10 - alluvial flat - nearly level, graded, alluvial surface between the piedmont slope and playa of bolsons or axial-stream floodplain of semi-bolsons.

LF12 - playa - ephemerally flooded, barren area on a basin floor that is veneered with fine textured sediments and acts as a temporary of final sink for drainage waters.

LF13 - depression - area of alluvial flats that periodically collects water but is not as barren as playa surfaces.

LF14 - sedimentary bedrock hill - small, isolated, rounded, bedrock crest surrounded by piedmont sediments.

LF15 - lava flow - area of volcanic bedrock and colluvium forming mesa or large hummocky plain (generally basaltic in study area).

LF19 - disturbed - area experiencing notable vehicle and grazer traffic around fence and gate intersections, or permanent water sources.

LF20 - aeolian terrain - area if aeolian deposition, either as sand sheets or dunes.

LF22 - ballena - rounded ridgelines of remnant fan alluvium.

LF23 - inset fans - a restricted floodplain of an ephemeral drainage (arroyo) entrenched into, and confined between fan piedmont segments.

Examples of these types of relationships are given below in the geomorphic mapping discussion in terms of relative topographic position, adjacency, down-slope sequencing, slope, shape, and degree of entrenchment, as well as by the image attributes described above. It should be noted that although some general relative age estimations might be made for the landforms, based on attributes such as type, relative position, desert pavement development (McFadden, Ritter, & Wells, 1989; Beratan & Anderson, 1998), or soil characteristics such as carbonate stage (Giles, 1981; Birkeland, 1999), no estimates of age are given in the following discussion.

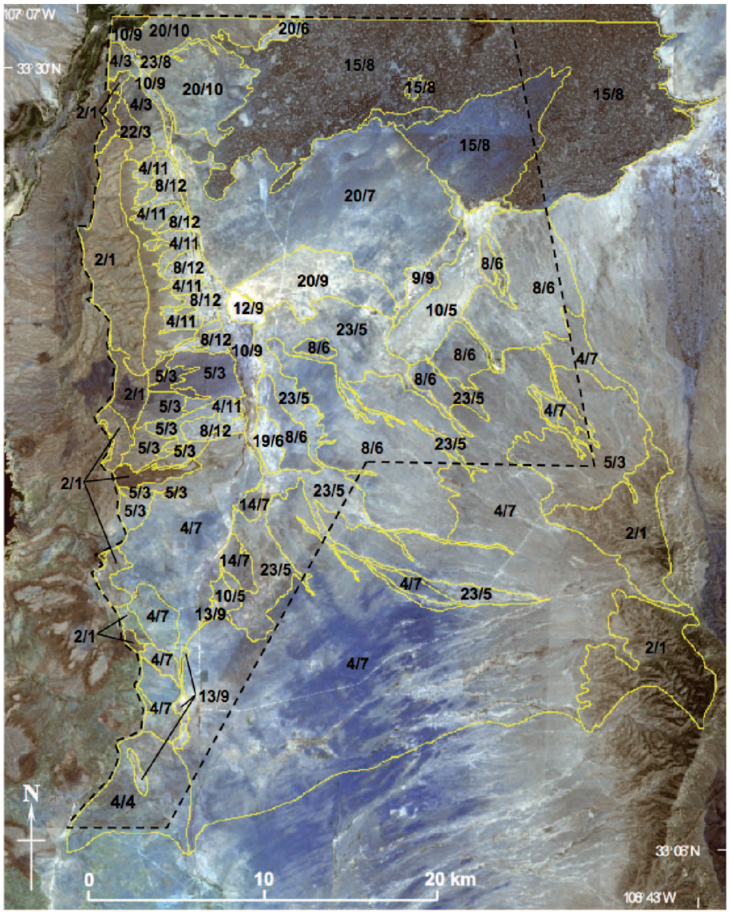
For this study, polygons defining segments of the geomorphic landscape were initially hand-drawn on 1:56,000 scale Landsat-7 Enhanced Thematic Mapper (ETM+) image plots and then subsequently digitized as GIS themes. Standard preprocessing and haze correction (Jensen 1996) was conducted using ERDAS Imagine 8.6 (Leica Geosystems, 2003) and ArcGIS 8.3 (Environmental Systems Research Institute, 2003) software. Topography was characterized using 1:15,000 scale, 20 ft.-interval topographic sheets produced from digital files of 1:24,000 USGS sheets. The Landsat ETM7 images have a pixel resolution of 30m x 30m, which was appropriate for the REAL methodology. Also, the 30m x 30m resolution provides enough detail to discern image textures, while still providing a sufficient overview of the relative spatial relationships of the landform segments (Parker & Bendix, 1996; Walsh, Butler, & Malanson, 1998). The relatively low cost and standard availability of Landsat TM scenes (Lillesand & Kiefer, 1994) also make them ideal for this approach. In future investigations the utility of using finer-resolution satellite imagery will be addressed in the contexts of our approach and objectives.

The satellite scene most often consulted for the current study was from June 17, 2002 (Figure 3). Generally, for Landsat7 ETM+ images, bands 5 and 7 prove useful for discrimination of rock types (Lillesand & Kiefer, 1994; Wilkie & Finn, 1996); however, personal preference in band-color combinations was recognized as an important criterion (Lillesand & Kiefer, 1994). In our case, Landsat7 ETM+ scenes displaying band combinations of 3, 2, 1 proved suitable for defining landforms in the current area of interest.

Visual recognition of the different appearances of areas across the Landsat7 ETM+ scene was an intuitive process. However, the intentional observation and recognition of traditional photo-reconnaissance attributes within the scenes allowed a more systematic approach (Paine, 1981; Lillesand & Kiefer, 1994). Characteristics such as color, hue, tone, texture, shape, size, pattern, and location all provided clues for the identification of individual landforms (Beratan & Anderson, 1998). These are traditionally recognized image attributes long used by interpreters. Color, hue, and tone, all provide information about different parent materials, surface age, and to some degree sediment size. These are first steps to distinguishing and mapping landform boundaries. Texture, such as fine or coarse, smooth or mottled, provides information about sediment size and the degree of surface erosion (dissection), particularly when comparing adjacent features. Shape and size are linked directly to the initial definitions of the landform types and their attributes within the classification scheme. Pattern manifests in two ways – linked to texture in terms of differing drainage patterns and scale of dissection (i.e. fine or coarse), and in terms of adjacency and down-slope sequencing where landforms have consistent positions relative to other surrounding landforms. While displayed pixel colors readily changed with differing TM band combinations on both computer screens and printer plots, other attributes such as texture (the frequency of tonal change) tended to remain stable. Slope trends and rapid transitions (as seen on the topographic sheets) coincident with the changes in the visual image attributes also facilitated assignment of the landform boundaries.

In summary, to map the geomorphology polygons, one must first adopt or devise a classification scheme suitable for the study area. From this classification, the spatial relationships

Figure 3. Landsat 7 ETM+ (Red-1, Green-2, and Blue-3) scene of study area with composite landform/vegetation unit labels. In this fractional code, the top number represents the landform and the bottom represents the plant community. See Tables 1 and 2 for explanations of mapping units. Yellow lines = landform boundaries; dashed black line = study area boundary.



of the landform types can be understood in terms of relative topographic position, adjacency, down-slope sequencing, slope, shape, and degree of entrenchment. Once these attributes are established, one can identify landforms using topographic maps and imagery that provide the additional image attributes of color, hue, tone, texture, shape, size, and pattern.

Landform – Vegetation Delineation

Landform and related plant community mapping within the study area took place by first identifying known plant community-landform relationships based on three sources: forty years experience in the Chihuahuan Desert by one of the investigators (W.G. Whitford), basic principles of ecological niche theory (Austin, 1980, 1985; Austin & Smith, 1989), and plant-landform relationships described in the literature (Buffington & Herbel, 1965; Dick-Peddie, 1993). This approach resulted initially in the identification of nine plant community-mapping units, representing dominant species and vegetation structure. These plant community types were then correlated to geomorphic landforms polygon that corresponded their physiographic settings.

Methodology Verification

The plant community map was verified by ground investigation throughout the study area. This was accomplished using 1:24,000-scale plotted satellite images showing the polygon boundaries, a 1 km x 1 km Universal Transverse Mercator grid, and global positioning instruments for navigation. A total of seventy-six polygon boundaries representing transitions between multiple examples of all of the plant communities were traversed using a random-walk methodology and confirmed as correct for both boundary placement and plant community identification. During field investigation some areas were found where more detailed units could be incorporated into previously determined polygons. For these cases, three additional plant community units were added for a total of twelve basic plant community types (Table 2). Additional detailed verification is currently underway based on a methodology suggested by Klimaszewski-Patterson (2009).

RESULTS

Geomorphic Mapping

Figure 3 shows the landform and plant community polygons over a Landsat ETM7 image using bands Red-1, Green-2, Blue-3. The scene encompasses an area bounded by the Fra Cristobal and San Andres ranges to the west and east, respectively, by a basaltic lava field to the north, and by the drainages feeding the Jornada Draw to the south. In the upper northwest corner, a reach of the Rio Grande can also be seen.

Geomorphically, the area possesses coarse, gravelly, upper fan segments, through fan piedmonts, to fine-textured fan toes and alluvial flats. While the fan segments at the foot of the Fra Cristobal range are considerably narrower than those of the San Andres range, the same landform elements occurred in both areas. The bedrock debris slopes of both ranges are mapped as mountain slope (LF2). Throughout the following discussion "LF" precedes landform unit numbers, and "V" precedes vegetation units. On Figure 3, however, these prefixes have been removed for clarity, and the landform and vegetation unit numbers are listed respectively. The dissected bedrock areas show abundant aspect shading between adjacent drainage slopes. Variations in tones and color indicate different bedrock types and resulting colluvium chemistry. Imaged differences between the common marine rocks (limestone, sandstone, and shale), and more limited basalts, arkosic sandstones, and gypsic limestones are the most pronounced. Two isolated areas of sedimentary bedrock hills (LF14) are also present on the valley bottom and are discernable from the adjacent low-lying areas by their topography, darker tone, and smoother image texture.

Below the mountain slopes, steep alluvial fans (LF5) debauch onto the lower-gradient fan piedmont (LF4) interfluves and slightly entrenched fan skirts (LF8) between them. The alluvial fans generally have lower reflectance than either the thin-soiled mountain slopes above or the finer-grained piedmont soils below. Some gullies and drainage paths on the alluvial fans, similar to those on the mountain slopes above, are also visible on the image. The alluvial fan slopes are also steeper than the piedmont slope below, which is evident on topographic maps. An area of ballenas (LF22 - remnant alluvial fan), near the northern end of the Fra Cristobals occupies a topographic position similar to the alluvial fans. This area exhibits abundant aspect shading between adjacent drainage slopes similar to the mountain slopes, yet the general slope is similar to the alluvial fans.

The fan piedmont (LF4) on the Fra Cristobal side differs notably from the alluvial fans above by its higher reflectance, and from the fan skirts (LF8) below by smoother image texture. The fan skirts show a much coarser and abundant mottling on the image, due in this case to vegetation patterning (Tongway, Valentin, & Seghieri, 2001). The transition from fan piedmont (LF4) to fan skirt (LF8) is not discernable at the 20-foot contour interval of the topographic

Table 2. Descriptions of general plant community types in Armendaris study area associated with general physiographic types. Equivalent community types according to Buffington and Herbal (1965), and Dick-Peddie (1993) are indicated by the respective bracketed labels: {}, []

V1. Rock outcrop bedrock-montane slopes: black-grama *Bouteloua eriopoda* grassland with scattered creosote *Larrea tridentata* and ocotillo *Fouquieria slendens* {3A}[Desert Grassland, Shrub-Mixed Grass Series].
V2. Rock outcrop–montane slopes: mixed grasses with scattered juniper and oak *Quercus* spp. {0}[Desert Grassland, Montane Grassland].
V3. Steep Piedmont slopes: creosotebush *Larrea tridentata* with scattered black-grama *Bouteloua eriopoda*, three-awn *Aristida* spp., bush muhly *Muhlenbergia porteri* {3B}[Desert Grassland, Grama-Threeawn Series].
V4. Gently sloping piedmonts: black grama *Bouteloua eriopoda* desert grassland with blue grama *Bouteloua gracilis* and hairy grama *Bouteloua hirsuta* on piedmonts {0}[Desert Grassland, Grama Grass Series].
V5. Basin drainage areas with fine textured soils: tobosa *Hilaria mutica* and burrograss *Scleropogon brevifolius* grassland, margins of clay dominated basins clay loam soils support vinemesquite *Panicum obtusum* {0}[Desert Grassland, Closed Basin-Playa-Alkali Sink Riparian].
V6. Run-on areas of mid-to-lower piedmont segments: burro grass *Scleropogon brevifolius* flats with tobosa *Pleuraphis mutica* {0}[Desert Grassland, Tobosa Series].
V7. Upland rolling plains topography on broad mid-to-lower piedmont segments: black grama *Bouteloua eriopoda* grassland with soaptree yucca *Yucca elata* {0/1A}[Desert Grassland, Grama Grass Series]. Localized occurrences of mesquite *Prosopsis glandulosa* also appear along with this type along fence lines on the opposite side of which mesquite is very abundant, probably due to disturbance.
V8. Lava flows with aeolian deposits: mixed black grama *Bouteloua eriopoda* grassland with creosote *Larrea tridentata* and tarbush *Flourensia cernua* shrubs {4B}[Desert Grassland, Shrub-Mixed Grass Series?]; and in drainage areas within lava field: burrograss *Scleropogon brevifolius* flats on silty, clay loam soils.
V9. Basins with high gypsum content soils: grass cover mixture of alkali sacaton *Sporobolis airoides* and some burro grass *Scleropogon brevifolius* {0}[Desert Grassland, Sacaton Series/ Closed Basin-Playa-Alkali Sink Riparian].
V10. Aeolian mantle with coppice dunes: mosaic of mesquite *Prosopsis glandulosa*, creosote *Larrea tridentata*, and alkali sacaton *Sporobolis airoides* {1C/2B}[Chihuahuan Desert Scrubland].
V11. Gently sloping lower piedmont interfluves within 1.5 km of permanent livestock watering points: creosote *Larrea tridentata* with black grama *Bouteloua eriopoda* {3C}[Disturbed Chihuahuan Desert Scrubland].
V12. Gently sloping lower piedmont erosional drainages within 1.5 km of permanent livestock watering points: tarbush *Flourensia cernua* and alkali sacaton *Sporobolis airoides*. {5C}[Disturbed Chihuahuan Desert Scrubland].

maps, although their differing topographies are readily seen on the ground. These two areas are best discerned on the satellite scene, especially on the Fra Cristobal piedmont.

On the San Andres piedmont, the transition across the alluvial fan (LF5), fan piedmont (LF4), and fan skirt (LF8) sequence is broader than on the Fra Cristobal piedmont, although there are also commonalties that make correlations of landform types possible. On both piedmonts, the alluvial fans (LF5) are darker in tone than the fan piedmont below. They also both show aspect shading of adjacent drainage slopes, similar to the mountain slopes above. The boundaries between fan piedmonts (LF4) and fan skirts (LF8) on the San Andres side are again not well defined on topographic maps, but are best seen as tonal differences on the TM image. The San Andres piedmont also has extensive areas of entrenched inset fan (LF23). These are defined by their relatively lighter tone, location adjacent the fan skirts, and entrenched drainage pattern that is easily seen on topographic maps.

The lowest areas of the basin consist of alluvial flats (LF10), playas (LF12), or depressions (LF13). The alluvial flats (LF10) exhibit extreme contrast in their mottling on the scene (due to vegetation patterning), and in combination with their low topographic position are easily mapped. The playa (LF12) exhibits the extreme reflectance typical of bare surfaces and fine-grained alkaline sediments. In addition, the playa is well defined on the topographic map. Depression areas (LF13) have characteristics that are transitional between the alluvial flats and playas, demonstrating their function as alluvial flat areas that periodically collect standing water. The depressions show both mottling and a relatively high reflectance. An area of modern surface disturbance (LF19) has also been mapped but is not part of this analysis. It too shows high reflectance due to relatively sparse vegetation cover.

A significantly large area of aeolian terrain (LF20) lies downwind to the northeast of the playa (LF12) and alluvial flats (LF10), extending onto a portion of the lava field (LF15). This aeolian cover is easily seen on the images, defined by its downwind position from the sediment sources, plume-like shape, randomly mottled pattern decreasing away from the sediment source, and relatively high reflectance where it covers the lava flow.

An area of lake plain (LF9) occurs to the southwest of the aeolian terrain at the toe of the San Andres piedmont where water appears to have periodically collected in the past. This area exhibits the same image and topographic characteristics as areas of alluvial flats (LF10) at the toe of the Fra Cristobal piedmont, and it has the same vegetation cover as the alluvial flats (as discussed below). An area mapped as alluvial flats (FL10) also occurs just upslope of the lake plain (LF9) and below the fan skirt (LF8). It is defined by topography, relative position to the fan skirt, and by its areas of higher reflectance texture similar to other areas of alluvial flat. It does not display, however, the same degree of mottling. This alluvial flat area is contiguous with a large area of inset fan (LF23) to the west with which it may share some geomorphic processes. These two areas also share the same plant community cover.

Landform - Plant Community Mapping

When the thirteen geomorphic polygon types are labeled in combination with the twelve plant community cover types, twenty-three different mapping classes result because either more than one type of plant community occurs on a given geomorphic unit type, or more than one type of geomorphic unit hosts a given type of plant community cover (Figure 3).

Mountain slopes (LF2) typically have a cover of V1-black grama grassland with scattered shrubs (creosotebush, tarbush, and ocotillo). Fan piedmonts (LF4) have either V3-creosotebush with scattered black-grama and three awn-bush muhly, V4-black grama desert grassland, with some blue grama and hairy grama, V7-black grama grassland with yucca, or V11-creosote with black grama.

Upper alluvial fan areas (LF5) have V3-creosotebush with scattered black-grama and three awn-bush muhly as well. V7 appears again in areas of sedimentary bedrock hills (LF14) and on the thin aeolian cover (LF20) downwind of the alluvial flats (FL10) and playa (LF12). Both LF14 and LF20 are essentially in areas that are part of the fan piedmont (LF4) so it is not surprising that they should share the same plant community cover. V12-areas of tarbush and alkali sacaton on the fan piedmont (LF4) are locations where erosion of the fan piedmont has destabilized the soil surface. This appears to have degraded the soil quality and increased the alkaline gypsic nature of the sediments.

Fan skirts (LF8) have been deposited near the toe of the Fra Cristobal fan piedmont, the vegetation is V12-tarbush and alkali sacaton. LF8 also supports extensive areas of predominantly V6-burro grass flats with some tobosa grass along the toe of the San Andres fan piedmont. Most of these areas consist of relatively finer-grained soils.

A limited area that possibly was an ephemeral lake in the past is mapped as lake plain (LF9). Here relatively fine-grained, high gypsum content soils have V9-a mixture of alkali sacaton with burro grass. This type of plant community also occurs in other topographically low areas that accumulate run-off from sedimentary bedrock, or experience aeolian deflation such as alluvial flats (LF10), playa (LF12), and localized depressions (LF13).

Alluvial flats (LF10) also support a cover of V5-tobosa grass and burro grass grassland in one isolated area near the southern end of the Fra Cristobals.

LF20, the aeolian mantled terrain, has a cover of V9-alkali sacaton with burro grass just downwind of the playa (LF9), but also supports V6-burro grass flats with some tobosa in a small area adjacent the lava field (LF15), V7-black grama grassland with yucca in areas farther from the playa sediment source, and V10-a mosaic of mesquite, creosote, and alkali sacaton where coppice dunes have formed.

Finally, relatively low lying inset fan surfaces (LF23) on the San Andres Mountains piedmont support V5-tobosa grass and burro grass grasslands or V6-predominantly burro grass flats with some tobosa grass. These inset fans appear to have slightly finer-grained, more alkaline soils.

DISCUSSION

Given the known ecological characteristics of plant communities in the Chihuahuan Desert, we hypothesized that the boundaries of plant communities were predictable based on landform patterns determined from satellite images, topography, and field analysis. This type of remote sensing-based predictive vegetation mapping is predicated on ecological niche theory and physiographic ecology (Austin, 1985; Franklin, 1995; Haines-Young, 1991; Strahler, 1981) where the spatial distribution of environmental variables, such as landforms, shape plant community distributions and allow predictive mapping (Collins, Glenn, & Roberts, 1993; Franklin, 1995). Using this approach, we produced a vegetation map which proved consistent with actual plant community distributions when verified on the ground.

Previous remote sensing studies in the region using spectral vegetation indices and phenological time-series were able distinguish shrubland, grassland, and mixed shrub and grass areas (Duncan et al., 1993; Eve, Whitford,& Havstadt, 1999; Peters et al., 1997), but did not distinguish specific plant communities among these general types. Spectral mixing, in which the radiation signal of sparse vegetation cover is overwhelmed by that of bare soils, sediment and rock, is a significant remote sensing problem which makes direct vegetation interpretation problematic in desert environments (Becker & Choudhury, 1988; Duncan et al., 1993; Dwivedi et al., 1993; Huete & Jackson, 1987; Okin & Roberts, 2001; Okin et al., 2001). Our geomorphically-based approach turned this apparent drawback to an advantage, using topography and basic Landsat TM spectral information to identify patterns of reflectance and textural variation attributable to specific landforms and subsequently correlating these to known plant community physiographic settings. This expedient mapping approach allowed us to obtain maximum benefit from limited resources. The use of satellite imagery is particularly appropriate for this method because of the reasonable cost and the effective targeting of particular areas of geomorphological and ecological interest; reducing the amount of time, labor, and resources typically required to conduct such an investigation using field mapping alone.

Our methodology is in some respects similar to the well recognized Gap Analysis approach for regional analysis in that satellite data provide the basis for the regional mapping (Jennings, 2000). While the Gap methodology provided some substantial results in non-arid regions, its results in arid regions were less reliable at identifying vegetative boundaries. Additionally GAP, and more integrated methodologies, like our own are based on the application of accepted scientific principles for regional characterization (Herrick et al., 2006). In stark contrast our approach succeeds in that the results can be achieved with a minimum of technological application and within days as opposed to months or even years. While the specific landform/vegetative categories will change and the settings will vary widely, the REAL methodology can be reproduced for arid environments. The use of imagery to identify landforms in more mesic environments is less likely to be as readily applicable and more likely to require a more lengthy interpretive process. For a triage approach to arid land management the speed of this REAL methodology is, in our estimation, the most significant improvement over GAP Analysis and similar methodologies.

A final note about the ability to reproduce this methodology is in order here. First, it is critical to understand that REAL is an integrative methodology and that it is the methodology and not the results from that methodology in this particular study area that is under consideration. Our methodology, if applied properly will result in broad-scale geomorphic-vegetative categories not unlike those identified using the GAP Analysis methodologies, and sharing the integrative characteristics of ecoregional categories such as those suggested by Bailey (1983) or Omernick (1987) for smaller scales. Such approaches to arid lands evaluation require visual interpretation of available satellite images and a team of scientists familiar with the ecological setting and possessing basic visual interpretive skills. By evaluating first the geomorphology based on a combination of imagery and a-priori knowledge of the area, then using first ecological principles to link these to expected vegetation the results will provide useful categories for management of arid lands. Although some variation in boundaries is inevitable whenever mapping is performed at broad scales, the overall patterns and categories will nonetheless prove useful.

ACKNOWLEDGMENTS

The authors sincerely thank the Armendaris Ranch and its general manager Mr. Tom Waddell for permission to conduct research on the property. Landsat 7 ETM+ imagery was kindly provided by Mr. Dallas Bash from the Directorate of the Environment, U. S. Army, Fort Bliss, Texas. This research was funded by a National Aeronautics and Space Administration/Jet Propulsion Laboratory Grant (#1241945).

REFERENCES

Argialas, D. P., & Miliaresis, G. C. (2001). Human factors in the interpretation of physiography by symbolic and numerical representations within an expert system . In Hoffman, R. F., & Marlham, A. B. (Eds.), *Interpreting remote sensing imagery: Human factors* (pp. 59–81). New York, NY: Lewis Publishers. doi:10.1201/9781420032819.sec2

Austin, M. P. (1980). Searching for a model for vegetation analysis. *Vegetatio*, *43*(1-3), 1–21.

Austin, M. P. (1985). Continuum concept, ordination methods, and niche theory. *Annual Review of Ecology and Systematics*, *16*(1), 39–61. doi:10.1146/annurev.es.16.110185.000351

Austin, M. P., & Smith, T. M. (1989). A new model for the continuum concept. *Vegetatio*, *83*, 35–47. doi:10.1007/BF00031679

Bailey, R. G. (1983). Delineation of ecosystem regions. *Environmental Management*, *7*(4), 365–373. doi:10.1007/BF01866919

Becker, F., & Choudhury, B. J. (1988). Relative sensitivity of normalized difference vegetation index (NDVI) and microwave polarization difference index (MPDI) for vegetation and desertification monitoring. *Remote Sensing of Environment*, *24*(2), 297–311. doi:10.1016/0034-4257(88)90031-4

Beratan, K. K., & Anderson, R. (1998). The use of landsat thematic mapper data for mapping and correlation of quaternary geomorphic surfaces in the southern Whipple Mountains, California. *International Journal of Remote Sensing*, *19*(12), 2345–2359. doi:10.1080/014311698214767

Birkeland, P. W. (1990). Soil-geomorphic research - a selective overview. *Geomorphology*, *3*(3-4), 207–224. doi:10.1016/0169-555X(90)90004-A

Birkeland, P. W. (1999). *Soil geomorphology* (3rd ed.). New York, NY: Oxford University Press.

Bowers, M. A., & Lowe, C. H. (1986). Plant-form gradients on Sonaran desert bajadas. *Oikos*, *46*(3), 284–291. doi:10.2307/3565825

Brown, D. E. (1994). *Biotic communities: Southwestern United States and Northwestern Mexico*. Salt Lake City, UT: University of Utah Press.

Buffington, L. C., & Herbel, C. H. (1965). Vegetational changes on a semidesert grassland range from 1858 to 1963. *Ecological Monographs*, *35*(2), 139–164. doi:10.2307/1948415

Burk, J. H., & Dick-Peddie, W. A. (1973). Comparative production of *Larrea divaricata Cav.* on three geomorphic surfaces in southern New Mexico. *Ecology*, *54*(5), 994–1102. doi:10.2307/1935575

Byambakhuu, I., Sigita, M., & Matsushima, D. (2010). Spectral unmixing model to assess land cover fractions in Mongolian steppe regions. *Remote Sensing of Environment*, *114*(10), 2361–2372. doi:10.1016/j.rse.2010.05.013

Clark, R. N. (1999). Spectroscopy of rocks and minerals, and principles of spectroscopy . In Rencz, A. (Ed.), *Manual of remote sensing* (pp. 3–58). New York, NY: John Wiley & Sons.

Cole, M. M., & Brown, R. C. (1976). The vegetation of the Ghanzi area of western Botswana. *Journal of Biogeography*, *3*(3), 169–196. doi:10.2307/3038009

Collins, S. L., Glenn, S. M., & Roberts, D. W. (1993). The hierarchical continuum concept. *Journal of Vegetation Science*, *4*(2), 149–156. doi:10.2307/3236099

Cornelius, J. M., Kemp, P. R., Ludwig, J. A., & Cunningham, G. L. (1991). The distribution of vascular plant species and guilds in space and time along a desert gradient. *Journal of Vegetation Science*, *2*(1), 59–72. doi:10.2307/3235898

Cunningham, G. L., & Burk, J. H. (1973). The effect of carbonate deposition layers (“caliche”) on the water status of Larrea divarcata. *American Midland Naturalist*, *90*(2), 474–480. doi:10.2307/2424473

Dane, C. H., & Bachman, G. O. (1965). *Geologic map of New Mexico (1:500,000)*. Washington, DC: U.S. Geological Survey.

Denny, C. S. (1965). *Alluvial fans in Death Valley region, California and Nevada*. Washington, DC: U. S. Government Printing Office.

Dick-Peddie, W. A. (1993). *New Mexico vegetation: Past, present, and future*. Albuquerque, NM: University of New Mexico Press.

Dorn, R. I. (1988). A rock varnish interpretation of alluvial-fan development in Death Valley, California. *National Geographic Research*, *4*(1), 56–73.

Duncan, J., Stow, D., Franklin, J., & Hope, A. (1993). Assessing the relationship between spectral vegetative indices and shrub cover in the Jornada Basin, New Mexico. *International Journal of Remote Sensing*, *14*(18), 3395–3416. doi:10.1080/01431169308904454

Dwivedi, R. S., Sankar, T. R., Venkataratnam, L., & Rao, D. P. (1993). Detection and delineation of various desert terrain features using Landsat-TM derived image transforms. *Journal of Arid Environments*, *25*(1), 151–162. doi:10.1006/jare.1993.1051

Emadi, M., Baghernejad, M., Pakparvar, M., & Kowsar, S. A. (2010). An approach for land suitability using geostatistics, remote sensing, and geographic information systems in arid and semiarid ecosystems. *Environmental Monitoring and Assessment*, *164*(1-4), 501–511. doi:10.1007/s10661-009-0909-6

Environmental Systems Research Institute. (2003). *ArcGIS 8.3 geographic information system software*. Redlands, CA: Environmental Systems Research Institute.

Eve, M. D., Whitford, W. G., & Havstadt, K. M. (1999). Applying satellite imagery to triage assessment of ecosystem health. *Environmental Monitoring and Assessment*, *54*(3), 205–227. doi:10.1023/A:1005876220078

Franklin, J. (1995). Predictive vegetation mapping: geographic modeling of biospatial patterns in relation to environmental gradients. *Progress in Physical Geography*, *19*(4), 474–499. doi:10.1177/030913339501900403

Franklin, S. E. (1987). Terrain analysis from digital patterns in geomorphometry and Landsat MSS spectral response. *Photogrammetric Engineering and Remote Sensing*, *53*(1), 59–65.

Gile, L. H., & Grossman, R. B. (1979). *The desert project soil monograph: Soils and landscapes of a desert region astride the Rio Grande Valley near Las Cruces, New Mexico*. Washington, DC: U. S. Department of Agriculture.

Gile, L. H., Hawley, J. W., & Grossman, R. B. (1981). *Soils and geomorphology in the basin and range area of Southern New Mexico: Guidebook to the desert project*. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources.

Glaser, P. H., Janssens, J. A., & Siegel, D. I. (1990). The response of vegetation to chemical and hydrological gradients in the Lost River Peatland, northern Minnesota. *Journal of Ecology*, *78*(4), 1021–1048. doi:10.2307/2260950

Graf, W. L. (1988). *Fluvial processes in Dryland rivers*. New York, NY: Springer.

Grover, H. D., & Musick, H. B. (1990). Shrubland encroachments in southern New Mexico, U.S.A.: An analysis of desertification processes in the American Southwest. *Climatic Change*, *17*(2-3), 305–330. doi:10.1007/BF00138373

Hadeel, A. S., Jabber, M. T., & Chen, X. (2010). Environmental change monitoring in the arid and semi-arid regions: A case study Al-Basrah Province, Iraq. *Environmental Monitoring and Assessment*, *167*(1-4), 371–385. doi:10.1007/s10661-009-1056-9

Haines-Young, R. (1991). Biogeography. *Progress in Physical Geography*, *15*(1), 101–113. doi:10.1177/030913339101500109

Harvey, A. M., & Wells, S. G. (1994). Late pleistocene and holocene changes in hillslope sediment supply to alluvial fan systems: ZzyZx, California . In Millington, A. C., & Pye, K. (Eds.), *Environmental change in Drylands: Biogeographical and geomorphological perspectives* (pp. 67–84). New York, NY: John Wiley & Sons.

Herrick, J. E., Bestelmeyer, S. A., Tugel, A. J., & Brown, J. R. (2006). An integrated framework for science-based arid land management. *Journal of Arid Environments*, *65*(2), 319–335. doi:10.1016/j.jaridenv.2005.09.003

Huete, A. R., & Jackson, R. D. (1987). Suitability of spectral indices for evaluating Revegetation characteristics on arid rangelands. *Remote Sensing of Environment*, *23*(2), 213–232. doi:10.1016/0034-4257(87)90038-1

Jennings, M. D. (2000). Gap analysis: Concepts, methods, and recent results. *Landscape Ecology*, *15*(1), 5–20. doi:10.1023/A:1008184408300

Jensen, J. R. (1996). *Introductory digital image processing*. Upper Saddle River, NJ: Prentice-Hall.

Karl, J. W., & Maurer, B. A. (2010). Spatial dependence of predictions from image segmentation: A variagram-based method to determine appropriate scales for producing land management information. *Ecological Informatics*, *4*(3), 194–202. doi:10.1016/j.ecoinf.2010.02.004

Key, L. J., Delph, L. F., Thompson, D. B., & Van Hoogenstyn, E. P. (1984). Edaphic factors and the perennial plant community of a Sonoran desert bajada. *The Southwestern Naturalist*, *29*(2), 211–222. doi:10.2307/3671027

Klimaszewski-Patterson, A. (2009). Examination of vegetation intercept-transect sampling in an arid environment. *Papers of the Applied Geography Conferences*, *32*, 233–331.

Kuchler, A. W. (1988). Other technicalities . In Kuchler, A. W., & Zonnevelde, I. S. (Eds.), *Vegetation mapping* (pp. 157–163). Dordrecht, The Netherlands: Kluwer Academic.

Leica Geosystems. (2003). *ERDAS imagine 8.6 geographic imaging software*. Los Angeles, CA: Leica Geosystems.

Lillesand, T. M., & Kiefer, R. W. (1994). *Remote sensing and image interpretation* (3rd ed.). New York, NY: John Wiley & Sons.

Mabbutt, J. A. (1977). *Desert landforms*. Cambridge, MA: MIT Press.

Malanson, G. P. (1993). *Riparian landscapes*. Cambridge, UK: Cambridge University Press. doi:10.1017/CBO9780511565434

McAuliffe, J. R. (1994). Landscape evolution, soil formation, and ecological patterns and processes in Sonoran Desert Bajadas. *Ecological Monographs*, *64*(2), 111–148. doi:10.2307/2937038

McAuliffe, J. R. (1995). Landscape evolution, soil formation, and Arizona's desert grasslands . In McClaran, M. P., & Van Devender, T. R. (Eds.), *The desert grassland* (pp. 100–129). Tucson, AZ: University of Arizona Press.

McFadden, L. D., Ritter, J. B., & Wells, S. G. (1989). Use of multiparameter relative-age methods for age estimation and correlation of alluvial fan surfaces on a desert piedmont, eastern Mojave Desert, California. *Quaternary Research*, *32*(3), 276–290. doi:10.1016/0033-5894(89)90094-X

Montaña, C., & Greig-Smith, P. (1990). Correspondence analysis of species by environmental variable matrices. *Journal of Vegetation Science*, *1*(4), 453–460. doi:10.2307/3235778

Okin, G. S., & Roberts, D. A. (2001). Remote sensing in arid regions: Challenges and opportunities. In S. Ustin (Ed.), *Manual of remote sensing, volume 5: Remote sensing for natural resource assessment*. Bethesda, MD: American Society for Remote Sensing and Photogrammetry.

Okin, G. S., Roberts, D. A., Murray, B., & Okin, W. J. (2001). Practical limits on hyperspectral vegetation discrimination in arid and semiarid environments. *Remote Sensing of Environment*, *77*(2), 212–225. doi:10.1016/S0034-4257(01)00207-3

Omernik, J. M. (1987). Ecoregions of the conterminous United States. *Annals of the Association of American Geographers. Association of American Geographers*, *77*(1), 118–125. doi:10.1111/j.1467-8306.1987.tb00149.x

Omuto, C. T., Vargas, R. R., Alim, M. S., & Paron, P. (2010). Mixed-effects modeling of time series NDVI-rainfall relationships for detecting human-induced loss of vegetation cover in drylands. *Journal of Arid Environments*, *74*(11), 1552–1563. doi:10.1016/j.jaridenv.2010.04.001

Paine, D. P. (1981). *Aerial photography and image interpretation for resource management* (3rd ed.). New York, NY: John Wiley & Sons.

Parker, K. C. (1991). Topography, substrate, and vegetation patterns in the northern Sonoran desert. *Journal of Biogeography*, *18*(2), 151–163. doi:10.2307/2845289

Parker, K. C. (1995). Effects of complex geomorphic history on soil and vegetation patterns on arid alluvial fans. *Journal of Arid Environments*, *30*(1), 19–39. doi:10.1016/S0140-1963(95)80036-0

Parker, K. C., & Bendix, J. (1996). Landscape-scale geomorphic influences on vegetation patterns in four environments. *Physical Geography*, *17*(2), 113–141.

Peters, A. P., Eve, M. D., Holt, E. H., & Whitford, W. G. (1997). Analysis of desert plant community growth patterns with high temporal resolution satellite spectra. *Journal of Applied Ecology*, *34*(2), 418–432. doi:10.2307/2404887

Peterson, F. F. (1981). Landforms of the basin and range province. *Nevada Agricultural Experiment Station Technical Bulletin, 28*.

Philips, D. L., & MacMahon, J. A. (1978). Gradient analysis of a Sonoran desert bajada. *The Southwestern Naturalist*, *23*(4), 669–680. doi:10.2307/3671189

Rachocki, A. (1981). *Alluvial fans: An attempt at an empirical approach*. New York, NY: John Wiley & Sons.

Satterwhite, M. B., & Ehlen, J. (1982). Landform-vegetation relationships in the northern Chihuahuan desert. *Catena Supplement*, *1*, 195–209.

Satterwhite, M. B., Rice, W., & Shipman, J. (1984). Using landform and vegetation factors to improve interpretation of landsat imagery. *Photogrammetric Engineering and Remote Sensing*, *50*(1), 83–91.

Schlesinger, W. H., Reynolds, J. F., Cunningham, G. L., Huenneke, L. F., Jarrell, W. M., & Virginia, R. A. (1990). Biological feedbacks in global desertification. *Science*, *247*(4946), 1043–1048. doi:10.1126/science.247.4946.1043

Seager, W. R., Clemons, R. E., & Callender, J. F. (Eds.). (1975). Guidebook of the Las Cruces country. In *Proceedings of the New Mexico Geological Society Guidebook 26th Field Conference*, Socorro, NM.

Seager, W. R., Hawley, J. W., Kottlowski, F. E., & Kelly, S. A. (1987). *Geology of the east half of Las Cruces and northeast El Paso 1º x 2º sheets, New Mexico (Geologic Map 57)*. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources.

Sharma, H. S. (1993). Geomorphological aspects of the processes of desertification in the northeastern Rajasthan (India). *Zeitschrift fur Geomorphologie . Supplementband*, *87*, 61–69.

Shreve, F. (1964). *Vegetation and flora of the Sonoran desert* (*Vol. 1*). Stanford, CA: Stanford University Press.

Smith, M. O., Ustin, S. L., Adams, J. B., & Gillespie, A. R. (1990). Vegetation in deserts: II: Environmental influences on regional abundance. *Remote Sensing of Environment*, *29*(1), 27–52. doi:10.1016/0034-4257(90)90075-W

Soil Survey Staff. (1980). *Soil survey of Dona Ana county*. Washington, DC: U.S. Department of Agriculture.

Soil Survey Staff. (1984). *Soil survey of Sierra county*. Washington, DC: U.S. Department of Agriculture.

Stein, R. A., & Ludwig, J. A. (1979). Vegetation and soil patterns on a Chihuahuan desert bajada. *American Midland Naturalist*, *101*(1), 28–37. doi:10.2307/2424898

Stephens, J. W., Butler, D. R., & Malanson, G. P. (1998). An overview of scale, pattern, process relationships in geomorphology: A remote sensing and GIS perspective. *Geomorphology*, *21*(3-4), 183–205. doi:10.1016/S0169-555X(97)00057-3

Strahler, A. H. (1981). Stratification of natural vegetation for forest and rangeland inventory using landsat digital imagery and collateral data. *International Journal of Remote Sensing*, *2*(1), 15–41. doi:10.1080/01431168108948338

Stubbendieck, J., Hatch, S. L., & Butterfield, C. H. (1997). *North American range plants* (5th ed.). Lincoln, NB: University of Nebraska Press.

Swanson, F. J., Kratz, T. K., Caine, N., & Woodmansee, R. G. (1988). Landform effects on ecosystem patterns and processes. *Bioscience*, *38*(2), 92–98. doi:10.2307/1310614

Thompson, M., Vlok, J., Rouget, M., Hoffman, M., Balmford, A., & Cowling, R. (2009). Mapping grazing-induced degradation in a semi-arid environment: A rapid and cost effective approach for assessment and monitoring. *Environmental Management*, *43*(4), 585–596. doi:10.1007/s00267-008-9228-x

Thompson, S. (1992). *Geology of the southern part of the Fra Cristobal Range, Sierra County, New Mexico*. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources.

Tongway, D. J. Valentin, C., & Seghieri, J. (2001). *Banded vegetation patterning in arid and semiarid environments: Ecological processes and consequences for management.* New York, NY: Springer.

Valverde, P. L., Zavala-Hurtado, J. A., Montaña, C., & Ezcurra, E. (1996). Numerical analysis of vegetation based on environmental relationships in the southern Chihuahuan desert. *The Southwestern Naturalist*, *41*(4), 424–433.

Verstappen, H. T. (1977). *Remote sensing in geomorphology*. New York, NY: Elsevier.

Walsh, S. J., Butler, D. R., & Malanson, G. P. (1998). An overview of scale, pattern, process relationships in geomorphology: A remote sensing and GIS perspective. *Geomorphology*, *21*(2), 183–205. doi:10.1016/S0169-555X(97)00057-3

Whitford, W. G. (2002). *Ecology of desert ecosystems*. New York, NY: Academic Press.

Wierenga, P. J., Hendrickx, J. M. H., Nash, M. H., Ludwig, J., & Daugherty, L. A. (1987). Variation of soil and vegetation with distance along a transect in the Chihuahuan desert. *Journal of Arid Environments*, *13*(1), 53–63.

Wilkie, D. S., & Finn, J. T. (1996). *Remote sensing imagery for natural resource monitoring*. New York, NY: Columbia University Press.

Wondzell, S. M., Cunningham, G. L., & Bachelet, D. (1987). *A hierarchical classification of landforms: Some implications for understanding local and regional vegetation dynamics (Tech. Rep. No. USDA Forest Service RM-150)*. Washington, DC: U.S. Department of Agriculture.

Wondzell, S. M., Cunningham, G. L., & Bachelet, D. (1996). Relationships between landforms, geomorphic processes, and plant communities on a watershed in the northern Chihuahuan desert. *Landscape Ecology*, *11*(6), 351–362. doi:10.1007/BF02447522

Yang, T. W., & Lowe, C. H. (1956). Correlation of major vegetation climaxes with soil characteristics in the Sonoran desert. *Science*, *123*(3195), 542. doi:10.1126/science.123.3196.542

Zevenbergen, L. W., & Thorne, C. R. (1987). Quantitative analysis of land surface topography. *Earth Surface Systems and Landforms*, *12*(1), 47–56. doi:10.1002/esp.3290120107

Zimmerman, R. C. (1969). *Plant ecology of an arid basin Tres Alamos-Redington area Southeastern Arizona*. Washington, DC: U. S. Government Printing Office.

Zimmerman, R. C., & Thom, B. G. (1982). Physiographic plant geography. *Progress in Physical Geography*, *6*(1), 45–59. doi:10.1177/030913338200600102

Zonn, I. S. (1988). An activity-based systems concept of anthropogenic desertification. *Journal of Arid Environments*, *17*(1), 103–108.

Daniel P. Dugas is an assistant professor in the Department of Geography at New Mexico State University where he specializes in Geomorphology. His current research focuses on the spatial/climatic association of pattern development at White Sands Dune field, biogeomorphic aspects of desert harvester ants, and landform-vegetation linkages.

Michael N. DeMers is an associate professor of geography at New Mexico State University where he specializes in Geographic Information Systems applications and design, landscape ecology, and applied geography education. His current applied research involves land use change, desert landscape analysis, and land classification.

Janet C. Greenlee is an affiliate faculty in geography at New Mexico State University where she specializes in applied Remote Sensing and Geographic Information Systems. Her current research involves identification and modeling of land-based sources of air quality contamination and correlation with health-related records.

Walter G. Whitford is a professor emeritus of biology at New Mexico State University and a collaborating scientist with the USDA-ARS Jornada Experimental Range where he conducts research on the ecology of arid lands. His current research focuses on the role of animals in geomorphic processes and soil ecology.

Anna Klimaszewski-Patterson is a master of applied geography student at New Mexico State University. Her studies focus on landscape ecology and Geographic Information System applications. Anna's current research involves assessing the accuracy of synthetic land classification schemes.