WATER RESOURCES RESEARCH, VOL. 44, W05S15, doi:10.1029/2006WR005850, 2008

Assessing vegetation change temporally and spatially in southeastern Arizona

D. M. King,[1] S. M. Skirvin,[2] C. D. Holifield Collins,[3] M. S. Moran,[3] S. H. Biedenbender,[4]
M. R. Kidwell,[3] M. A. Weltz,[5] and A. Diaz-Gutierrez[6]

Received 21 December 2006; revised 25 July 2007; accepted 26 December 2007; published 4 April 2008.

[1] Vegetation species cover and photographic data have been collected at multiple grass- and shrub-dominated sites in 1967, 1994, 1999, and 2005 at the U.S. Department of Agriculture Agricultural Research Service Walnut Gulch Experimental Watershed (WGEW) in southeastern Arizona. This study combines these measurements with meteorological and edaphic information, as well as historic repeat photography from the late 1880s onward and recent satellite imagery to assess vegetation change at WGEW. The results of classification and ordination of repeated transect data showed that WGEW had two main vegetation structural types, shrub dominated and grass dominated. Spatial distribution was closely linked to soil type and variations in annual and August precipitation. Other than the recent appearance of *Eragrostis lehmanniana* (Lehmann lovegrass) at limited sites in WGEW, little recruitment has taken place in either shrub or grass vegetation types. Effects of recent drought on both vegetation types were apparent in both transect data and enhanced vegetation index data derived from satellite imagery. Historic photos and a better understanding of WGEW geology and geomorphology supported the hypothesis that the shift from grass- to shrub-dominated vegetation occurred substantially before 1967, with considerable spatial variability. This work reaffirmed the value of maintaining long-term data sets for use in assessments of vegetation change.

Citation: King, D. M., S. M. Skirvin, C. D. Holifield Collins, M. S. Moran, S. H. Biedenbender, M. R. Kidwell, M. A. Weltz, and A. Diaz-Gutierrez (2008), Assessing vegetation change temporally and spatially in southeastern Arizona, *Water Resour. Res.*, *44*, W05S15, doi:10.1029/2006WR005850.

1. Introduction

[2] There is mounting evidence of vegetation change over the past 100 years in grasslands across the Sonoran and Chihuahuan deserts in the Southwestern United States (see, for example, the review by *Van Auken* [2000]). This change includes grass-to-shrub conversion in the uplands [*Biedenbender et al.*, 2004], shrub encroachment in the channels (M. H. Nichols and K. Renard, Geomorphic adjustments of Walnut Gulch, Arizona, USA, 1935–2005, submitted to *Water Resources Research*, 2006), and regional nonnative species invasion [*McClaran*, 2003]. There is also a great deal of controversy about why this is happening, with conflicting reports on the roles of livestock and wildlife grazing, drought, fire, and climate [*Peters and Gibbens*, 2006; *Houghton et al.*, 1999]. Furthermore, there is uncertainty caused by studies showing vegetation changes, such as shrub encroachment or nonnative species invasion, at some locations and not at others with seemingly identical hydro-ecological histories.

[3] This combination of spatially inconsistent change and the not-yet-fully-understood temporal causes is not an abstract issue, but rather a serious problem for the public. Cattle growers and producers do not have sufficient information and understanding of vegetation change to make critical land management decisions related to range sustainability. Physical scientists studying drought, flood and erosion cannot discriminate the changes in vegetation induced by ecohydrological, climate and human factors, thus stifling research in multiple related disciplines. Land management agencies and extension agents are awaiting decisive results that can be shared with land users to protect the land and its resources. This frustration has made long-term vegetation measurements extremely valuable and has stimulated analysis of all related data including historical notes, century-old government surveys, repeat landscape photography and recent satellite imagery.

[4] The U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) Southwest Watershed Research Center (SWRC) Walnut Gulch Experimental Watershed (WGEW) in southeastern Arizona has been the site of long-term, spatially distributed vegetation measurements in support of hydrologic studies with the stated goal of

---

[1] School of Natural Resources, University of Arizona, Tucson, Arizona, USA.

[2] Department of Geography and Regional Development and Department of Mining and Geological Engineering, University of Arizona, Tucson, Arizona, USA.

[3] Southwest Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, Tucson, Arizona, USA.

[4] Coronado National Forest, Sierra Vista Ranger District, Forest Service, U.S. Department of Agriculture, Hereford, Arizona, USA.

[5] Exotic and Invasive Weeds Research Unit, Agricultural Research Service, U.S. Department of Agriculture, Reno, Nevada, USA.

[6] Área de Producción Ecológica y Recursos Naturales, IFAPA, Córdoba, Spain.

0043-1397/08/2006WR005850$09.00

following vegetation changes over time. It has now been over 100 years since the first panoramic photographs were taken [*Hastings and Turner*, 1965] and 40 years since the intensive vegetation measurements at 55 shrub- and grass-dominated sites were initiated in 1967 (J. L. Gardner, Southwest Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, unpublished notes, 1967). During that period, hundreds of studies about erosion, rainfall, runoff and general hydrology have been published on the basis of the long-term, high-density hydrologic record of WGEW [*Renard et al.*, 2008]. This excellent quantification and understanding of the hydrology coincident with the long-term, distributed vegetation measurements could provide a golden opportunity to clarify the link between physical and biological changes over time, and geomorphology and vegetation variations over space.

[5] This study synthesizes four data sets at WGEW: (1) a set of vegetation cover, species and photographic data collected at 53 sites in 1967 and 1994, (2) vegetation cover, species and photography at 13 of the 53 sites in 1967, 1994, 1999 and 2005 (and one site added in 1994), encompassing the recent 5-year period of drought and extreme maximum temperatures, (3) spatially distributed rainfall data from 1954 to the present and (4) historic repeat photography from the late 1800s to the present and recent satellite imagery. The overall goal was to study temporal and spatial vegetation change at WGEW and offer insight to similar rangelands in southeastern Arizona. The specific objectives were (1) to uncover spatial patterns and outliers in vegetation data through ordination analysis of data from 53 sites measured in 1967 and 1994 and 13 sites in 1967, 1994, 1999 and 2005, representing grass- and shrub-dominated sites in the watershed; (2) to explore temporal and spatial trends in vegetation structure and abundance at selected grass- and shrub-dominated sites from 1967 to 2005; and (3) to provide context for vegetation change at WGEW through analysis of soils, climate and historic photographs.

2. Background

[6] There are multiple analyses of long-term vegetation measurements that report changes in vegetation cover and species composition in the American Southwest, and most support the notion of shrub encroachment and nonnative species invasion in grasslands over the past 100 years [e.g., *Gibbens et al.*, 2005; *McClaran*, 2003]. Other studies have theorized that some of these changes are irreversible without active management intervention [*Peters et al.*, 2004; *Rango et al.*, 2005; *Goslee et al.*, 2003]. The serious implications of such vegetation changes, including local increased erosion, regional decreased water yield and global disruption of biogeochemical function, have been reported in multiple reviews [*Huxman et al.*, 2005; *Schlesinger et al.*, 1990; M. S. Moran et al., Value of long-term data collection for understanding and predicting ecosystem dynamics, submitted to *Water Resources Research*, 2006]. However, there is as yet no consensus on what management strategy should be used to reduce or prevent such damage to the land and resources. This is because studies have also uncovered perplexing spatial and temporal anomalies that have been difficult to interpret and explain.

[7] For example, at the Jornada Experimental Rangeland (JER) near Las Cruces, New Mexico, there is convincing evidence based on field surveys, historic photography, and 100-year vegetation measurements that over 70% of the range has been converted from Bouteloua eriopoda (Torr.) Torr. (black grama) grassland to Prosopis *glandulosa* Torr./Flourensia cernua DC. (honey mesquite/tarbush) shrub land in the last 100 years. There are studies that report this conversion may be due to antecedent precipitation [*Gibbens and Beck*, 1988], may be sustained by erosion [*Walton et al.*, 2001; *Rango et al.*, 2005], may be initiated by overgrazing [*Peters and Gibbens*, 2006] and may be accelerated by climate change [*Schlesinger et al.*, 1990]. There are also studies that hypothesize that this change may be a natural long-term cycle of grassland–to–shrub land–to–grassland change [*Van Devender*, 1995] and may be irreversible under present conditions [*Peters et al.*, 2004].

[8] Similarly, at the Santa Rita Experimental Range (SRER) south of Tucson, Arizona, there is evidence that the encroachment of unpalatable *Haplopappus tenuisectus* (Greene) Blake (burroweed) has waxed and waned three times in the past 100 years without any concerted management effort [*McClaran*, 2003]. In fact, this cyclical trend has been unresponsive to documented management efforts such as grazing rotations. In contrast, the recent invasion of nonnative *Eragrostis lehmanniana* Nees (Lehmann lovegrass) in native grasslands at SRER has resulted in a complex competition that appears unrelated to the abundance of native grasses or grazing intensity, but may be sensitive to the frequency and distribution of rainfall [*Abbott and Roundy*, 2003]. Further, at some locations the *Prosopis velutina* Woot. (velvet mesquite) cover more than doubled in the past 50 years [*McClaran*, 2003], and numerous studies have reported that *P. velutina* cover did not differ between burned and unburned areas [*Martin*, 1983]. Yet, livestock grazing rotation and prescription burns are common management strategies to reduce or eliminate shrub encroachment and nonnative species invasion.

[9] These studies of long-term vegetation changes have been supplemented by analyses of spatial patterns of vegetation. At WGEW, the direction and timing of landscape change apparently differs with landscape position. On the basis of radiocarbon dating of soil organic matter and analysis of stable carbon isotopes, *Biedenbender et al.* [2004] reported that the ridge tops and midslopes at WGEW where shrubs are dominant and grasses are practically nonexistent, had been dominated by grasses in 400 BP. Furthermore, this decline in midslope and ridge top grasses occurred within the last several decades. Thus, the decline in grasses did not occur consistently across heterogeneous landscape positions despite exposure to similar land uses and climatic cycles.

[10] It is this history of unsuccessful management strategies devised to slow or reverse a relentless trend toward vegetation change that has spawned multiple analyses of long-term vegetation changes, including this study. This study also responds to the paucity of publications about WGEW vegetation, despite the unique combination of long-term measurements of vegetation, hydrology and climate available at one location [*Renard et al.*, 2008]. This initial compilation and analysis of WGEW vegetation data is the first step in an anticipated, comprehensive study of the

hydrological, ecological and climatic impacts on vegetation in southeastern Arizona.

3. Materials and Methods

[11] The following subsections include descriptions of the vegetation measurements, photographs, meteorological measurements and satellite images collected during the study. The approaches used for the ordination and spatial and temporal dynamics assessments are also discussed.

3.1. Vegetation Measurements and Photographs

[12] The protocol for vegetation measurements at WGEW was designed and implemented by Gardner (unpublished notes, 1967) "for the purpose of following any vegetation changes that may occur with time." Permanent, paired vegetation transects were established at grass- and shrub-dominated sites adjacent to 55 rain gauges distributed across the watershed (Figure 1a), and vegetation measurements made at 53 of these sites in 1967 were repeated in 1994. Of these 53 sites, paired transects at 13 sites were measured again in 1999 and 2005, and an additional site was added in 1994, for a total of 14 sites followed over 11 to 38 years (Figure 1b). This protocol for measurement is described in detail by *Skirvin et al.* [2008] and summarized here (Table 1). Each site has two 30.5 m (100 ft) parallel transects 15.2 m (50 ft) apart. The beginning and end of each transect were marked with steel pegs, between which a 30.5 m (100 ft) measuring tape was stretched for measurement. The line intercept method [*Bonham*, 1989] was used to measure woody and herbaceous plants by species, including individual plant canopy cover, plant height and diameter (from 1994 on), basal cover (only in 1967), and counts of plants by species. Beginning in 1994, point observations of ground cover type were made at 30 cm (1 ft) intervals along the transect tape and recorded as bare ground, rock, litter or plant crown for a total of 200 observations per site on paired transects. In 1967, 1994 and 2005, repeat photographs were taken of each transect line and the general landscape of each site [*Skirvin et al.*, 2008, Figure 2]. In addition to the repeat photos made for the vegetation measurement sites, historic landscape photographs were taken at several locations in WGEW from the early 1800s to the present (Figure 1b and Table 2).

[13] The vegetation measurement sites were located in WGEW across a mean annual precipitation gradient from 305 mm to 406 mm and an elevation range of 1250 m to 1720 m from the southwest (outlet) to the northeast. The soils include sandy loam, fine sandy loam, loamy sand and clay loam, with a gravel and coarse fragment content estimated at nearly 50% over much of the watershed [*Natural Resource Conservation Service*, 2003] (Figure 1a). A vegetation map developed and described by *Skirvin et al.* [2008] shows that the western half of WGEW is dominated by woody vegetation and the eastern half is dominated by native grasses, separated by a complex transitional zone. The 13 sites measured in all 4 years, plus the additional site measured starting in 1994, were selected to represent 7 shrub-dominated sites and 7 grass-dominated sites in distinctive soil types (Figure 1b).

[14] In particular, sites 83, 28, 87, 39, 91 and 82 are located in soil types that have a strong correlation with the current vegetation (Table 3). The Luckyhills-McNeal Complex is at the lowest end of the 300–400 mm precipitation zone, with low slopes and a highly eroded A horizon. Immediately to the east, the McAllister-Stronghold Complex is characterized by a thicker A horizon, a more developed argillic layer, a deeper calcic layer, and not as much erosion as the Luckyhills-McNeal Complex. Further to the east at the highest end of the 300–400 mm precipitation zone, the Elgin-Stronghold and Stronghold-Bernardino complexes are older, more stable soils with steeper slopes and a well-developed argillic horizon. The soils in the low- and high-precipitation zones respectively support shrub-dominated and grass-dominated vegetation, while the intermediate soil complex is characterized by a mix of shrub- and grass-dominated sites.

3.2. Meteorological Measurements

[15] Each vegetation measurement site was associated with a rain gauge measuring continuous precipitation at 5-min intervals that is archived at the USDA ARS SWRC [*Goodrich et al.*, 2008] and available online at http://www.tucson.ars.ag.gov/dap/. Most of the 88 rain gauges are turned off each winter; so the annual precipitation sums presented here are for the six rain gauges (4, 13, 42, 44, 60 and 68) that have been monitored all year since 1954 (Table 4 and Figure 1b). There is also a climate station in Tombstone, Arizona, that has recorded daily precipitation and air temperature since 1893 (Table 4 and Figure 1b) (Western Regional Climate Center (WRCC) data available at http://www.wrcc.dri.edu/summary/Climsmaz.html). The average summer precipitation for the years from 2001 to 2004 was the lowest over any 4-year period in the 51-year record at WGEW and was also associated with the highest June temperatures on record at the Tombstone climate station. This combination of extreme heat and drought has been known to induce woody plant die off in the Southwest United States [*Breshears et al.*, 2005].

3.3. MODIS Measurements

[16] The Moderate Resolution Imaging Spectroradiometer (MODIS) sensors onboard the Terra and Aqua Earth-orbiting satellites (launched 1999 and 2002, respectively) were designed to monitor a variety of Earth surface properties, including vegetation cover, at high temporal (daily to ~biweekly) and moderate spatial (250 m and 1 km pixel size) resolutions [*Justice et al.*, 2002]. Land science products derived from MODIS spectral data include the enhanced vegetation index (EVI) product, available at both

Figure 1. (a) Locations of 53 vegetation transect sites at WGEW overlain on a map of soil units, where numbers designate associated rain gauge numbers. (b) Location of 14 vegetation transect sites overlain on a map of the Luckyhills-McNeal, McAllister Stronghold, and Elgin Stronghold Bernardino complex soil units, where S and G represent shrub- and grass-dominated sites. Sites of historic vegetation photographs are designated by the photo number and an arrow showing the general direction toward which the photo was taken. Locations of rain gauges 4, 13, 42, 44, 60, and 68 show where precipitation was measured all year long 1954 to present.

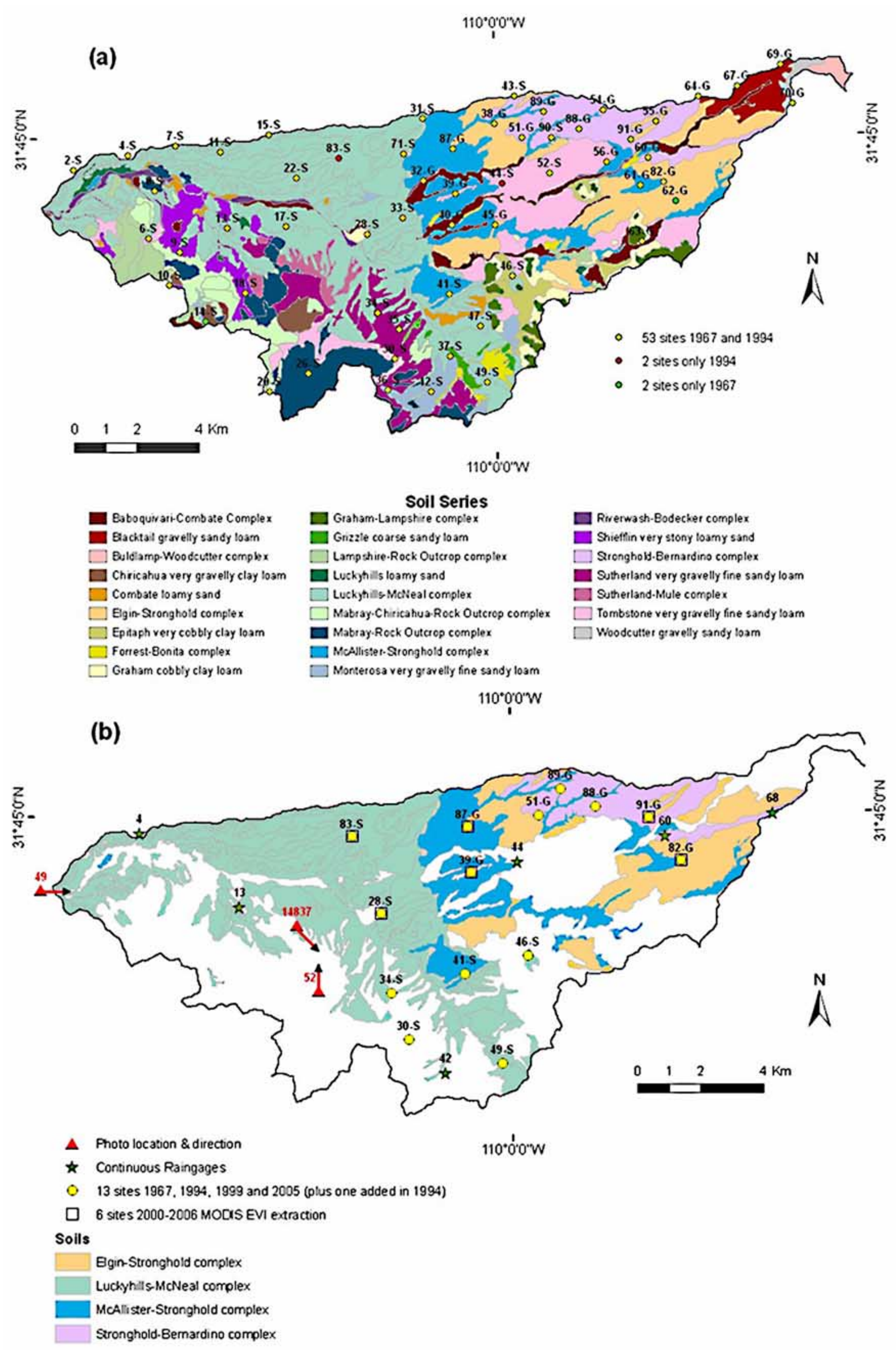
110°0'0"W
(a)
31°45'0"N
N
53 sites 1967 and 1994
2 sites only 1994
2 sites only 1967
0 1 2 4 Km
Soil Series
Baboquivari-Combate Complex
Blacktail gravelly sandy loam
Buldlamp-Woodcutter complex
Chiricahua very gravelly clay loam
Combate loamy sand
Elgin-Stronghold complex
Epitaph very cobbly clay loam
Forrest-Bonita complex
Graham cobbly clay loam
Graham-Lampshire complex
Grizzle coarse sandy loam
Lampshire-Rock Outcrop complex
Luckyhills loamy sand
Luckyhills-McNeal complex
Mabray-Chiricahua-Rock Outcrop complex
Mabray-Rock Outcrop complex
McAllister-Stronghold complex
Monterosa very gravelly fine sandy loam
Riverwash-Bodecker complex
Shiefflin very stony loamy sand
Stronghold-Bernardino complex
Sutherland very gravelly fine sandy loam
Sutherland-Mule complex
Tombstone very gravelly fine sandy loam
Woodcutter gravelly sandy loam
(b)
14837
49
52
N
0 1 2 4 Km
Photo location & direction
Continuous Raingages
13 sites 1967, 1994, 1999 and 2005 (plus one added in 1994)
6 sites 2000-2006 MODIS EVI extraction
Soils
Elgin-Stronghold complex
Luckyhills-McNeal complex
McAllister-Stronghold complex
Stronghold-Bernardino complex

Figure 1

Table 1. Summary of Historic Vegetation Data From WGEW

Year	Sites	Measurements	Time of Year
1967	55 sites	2 100-ft transects and photos (total shrub cover, grass basal cover, and counts of plants by species, plus photos)	all in summer
1994	53 sites (same as 1967 sites, but 2 dropped and 2 added)	2 100-ft transects and photos (measurements like 1967, but total grass cover instead of grass basal cover, and added surface roughness, biomass and ground cover measurements)	39 in summer, 15 in Dec
1999	14 sites (13 from the original 1967 55 sites and 1 is the 1994 "added" site)	2 100-ft transects; no photos (measurements like 1994, but standardized canopy cover measurements); biomass collected at 2 sites (as in 1994)	Oct–Nov
2005	14 sites (same as 1999)	2 100-ft transects and photos (measurements like 1999)	Jul–Dec

250 m and 1 km resolutions, which have demonstrated sensitivity to photosynthesizing vegetation while minimizing artifacts due to variations in soil background and changing atmospheric conditions [*Huete et al.*, 2002]. MODIS EVI data were extracted from 1-km pixels encompassing each of six vegetation transect sites and averaged as pairs (see Table 3) for the period 2000–2005 in order to gain a more detailed view of site vegetation dynamics between the years of transect data collection in 1999 and 2005. These years spanned the period of drought and high summer temperatures expected to impact both shrub- and grass-dominated vegetation types (Table 4).

3.4. Ordination Approach and Methods

[17] The line intercept vegetation transect data collected at WGEW represent variations in vegetation across space and time. With more than 100 plant species recorded at 84 locations in space and as many as 4 samples over time, the transect data form a substantial multivariate data set of 24,000 individual records [*Skirvin et al.*, 2008] that are not easy to summarize or interpret. Classification and ordination of transect data were performed to provide both an overview of the vegetation data and a starting point for hypothesis generation [*Minchin*, 1987; *Gauch*, 1982; *McCune and Grace*, 2002].

[18] Two overlapping subsets of transects were selected for this analysis: 53 sites surveyed in 1967 and 1994; and 13 sites surveyed in 1967, 1994, 1999, and 2005 (locations are shown in Figure 1). Plants were identified to species whenever possible, to genus, or to life form level such as grass, shrub, forb, and so on; these identification levels are collectively referred to as species in this work. Plant species nomenclature was normalized to the USDA-NRCS PLANTS 2005 database (available at http://plants.usda.gov). The 1967–1994 data set contained 94 species, and the 1967–1994 to 1999–2005 set contained 97 species.

[19] Absolute percent cover was selected for use as a vegetation abundance measure in classification and ordination, as it is consistently repeatable [*McCune and Grace*, 2002] and could be readily obtained from the line intercept measurements. Absolute percent cover by species was computed for each site by summing individual species intercept lengths and dividing by the transect length and multiplying by 100, and then calculating an average of the two transects at each site.

[20] An initial analysis was performed to identify outliers using two distance measures (Euclidean and Sorensen). Outliers were flagged as species or sites more than two standard deviations in mean distance from all other species or sites. Sites were classified using agglomerative hierarchical clustering with Ward's method linkage and Euclidean distance in PC-ORD4 software, and were evaluated to the highest two levels of grouping. NMS ordination was used with Sorensen distance in PC-ORD4 software in "autopilot" mode [*McCune and Mefford*, 1999]. Random starting configurations were used in 15 runs with real data and 30 runs with randomized data, a maximum of 200 iterations, and a stability criterion of 0.0001 standard deviations in the stress factor over the last 10 iterations. The software selected the number of dimensions in ordination output on the basis of the rate of decrease in the stress factor with increasing number of dimensions.

3.5. Spatial and Temporal Dynamics Assessment Approach

[21] The greatest spatial coverage of vegetation was provided by the 53 sites surveyed 1967–1994, while the subset of 13 sites surveyed 1967–1994 to 1999–2005 gave the longest temporal coverage. Vegetation cover and groundcover were evaluated to assess whether the temporal subset was representative of the larger set of sites, and to examine the nature of vegetation change at these sites. Data

Table 2. Historic Repeat Photography at WGEW

Figure	Year, Archive Location, and Photographer	Source and Archive Number
8	1884, Arizona Historical Society (AHS)/Tucson, photographer unknown	AHS 5191 DLC, stake 52
	1960: Desert Laboratory Collection (DLC), James R. Hastings	AHS 5191 DLC, stake 52
9	1890,[a] Arizona Historical Society (AHS)/Tucson, George Roskruge	AHS 19324 DLC, stake 49b
	1960, Desert Laboratory Collection (DLC), James R. Hastings	AHS 19324 DLC, stake 49b
	1994, Desert Laboratory Collection (DLC), Dominic Oldershaw	AHS 19324 DLC, stake 49b
10	1880,[a] Arizona Historical Society (AHS)/Tucson, Watkins Photo	AHS 14837

[a] Approximate date.

Table 3. Soil Units[a]

Soil Unit	Soil Description	Dominant Vegetation
Luckyhills-McNeal Complex rain gauges 83 and 28	slope 3–8%; gravel 45–50%; calcic layer at 25–50 cm; permeability: moderate; thin argillic layer; precipitation: 300 mm	dominated by woody vegetation
McAllister-Stronghold Complex rain gauges 87 and 39	slope 3–8%; gravel 35–45%; calcic layer at 50–100 cm; permeability: moderately slow; moderately developed argillic horizon	mixed shrub and grass areas
Elgin-Stronghold and Stronghold-Bernardino complexes rain gauges 91 and 82	slope 10–30%; gravel 25–55%; calcic layer at 25–50 cm; permeability: slow to moderate; well-developed argillic horizon; precipitation: 400 mm	dominated by native grasses, with scattered shrubs

[a]Source: *Natural Resource Conservation Service* [2003].

for six selected sites paired within distinctive soil complexes were also evaluated.

[22] Statistical tests were performed to look for significant changes in absolute cover of dominant shrub and grass species (see Table 5 for list) at the 13 sites. Tests included the *t*, sign, and signed rank test for samples paired by consecutive years, as frequently used in analysis of ecological change [e.g., *Beever et al.*, 2005; *Rideout et al.*, 2003; *Moir et al.*, 2000]. Comparisons were made for 13 sites as a group, and for the 6 shrub-dominated and 7 grass-dominated sites as separate groups. Grass cover was recorded as basal cover in 1967 only, and could not be meaningfully compared with grass canopy cover recorded in 1994, 1999, and 2005.

[23] Additional variables were generated from transect data for 6 shrub-dominated sites and were evaluated statistically as above. The variables included: number of individual plants of all species; number of individual plants of dominant shrubs only; total intercept of dominant shrubs; and mean intercept per dominant shrub individual. Ground cover hits on crown cover were compared among the 6 shrub and 7 grass sites using the *t*, sign, and signed rank test for samples paired by year.

4. Results

[24] The results presented in this section provide an overview of the main vegetation types at WGEW sampled by transect data and evidence for temporal and spatial dynamics within the main vegetation types.

4.1. Vegetation at WGEW

[25] Transect data from the 53 sites indicated that native and exotic grasses were found at all elevations throughout WGEW. Important native forage species included *B. eriopoda*, *Bouteloua curtipendula* (Michx.) Torr. (sideoats grama), *Tridens muticus* (Torr.) Nash (slim tridens), and *Muhlenbergia porteri* Scribn. ex Beal (bush muhly). The most widespread invasive species was *E. lehmanniana* and, to a lesser extent, *Eragrostis cilianensis* (All.) Vign. ex Janchen (stinkgrass) and *Hackelochloa granularis* (L.) Kuntze (pitscale grass). The native perennial grass species utilize the C_4 photosynthetic pathway, with summer growth tied to monsoon rains that typically begin in July [*McClaran*, 1995].

[26] Woody vegetation at WGEW consisted of shrubs, subshrubs (suffrutescents), and trees. Prominent shrub species included *Acacia constricta* Benth (whitethorn acacia), *L. tridentata*, and *F. cernua*. Common subshrubs include *Zinnia acerosa* (DC.) Gray (desert zinnia), *Parthenium incanum* Kunth (mariola), and *Calliandra eriophylla* Benth (fairy duster). Trees were found along limited riparian zones and in open woodland at higher elevations, including *P. velutina* and oak and juniper species (*Quercus* and *Juniperus* spp).

[27] Other vegetation life forms at WGEW included annual and perennial forbs, cacti, and other xerophytes including *Yucca*, *Agave*, and *Nolina* species. These other life forms typically formed a small portion of total vegetative cover, although forbs can be transiently abundant following sufficient precipitation. Total absolute vegetation cover was spatially variable and typically low in this semiarid area, ranging between 4% and 70% and averaging 30–35% at transect sites.

4.2. Spatial Patterns and Outliers in Vegetation Data

4.2.1. Outlier Analysis

[28] On the basis of vegetation measurements made in 1967 and 1994, sites containing an abundance of unusual species or mixes of species were flagged as outliers (Figure 2).

Table 4. Average Meteorological Conditions in the 4-Year Periods Prior to the Vegetation Measurements[a]

Year	Average Annual Precipitation From WGEW Rain Gauges, mm	Average Summer Precipitation (May–Oct) From WGEW Rain Gauges, mm	Average Winter Precipitation (Nov–Apr) From WGEW Rain Gauges, mm	Average January Minimum Temperature From Tombstone Climate station, deg C	Average June Maximum Temperature From Tombstone Climate station, deg C
1963–1966	316 (26)	243 (25)	72 (2)	0.5 (1.8)	33.7 (0.9)
1990–1993	370 (25)	218 (16)	152 (10)	2.0 (1.4)	35.2 (2.3)
1995–1998	284 (33)	206 (27)	78 (8)	2.3 (0.3)	35.0 (1.1)
2001–2004	250 (17)	169 (13)	81 (6)	2.0 (1.7)	35.9 (1.1)

[a]Standard deviations are given in parentheses. Six long-term rain gauges provided the data which were averaged over the 4-year periods (n = 24).

Table 5. Vegetation Cover for Dominant Shrub and Grass Species Averaged Over 53 and 13 Vegetation Measurement Sites in WGEW[a]

Year	Shrubs and Percent Cover	Grass and Percent Cover	Total Percent Cover[b]
		53 Transects	
1967	ACCO (7), FLCE (3), LATR (2)	BOER (1), BOCU (0.1), TRMU (0.1)	22[c]
1994	ACCO (6), LATR (4), FLCE (3)	BOER (2), BOCU (1), MUPO (1), TRMU (0.4)	39
		13 Transects	
1967	ACCO (6), LATR (1), FLCE (1)	BOER (1), TRMU (0.1), BOCU (0.1)	19[c]
1994	ACCO (4), LATR (2), FLCE (2)	BOER (3), MUPO (1), BOCU (1), TRMU (0.2)	38
1999	ACCO (5), LATR (3), FLCE (2)	BOER (3), MUPO (1), BOCU (1), ERLE (0.4), TRMU (0.4)	43
2005	ACCO (3), LATR (2), FLCE (2)	BOER (4), MUPO (2), ERLE (2), TRMU (1), BOCU (1)	43
		6 Shrub Transects	
1967	ACCO (13), LATR (3), FLCE (2)	BOER (0.4)	30[c]
1994	ACCO (7), FLCE (4), LATR (4)	MUPO (3), BOER (0.4)	49
1999	ACCO (9), LATR (6), FLCE (4)	MUPO (3), BOER (1), ERLE (1)	45
2005	ACCO (6), LATR (5), FLCE (3)	MUPO (4), BOER (1), ERLE (1)	40
		7 Grass Transects	
1967	na	BOER (1), TRMU (0.2), BOCU (0.2)	9[c]
1994	ACCO (0.4)	BOER (5), BOCU (1), TRMU (0.4)	28
1999	ACCO (1)	BOER (6), BOCU (1), TRMU (1), ERLE (0.3)	42
2005	ACCO (1)	BOER (7), ERLE (2), TRMU (1), BOCU (1)	47

[a] Key: ACCO, *Acacia constricta*; BOCU, *Bouteloua curtipendula*; BOER, *Bouteloua eriopoda*; ERLE, *Eragrostis lehmanniana*; FLCE, *Flourensia cernua*; LATR, *Larrea tridentata*; MUPO, *Muhlenbergia porteri*; TRMU, *Tridens muticus*; na, not applicable (not found at site).

[b] Mean over all sites.

[c] Note that grass cover in 1967 was measured as basal cover and cannot be directly compared with canopy cover measured in 1994 and subsequently.

While most sites were located on ridge tops or open hillsides, two sites in the bottom of large washes (broad valleys) showed evidence of long-term disturbance, indicated by vegetation composition and confirmed by site visits in 2005. One site was uniquely dominated by *P. velutina* (site 40, Figure 2); the other was within an exurban subdivision (site 32, Figure 2) and had more forb and subshrub species than other rangeland sites. The three highest-elevation sites (above 1615 m) had a different mix of species than most of the watershed (between 1220 and 1615 m elevation),

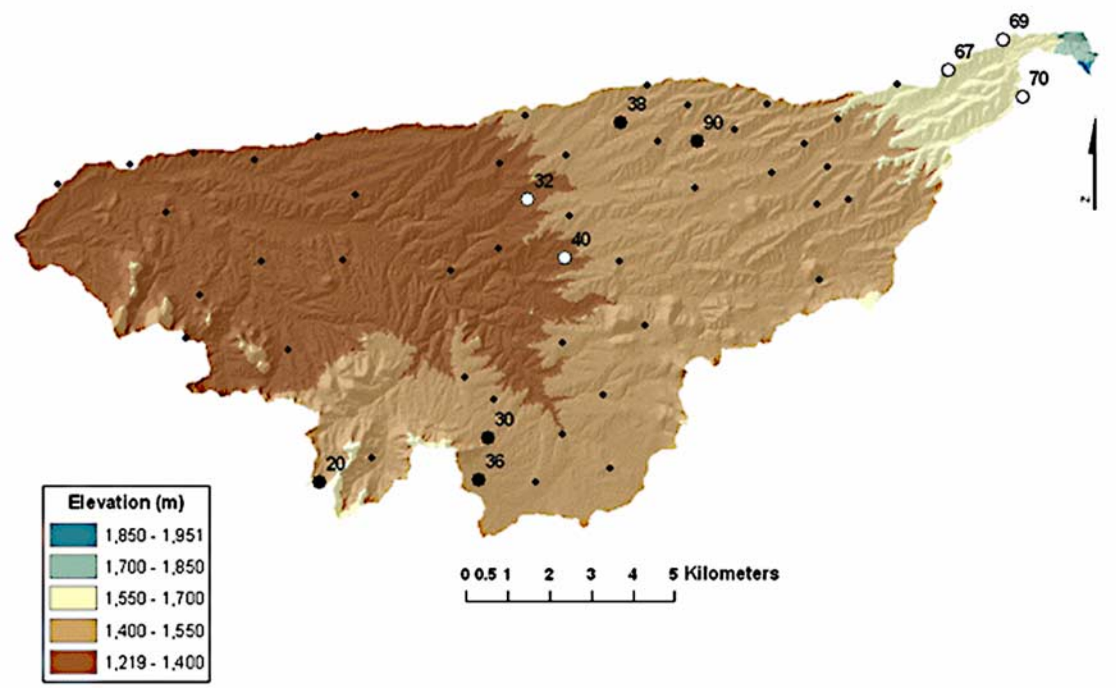

Figure 2. Results of outlier identification (sites more than 2 standard deviations in mean distance from all other sites) and classification and ordination analysis. Key: white circles, outlier sites with substantially different vegetation; large black circles, sites with evidence of a shift from grass to shrub dominated; and small black circles, sites with no apparent shift in dominant vegetation.

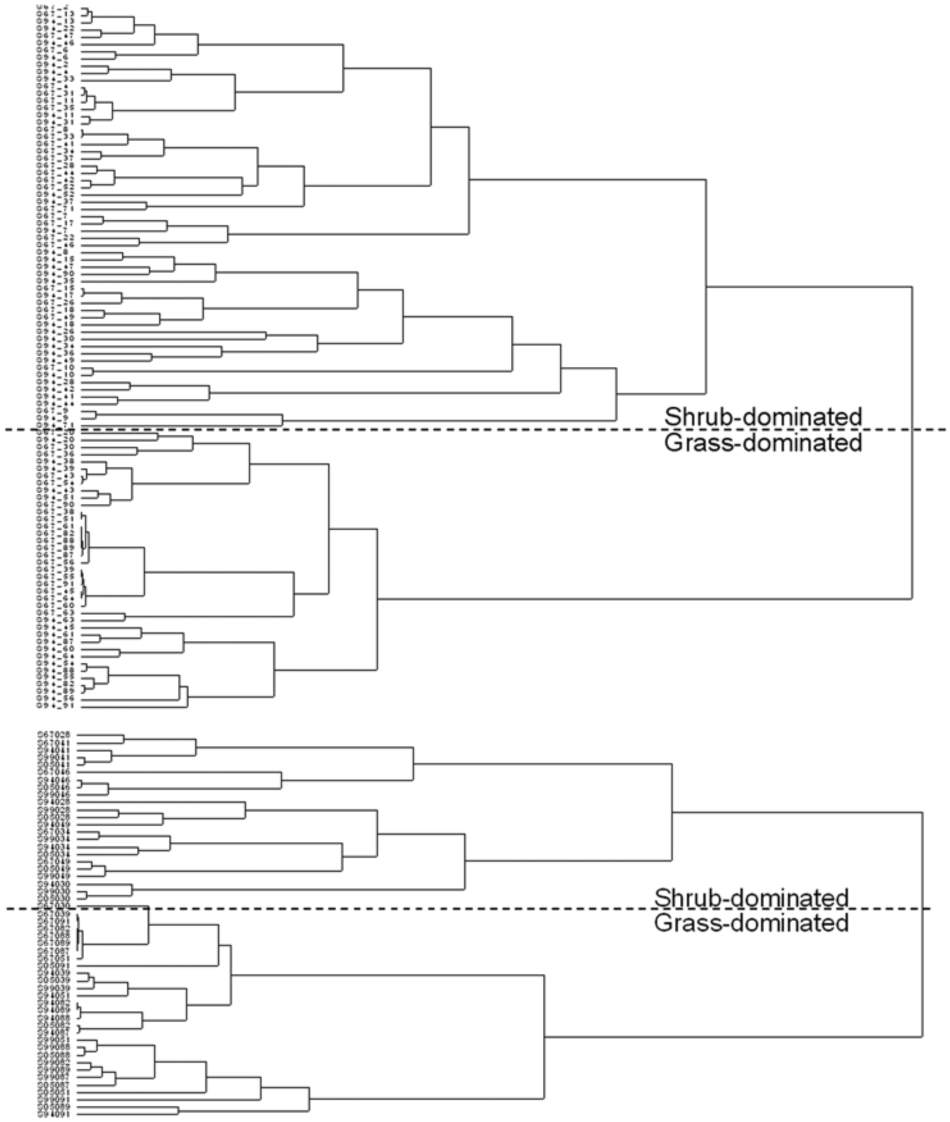

Figure 3. (top) Classification dendrogram of 53 sites 1967–1994. (bottom) Classification dendrogram of 13 sites 1967–2005. All sites were coded with letter prefix (here “S”) to designate sample number for use in the classification software.

including more trees and perennial grasses. These five sites were judged to be substantially different from most of the watershed and were removed from the data set, leaving a total of 48 sites.

[29] On the basis of measurements made in 1967, 1994, 1999 and 2005, two sites were flagged as outliers in 2005 using Euclidean distance. One of these sites was flagged in 1999 using Sorensen distance. Since there was no consistency in these results, all 13 sites were retained.

[30] In both data sets, different species were flagged as outliers by the different distance measures. These were a handful of frequently occurring species, including shrubs *A. constricta*, *L. tridentata*, and *F. cernua*; subshrubs *Z. acerosa*, *P. incanum,* and *C. eriophylla*; and grasses *B. eriopoda*, *B. curtipendula*, and *Dasyochloa pulchella* (Kunth) Willd. ex Rydb.(fluffgrass). Because of the lack of consistent results, no species were removed on the basis of the outlier analysis. Rare species that occurred only one time on one site, however, were removed from both data sets. This resulted in final totals of 66 species in the 1967–1994 data, and 68 species in the 1967–1994 to 1999–2005 data.

4.2.2. Classification

[31] Classification results were summarized in dendrograms, shown in Figure 3. For both data sets, the two highest-level clusters represented grass-dominated and shrub-dominated sites. “Shrub-dominated” here refers to the presence of numerous individuals of *A. constricta*, *L. tridentata*, and/or *F. cernua*, which together constituted the bulk of total vegetation cover at such sites. “Grass-dominated” refers to open sites with widespread, appreciable grass cover and infrequent shrubs such as *Ephedra trifurca* Torr. ex S. Wats. (mormon tea) and *Yucca elata* (Engelm.) Engelm. (soaptree yucca), and the common, low-growing subshrub, *C. eriophylla*.

[32] Detailed examination of the 1967–1994 results (Figure 3) showed that three sites moved between highest-level clusters during this interval, suggesting a possible

transition from grass-dominated to shrub-dominated vegetation (sites 30, 36, 90). Vegetation data and transect photographs showed that the three dominant shrub species were present on all three sites in 1967. At sites 36 and 90, these shrubs increased substantially in cover on the transect lines by 1994, while a number of grass species disappeared. Site 30 had decreased cover of the dominant shrub species by 1994, but increased cover of several other shrub species. The location of these sites is shown in Figure 2.

[33] Site 30 was positioned between shrub- and grass-dominated clusters in the 1967–1994 to 1999–2005 classification, plotting closer to the grass-dominated sites in 1967 and to shrub-dominated sites thereafter. Similar to the data for the larger 1967–1994 data set, shrub-dominated sites were generally grouped in the upper half, and grass-dominated sites in the lower half, of the dendrogram (Figure 3).

4.2.3. Ordination

[34] For measurements made in 1967 and again in 1994, graphical ordination results (Figure 4a) displayed two main groups of sites in two dimensions. The size of site symbols could be scaled to represent species abundance for one species at a time (Figures 4b and 4c), which showed that shrub-dominated sites plotted in one group, and grass-dominated sites plotted in the other group. Vectors linking 1967 and 1994 points for each site made the shrub-grass distinction more obvious and showed that most grass-dominated sites moved in a similar multivariate "direction" over time, while trajectories of shrub-dominated sites varied more (Figure 4a). Of the sites for which classification indicated a vegetation shift, sites 30 and 36 plotted within the shrub-dominated group in both years. Site 90 and site 20 plotted in the intermediate zone between major groups, but did not cross the line between types. Transect data for site 20, located on thin soils covering limestone bedrock, showed an anomalous pattern of decreased cover by dominant shrub species, accompanied by the appearance of several grass species by 1994.

[35] For measurements made in 1967, 1994, 1999 and 2005, ordination results indicated two dimensions within the data. Two groups of sites were readily apparent, with vegetation data again indicating a shrub-dominated versus grass-dominated distinction. Site 30 plotted with shrub-dominated sites.

4.3. Trends in Species Abundance, Vegetation Cover, and Ground Cover

4.3.1. Species Abundance

[36] Absolute vegetation cover data (Table 5) indicated that species abundances were very similar between the 53 sites and the 13-site subset in 1967 and 1994. Both overall percent cover and cover by species were comparable, lending support for the selection of the 13 sites as proxies for larger shrub- and grass-dominated areas of WGEW.

[37] Relatively small shifts in species abundance over time were apparent within the shrub- and grass-dominated groups both for aggregated sites (Table 5) and individual sites. Species that first appeared on transects, or increased to 0.2% cover or more, between survey years included *M. porteri* at 5 shrub sites, *A. constricta* at 3 grass sites, and *E. lehmanniana* at both types of sites.

[38] Detailed transect records showed that *E. lehmanniana* was not observed at any WGEW site in 1967, but appeared by 1994 at 7 sites that were not surveyed again. *E. lehmanniana* appeared at the 13 sites for the first time in 1999, at 3 shrub-dominated and 4 grass-dominated sites. In 2005, it persisted at 1 shrub-dominated and 3 grass-dominated sites, disappeared at 2 shrub-dominated sites and 1 grass-dominated site, and appeared at 1 shrub-dominated and 1 grass-dominated site. *E. lehmanniana* cover was less than 1% in all years at all but one site, where it increased to 8% cover and constituted 24% of total vegetation cover by 2005 (site 91, Table 6).

4.3.2. Vegetation and Ground Cover

[39] Trends in absolute vegetation cover from 1967 to 2005 at the 13 sites were evaluated statistically. Pairwise comparisons of percent cover by years showed no significant change in cover ($\alpha = 0.05$) for dominant native grasses or *E. lehmanniana* after 1994 (Figure 5). However, measurements of grass canopy cover from 1994 to 2005 were made at different seasons, which could account for some noise in the data that may have prevented any detection of year-to-year differences.

[40] Cover for 3 dominant shrub species at 6 shrub-dominated sites increased significantly between 1994 and 1999 ($\alpha = 0.05$ for 3 tests) and decreased significantly between 1999 and 2005 ($\alpha = 0.05$ for t test) (Figure 5c). Pairwise comparisons by years for additional variables at 6 shrub-dominated sites showed significant change between 1999 and 2005 (Table 7): total shrub intercept and mean intercept per shrub individual both decreased ($\alpha = 0.05$ for 3 tests). The differences in numbers of individuals of all species and of dominant shrubs only were not significant at the $\alpha = 0.05$ level. The significant decreases in shrub cover, total intercept, and mean individual intercept (plant size) together indicated overall decreased shrub biomass between 1999 and 2005, while grass biomass showed no significant changes during this period.

[41] Vegetation cover 1967–2005 for 6 paired sites is summarized in Table 6. These sites were selected to represent large areas of WGEW where soil type and current vegetation type are closely coupled (Table 3 and Figure 1b). Sites 28 and 83 on Luckyhills-McNeal complex soils maintained little or no grass cover and substantial shrub cover, typical of shrub-dominated areas in the western watershed. Sites 39 and 87 on McAllister-Stronghold complex soils, in a transitional part of the watershed, had little grass cover and no cover of the dominant shrubs. Sites 82 and 91 on Elgin-Stronghold and Stronghold-Bernardino complex soils maintained grass cover at somewhat higher levels than the McAllister-Stronghold sites.

[42] Ground cover point data indicated crown cover hits decreased by approximately one third for both grass- and shrub-dominated sites between 1994 and 1999 (Table 8). Shrub-dominated sites experienced a further 22% decline in crown cover hits between 1999 and 2005, with an 8% decline at grass-dominated sites. Net decrease in crown cover hits between 1994 and 2005 was 40% at grass-dominated sites and 44% at shrub-dominated sites. Of these results, only the decrease at grass-dominated sites between 1994 and 1999 was significant at the $\alpha = 0.05$ level. Litter observations may have been affected by data acquisition occurring in different seasons (growing season versus fall senescence), therefore their long-term temporal trends were not interpreted as having implications for vegetation dynamics.

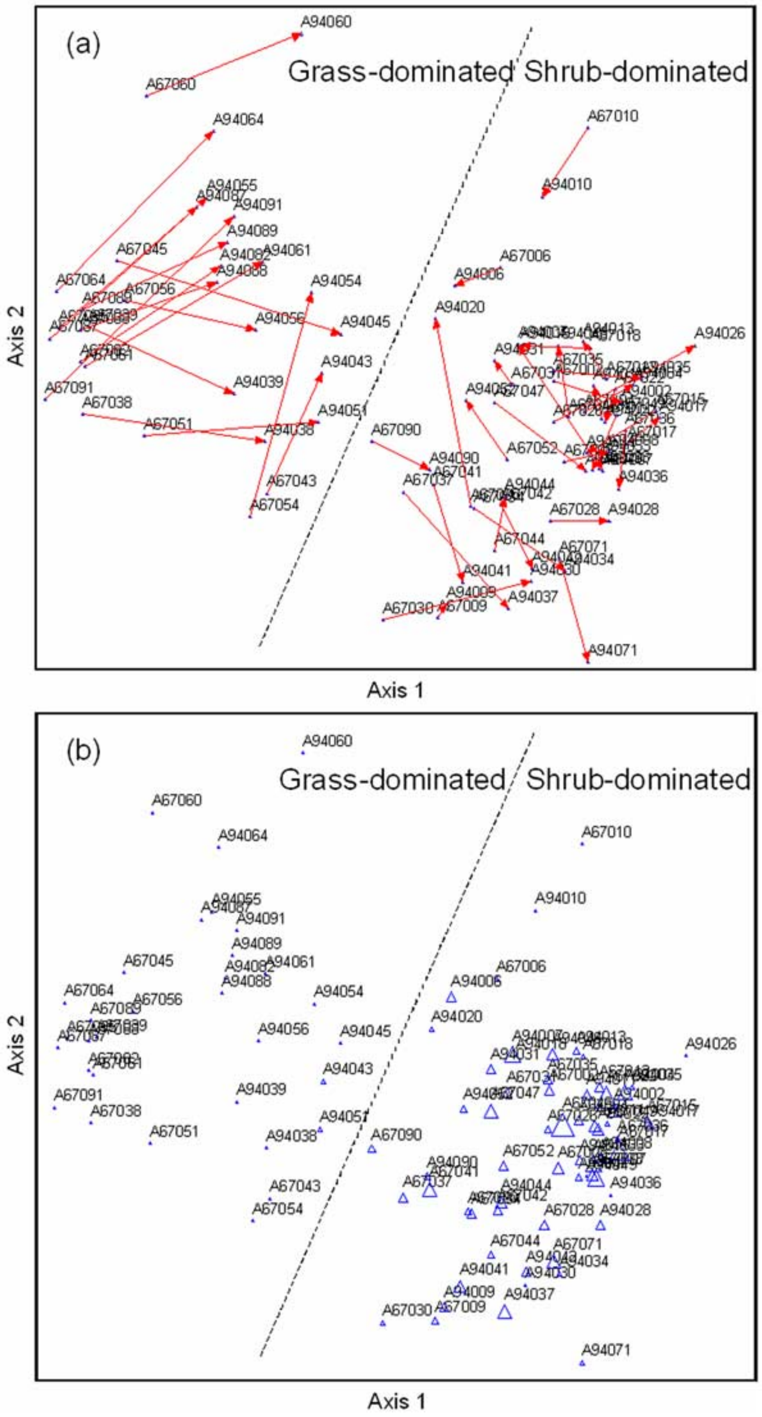

Figure 4. Ordination graphical results. All sites were coded with arbitrary letter prefix "A" to designate sample number for use in the ordination software. (a) Ordination of 53 sites 1967–1994: site trajectories through time showing the distinction between grass- and shrub-dominated sites. (b) Ordination of 53 sites 1967–1994: relative abundance of dominant shrub *A. constricta* at transect sites. (c) Ordination of 53 sites 1967–1994: relative abundance of grass species *B. eriopoda* at transect sites. Abundance is proportional to symbol size.

[43] Despite the general lack of statistically significant vegetation cover and ground cover change (with the exception of decreased grass crown hits 1994–1999 and shrub cover 1999–2005), temporal trends in the data support the hypothesis that recent multiyear drought has progressively impacted vegetation, especially the dominant shrub types. The effect of long-term drought on WGEW vegetation is evident in the EVI time series for 6 transect sites (Figure 6). The long-term trend of EVI had a negative slope for years 2000 through 2005 at all 6 sites indicating reduced vegetation "greenness" (photosynthesizing

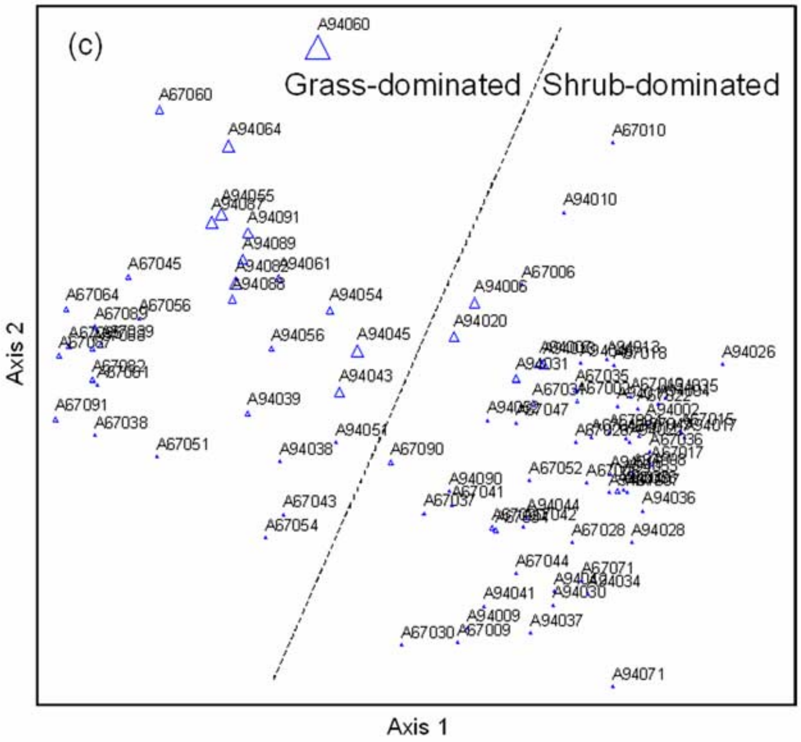

Figure 4. (continued)

vegetative material) at both shrub- and grass-dominated sites. EVI profiles were very similar for the two types of sites over all years, although peak EVI values were higher for grass-dominated sites than for shrub-dominated sites during the summer growing season.

5. Discussion of Spatial and Temporal Vegetation Change

[44] The results of classification and ordination of repeated transect data supported the concept of two main vegetation structural types on the WGEW: shrub-dominated (one or more of the three dominant species comprising 20% or more of total cover), and grass-dominated (less than 15% of total cover contributed by nondominant shrub species). Relatively small shifts in species cover over time were observed in data from the 13 representative transects. There was a significant decrease in grass crown cover hits at grass-dominated sites indicating the presence of fewer individual plants between 1994 and 1999. However, grass cover at these sites did not change significantly, suggesting that little recruitment is taking place and cover has been maintained by fewer, perhaps larger plants. Historic photos of WGEW support the conclusion that the shift from grass- to shrub-dominated vegetation occurred substantially before 1967, with considerable spatial variability, and any ongoing vegetation change is incremental rather than wholesale.

[45] Cover for 3 dominant shrub species at the 6 shrub-dominated sites increased between 1994 and 1999 and decreased at these sites between 1999 and 2005. The decreases in crown cover hits at shrub-dominated sites were not significant during either interval of increased shrub cover 1994–1999 or decreased shrub cover 1999–2005. This suggests that existing shrubs generally increased in size through 1994, then decreased in size through 2005 because of drought-induced die-back of limbs (also observed in the field in 2005). The possibility of stand replacement by younger, smaller shrubs was judged less likely in view of the drought conditions existing after 1999.

[46] The recent appearance of invasive grass *E. lehmanniana* between 1967 and 1994 and its spread on the landscape was documented in transect data. Its occurrence and abundance across the watershed is likely underestimated by these data, however, because of the restricted landscape positions where transects were originally located. At present, *E. lehmanniana* is widespread in disturbed areas, such as road right of ways, where no transects are located.

Table 6. Absolute Percent Cover of Dominant Shrubs, Native Grasses and *E. lehmanniana* at Six Sites in 1967, 1994, 1999 and 2005[a]

	Luckyhills-McNeal						McAllister-Stronghold						Elgin-Stronghold and Stronghold-Bernardino					
	RG 28			RG 83			RG 87			RG 39			RG 91			RG 82		
	S	G	E	S	G	E	S	G	E	S	G	E	S	G	E	S	G	E
1967	16						0			0			0			0		
1994	23	1	–	23	0	–	0	8	–	0	3	–	0	11	–	0	8	–
1999	25	1	0	39	0	–	0	5	–	0	4	0	0	20	0	0	9	0
2005	14	1	–	26	0	–	0	9	–	0	3	0	0	9	8	0	11	0

[a] See Table 5 for list of shrubs. Key: RG, rain gauge; S, shrub-dominated site; G, grass-dominated site; and E, *E. lehmanniana*. For "E," the entry 0 indicates that *E. lehmanniana* was measured but the cover was less than 1%; the entry "–" indicates that *E. lehmanniana* was not encountered on the transects.

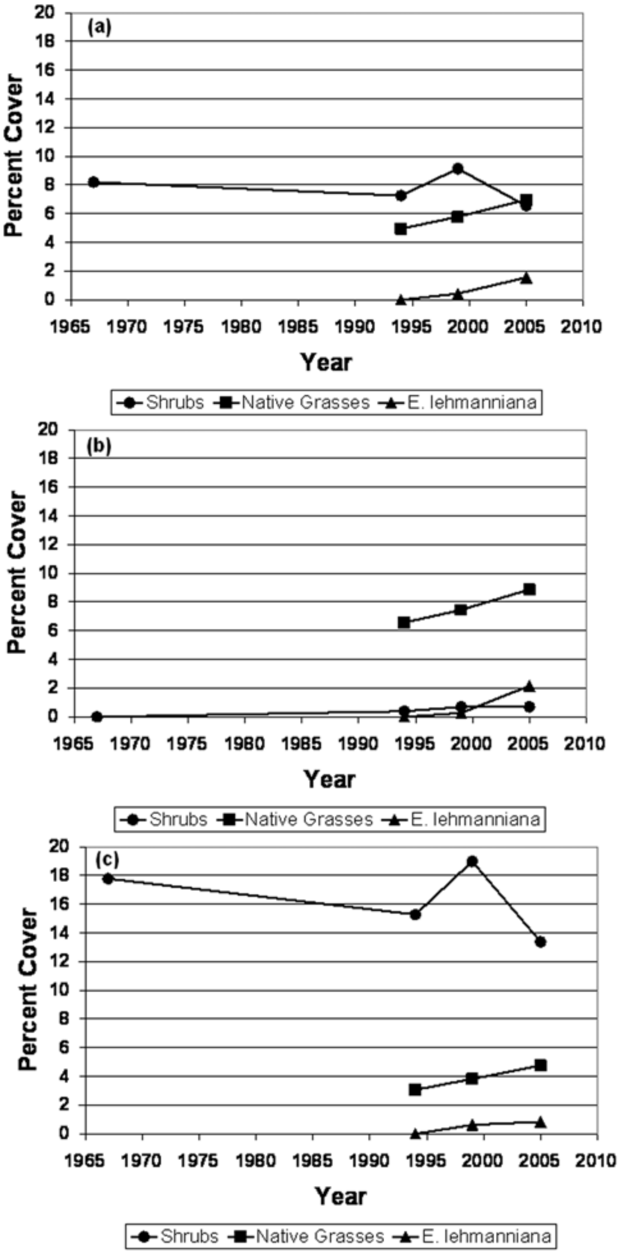

Figure 5. (a) Absolute percent cover of dominant shrubs, native grasses, and nonnative grass *E. lehmanniana* in 1967, 1994, 1999, and 2005 for 13 sites in WGEW. (b) Same as Figure 5a but for seven grass-dominated sites only. (c) Same as for Figure 5a but for six shrub-dominated sites only.

Table 7. Dynamics of Dominant Shrub Species at Six Shrub Sites, 1994–2005

Year	Mean Number of All Individuals	Mean Number of Individual Shrubs	Mean Total Shrub Intercept, m	Mean Intercept Per Individual Shrub, m
1994	115	27	9.3	0.35
1999	89	25	11.6	0.49
2005	107	30	8.2[a]	0.28[a]

[a] Values changed significantly from the preceding year. Null hypothesis (no difference from preceding year) was rejected at $\alpha = 0.05$ level.

5.1. Influence of Soils

[47] The distinctions between soil properties of shrub- versus grass-dominated areas may be a function of the geomorphological history of the WGEW. Soils of much of WGEW developed on alluvial fan remnants since the middle Pleistocene period; as in much of southern Arizona, the deepest, most developed soil profiles correspond to the oldest geomorphic surfaces of mid to late Pleistocene age [*Menges and Pearthree*, 1989]. Such soils, especially those formed on noncalcareous parent material, develop a clay-enriched argillic horizon underlain by a calcic horizon marking the depth to which percolation occurs over long periods of time. These soils are typically described as "clay loam" or "loamy upland" ecological sites [*McAuliffe*, 1995] and correspond to less dissected parts of the McAllister-Stronghold, Elgin-Stronghold and Stronghold-Bernardino complex soils (Figure 1). The high clay content at depth contributes to low hydraulic conductivity with high field capacity; the brief, episodic pulses of precipitation characteristic of this area may rarely allow significant infiltration into these soils. Plants that thrive in these areas tend to be shallow rooted to take advantage of shallow infiltration, such as perennial grasses and drought-tolerant xerophytic shrubs and cacti. These assemblages are typical of most WGEW grass-dominated sites, including study sites 39, 82, 87, and 91 (Table 3).

[48] Where more erosion has dissected the older geomorphic surface (the Upper Whetstone Pediment of Figure 7) the underlying calcic horizon may be in places near the surface, but overall the soil retains a deep argillic Bt horizon corresponding to loamy upland–limy slope ecological sites [*McAuliffe*, 1995] and the more dissected parts of the McAllister-Stronghold, Elgin-Stronghold, and Stronghold-Bernardino complex soils. Grass-dominated sites are still widespread in these areas of the central watershed, but are intermingled with shrub sites in what appears to be a complex transitional zone [*Skirvin et al.*, 2008].

[49] In locations where erosion has removed much of the Pleistocene soil profile, calcic horizons have been exposed at the surface to form parent material for younger soils. Ecological sites in these areas may be described as "limy slopes" or "limy upland," including the Luckyhills-McNeal complex soils that occur in the Dissected Whet-

Table 8. Ground Cover Point Data for All 14 Sites and Averaged Over the 7 Grass-Dominated Sites and 7 Shrub-Dominated Sites[a]

	Crown Cover, Percent Hits			Litter Cover, Percent Hits			Bare Soil, Percent Hits			Rock, Percent Hits		
Year	T	G	S	T	G	S	T	G	S	T	G	S
1994	15	20	10	22	21	22	23	16	31	38	42	33
1999	10	13[b]	6	35	34	35	25	20	30	31	34	28
2005	9	12	5	13	10	16	34	30	38	45	49	41

[a] Key: T, all hits; G, grass-dominated sites; and S, shrub-dominated sites.
[b] Value changed significantly from the preceding year. Null hypothesis (no difference from preceding year) was rejected at $\alpha = 0.05$ level.

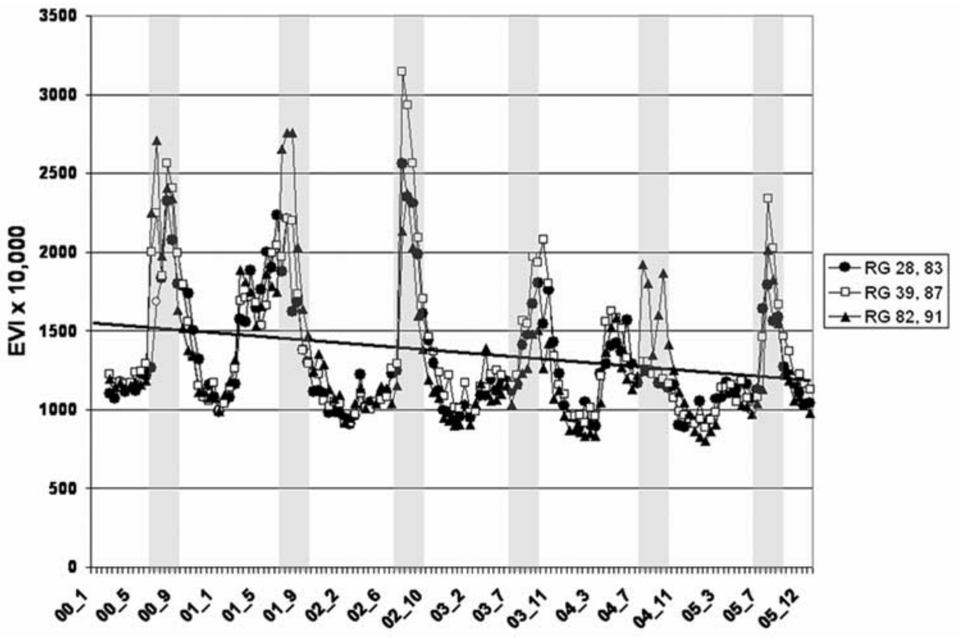

Figure 6. MODIS EVI time series data 2000–2005, averaged at pairs of sites shown above (also listed in Tables 3 and 6). The ticks on the *x* axis represent year and month; the shaded bars designate the time period July to September for each year; and the solid line represents overall series trend over time. Peaks represent maximum vegetation "greenness" for both shrub-dominated (RG 28, 83) and grass-dominated (RG 39, 87 and 82, 91) sites during the summer growing season July–September.

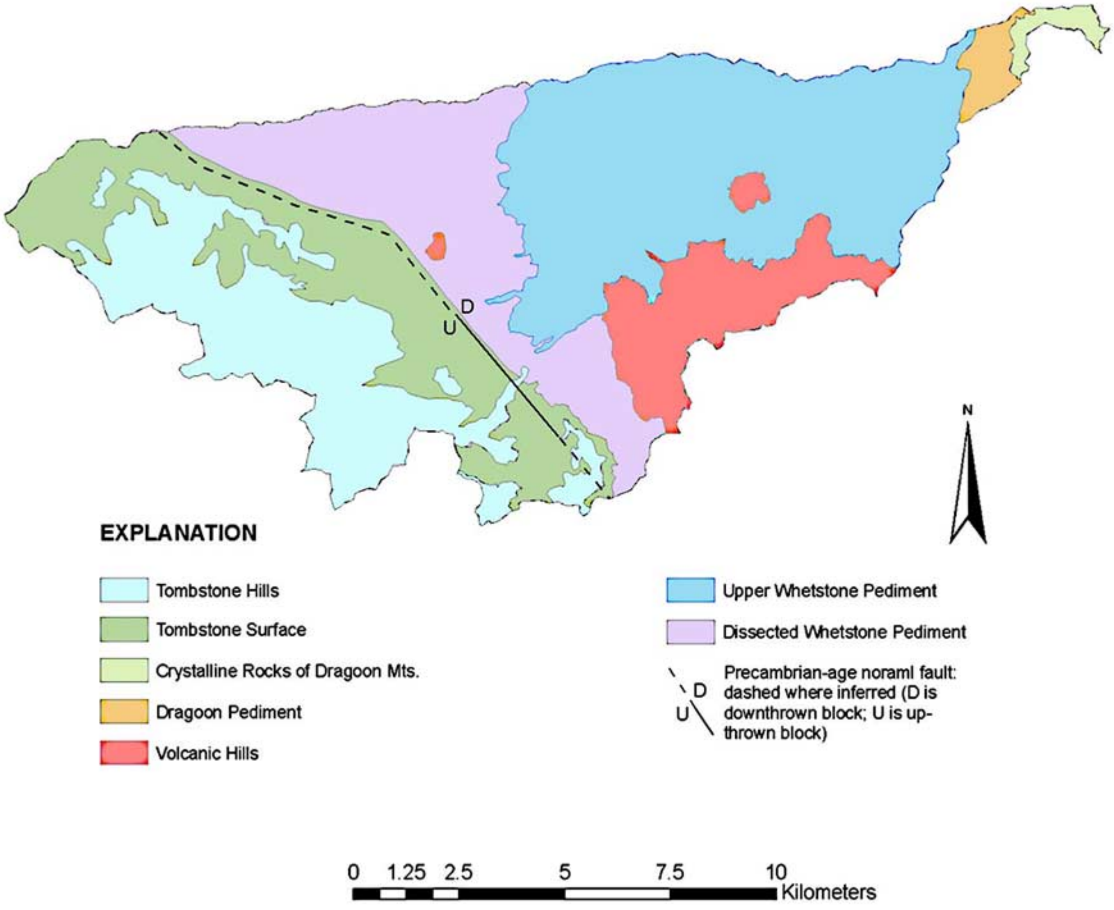

Figure 7. Map showing major geomorphic features of the Walnut Gulch Experimental Watershed including bedrock areas, erosional surface, and pediment.

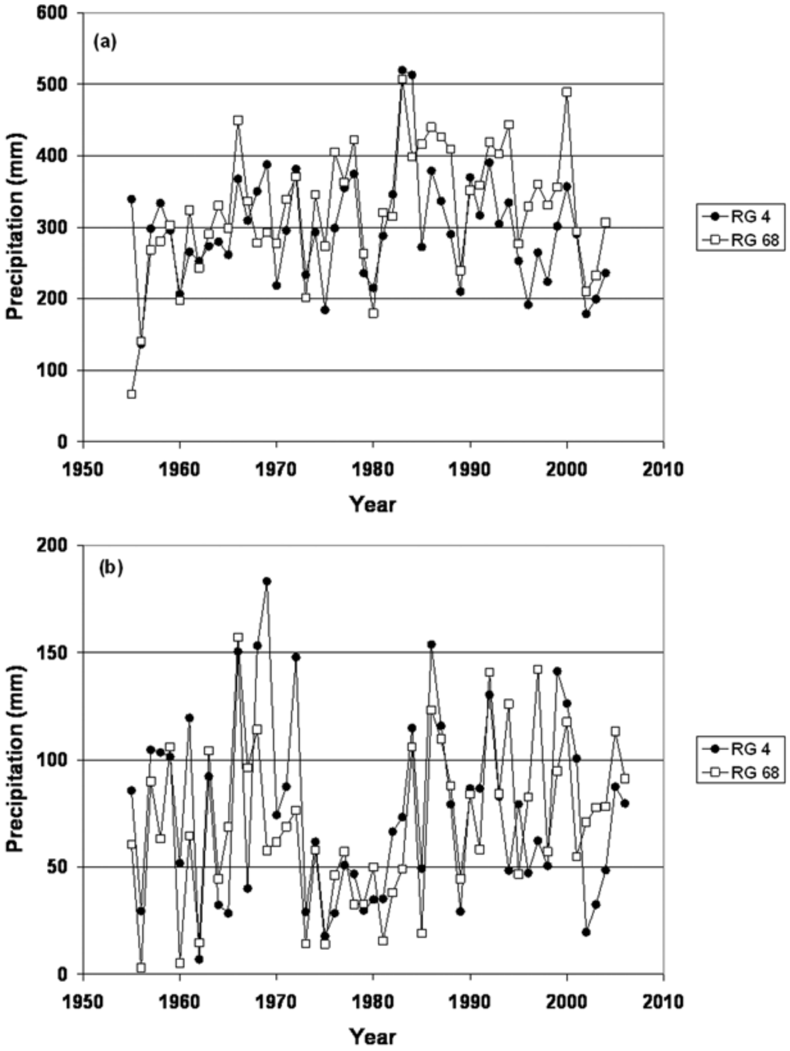

Figure 8. (a) Total annual precipitation measured by rain gauge 4 (RG 4) at the west end of WGEW and rain gauge 68 (RG 68) at the east end of WGEW. (b) Total precipitation at rain gauges 4 and 68 for the month of August only.

stone Pediment area of Figure 7. Shrub-dominated sites, such as study sites 28 and 83, occurred throughout the Dissected Whetstone Pediment area and on shallow soils of the Tombstone Surface, overlying limestone and other bedrock, in the lower elevations of the watershed. Holocene-age gravelly alluvium, found in channels and terrace deposits (“sandy loam upland” or “sandy bottom” ecological sites), tends to be coarse and permeable, with little soil profile development. Brief precipitation episodes may infiltrate to deeper levels in these soils, but with low field capacity, soil water cannot be retained for long periods. Deeper-rooted woody vegetation tends to dominate such areas, with tap roots that can exploit residual moisture at deeper levels in the soils (see discussion by *Fravolini et al.* [2003]). Transect site 40 (Figure 1), dominated by *P. velutina*, provided a striking example of woody vegetation on Holocene soils, which were generally under sampled by transect locations.

5.2. Influence of Climate

[50] Climate records showed that both precipitation and temperature have changed over time at WGEW. Annual precipitation totals increased through the mid-1990s, due largely to an increase in the number of small winter precipitation events [*Nichols et al.*, 2002]. WGEW rain gauge data since the late 1990s showed substantial declines in cool season, warm season, and annual precipitation totals (Table 4), reflecting the severe drought experienced in southeastern Arizona. Temperature records for the Tombstone climate station showed record high temperatures that accompanied the drought (Table 4). The shift in seasonal distribution to more winter and less summer precipitation was expected to favor C_3 shrubs [*Nichols et al.*, 2002; *Brown et al.*, 1997; *Neilson*, 1986]; however, recent severe drought [*McPhee et al.*, 2004] has left all vegetation types vulnerable.

[51] The recent declines in annual precipitation have been unevenly distributed in space at WGEW. Since 1990, rain gauges on the eastern (higher-elevation) side of the watershed have received on average 20% more precipitation than those on the western (lower-elevation) side (Figure 8a). Prior to 1990, there was little difference (5%) in multiyear mean annual precipitation. Most notably, in spite of decreased net warm season precipitation, precipitation during

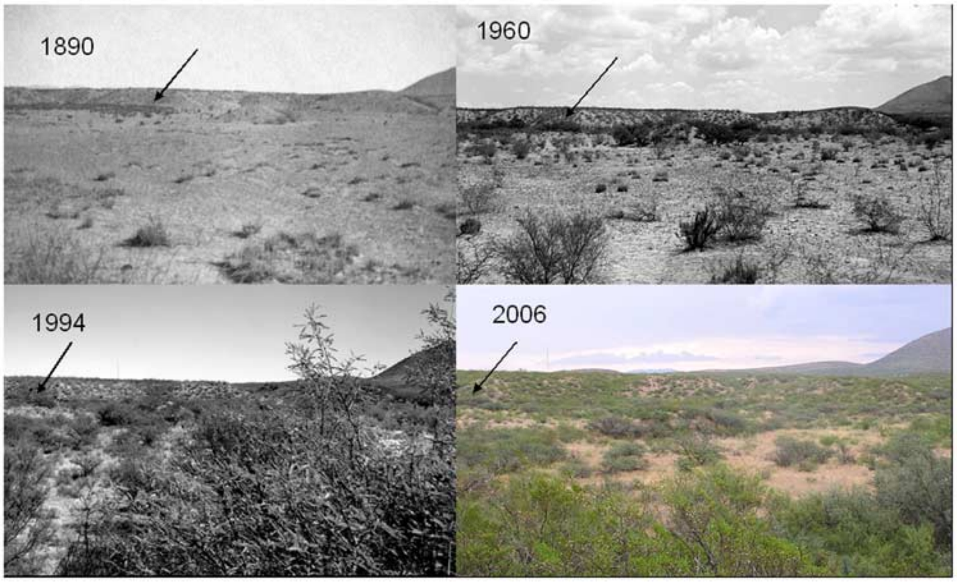

Figure 9. Historic repeat photography of WGEW (stake 49b in Table 2 and Figure 1b): (top left) circa 1890, (top right) 1960, (bottom left) 1994, and (bottom right) 2006. Arrow points to approximately the same location on inset terrace in each photograph. Significant shrub cover is visible in the 1890 photograph on the inset terrace and on the upland slopes and higher surface behind the terrace.

the month of August has increased to greater than mid-1990s levels on both ends of the watershed (Figure 8b).

[52] Transect data collected in 2005 were expected to show the effects of multiyear drought on both shrub- and grass-dominated vegetation types. Cover of the dominant shrub species decreased at shrub sites, however, grass cover remained unchanged at both types of sites (Table 8). August precipitation, which has remained at predrought levels across the watershed, may be responsible for the maintenance of approximately constant grass cover levels over time. Studies have found August precipitation in this region to be better correlated with grass production than any other single month, and better correlated than total growing season precipitation [*Khumalo and Holechek*, 2005; *Cable and Martin*, 1975].

[53] Drought effects on shrub- and grass-dominated vegetation types were apparent in remote sensing–based EVI data. The trend toward lower EVI at shrub-dominated sites was consistent with observed decreased shrub cover for this period. However, the similar decline in EVI at grass-dominated sites during this period remains difficult to reconcile with ground-based measurements that showed no significant change. This difference may have been due to the presence of senescent grass cover which would have resulted in a decrease in EVI but not in ground measured canopy cover. Taken as a whole, the data suggested that drought has impacted both vegetation types. However, grass-dominated areas may have experienced less drought stress because of anomalously high August precipitation during the drought period.

5.3. Long-Term Context for Recent Vegetation Change at WGEW

[54] The data presented here show no evidence of widespread shifts from grass-dominated to shrub-dominated

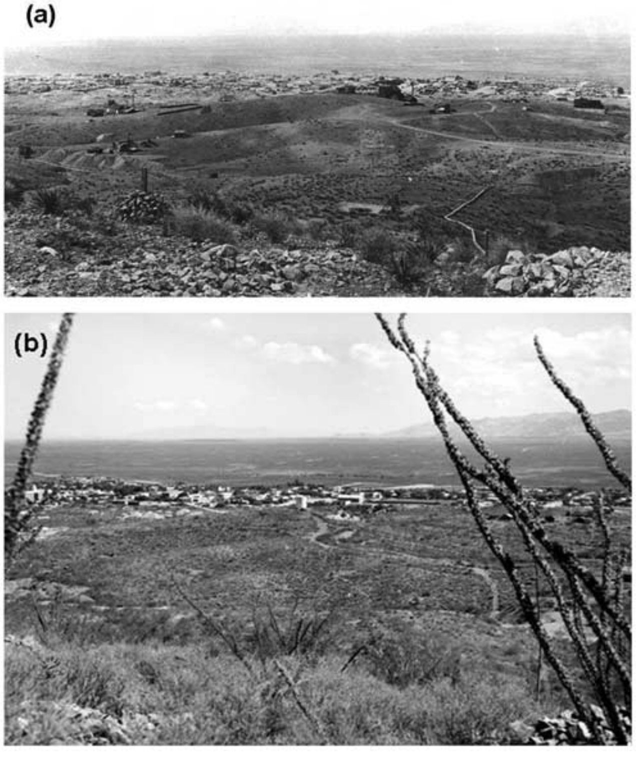

Figure 10. Historic repeat photography of WGEW (stake 52 in Table 2 and Figure 1b). (a) View looking north toward the Dragoon Mountains taken circa 1890. Shrub cover is visible on the hill in the foreground, grading to grass cover on the low hills in the middle distance. (b) Grass cover has been replaced by shrubs. Town of Tombstone is in background.

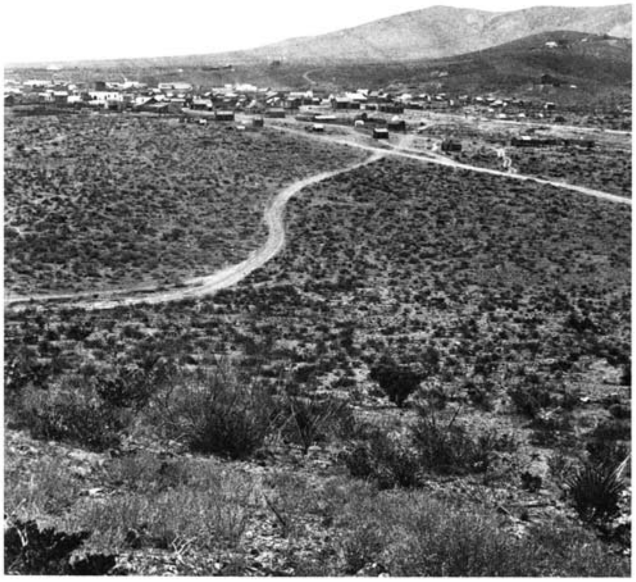

Figure 11. Historic photography of WGEW (photo 14837 in Table 2 and Figure 1b) circa 1880. View is of Tombstone looking east toward the Contention Mine. Shrub cover appears well established between foreground and town of Tombstone in background.

conditions at WGEW since 1967. In fact, vegetation has changed very little overall in total cover and composition at the majority of observed locations. Most of these locations were adjacent to rain gauges on ridge tops or open slopes, corresponding to old alluvial fan surfaces or erosional sideslopes. Younger surfaces such as channels and terraces, where woody vegetation would be expected to establish most readily, were sampled at only two locations (sites 32, 40), where transect photographs showed that significant numbers of woody shrubs and subshrubs were already present in 1967.

[55] Most of the limited historical photography of the Walnut Gulch area available for the period prior to 1967 shows less abundant shrubs than in subsequent transect photography [e.g., *Turner et al.*, 2003, plates 52a and 54a–54c]. Numerous authors attribute the increase of shrubs and concomitant increase in erosion over the last 130 years to the introduction of large numbers of domestic livestock to this area in the 1890s, followed by a number of long droughts. However, in photography dating from the 1890s, shrubs appeared already established on upland surfaces, with later repeat photography documenting the infill of woody species within broad channel floodplains (Figure 9).

[56] Photographs of the Tombstone area taken in the 1890s showed grass-dominated areas that appear shrub dominated in later photography (Figure 10) [*Turner et al.*, 2003, plate 52a]. However, an earlier photograph taken in approximately 1880 showed areas that appeared shrub dominated in the earliest years of settlement and mining at Tombstone (Figure 11). Substantial spatial variability in vegetation distribution was apparently already present by the beginning of large-scale human impacts on the landscape in the 19th century.

6. Concluding Remarks

[57] These are the first published results of the 40-year record of vegetation measurements at WGEW. Combined with historic photographs, recent satellite imagery and the rich database of soils and climate at WGEW, these results offer a unique insight into vegetation dynamics over the past century near the boundary between the Sonoran and Chihuahuan deserts. More detailed information can be extracted from these data with respect to changes in species abundance and the spatial patterns of species distributions over the past four decades in southeastern Arizona, similar to the results of *Johnson et al.* [2000] elsewhere in the Chihuahuan desert region. Management and research priorities will have to be assessed in order to plan future transect surveys, with the level of detail in plant identification to be balanced against the desirability of broad spatial coverage to capture landscape heterogeneity.

[58] **Acknowledgments.** The authors wish to express sincere thanks to Mary Nichols, Bill Emmerich, Ross Bryant, Christina Contreras, Ryan Manon, Charlie Escapule, John Sottilare, Kevin Loeffelmann, and the personnel at the USDA-ARS Southwest Watershed Research Center, Tucson, and the USDA-ARS Tombstone facility for their cooperation and assistance; to Grant Casady (University of Arizona Office of Arid Lands Studies) for extracting the MODIS EVI data for the WGEW sites; to Mitch McClaran (University of Arizona) for his assistance during the analysis of these data; and to Steve Archer (University of Arizona) for his contribution to the ordination analysis.

References

Abbott, L. B., and B. A. Roundy (2003), Available water influences field germination and recruitment of seeded grasses, *J. Range Manage.*, *56*, 56–64.

Beever, E. A., D. A. Pyke, J. C. Chambers, F. Landau, and S. D. Smith (2005), Monitoring temporal change in riparian vegetation of Great Basin National Park, *West. N. Am. Nat.*, *65*(3), 382–402.

Biedenbender, S. H., M. P. McClaran, J. Quade, and M. A. Weltz (2004), Landscape patterns for vegetation change indicated by soil carbon isotope composition, *Geoderma*, *119*, 69–83.

Bonham, C. D. (1989), *Measurements for Terrestrial Vegetation*, 338 pp., John Wiley, New York.

Breshears, D. D., et al. (2005), Regional vegetation die-off in response to global-change-type drought, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 15,144–15,148.

Brown, J. H., T. J. Valone, and C. G. Curtin (1997), Reorganization of an arid ecosystem in response to recent climate change, *Proc. Natl. Acad. Sci. U. S. A.*, *94*, 9729–9733.

Cable, D. R., and S. C. Martin (1975), Vegetation responses to grazing, rainfall, site condition and mesquite control on semi-desert range, *Res. Pap. RM-KG*, For. Serv., U.S. Dep. of Agric., Washington, D. C.

Fravolini, A., K. R. Hultine, D. F. Koepke, and D. G. Williams (2003), Role of soil texture on mesquite water relations and response to summer precipitation, in *Santa Rita Experimental Range: 100 Years (1903–2003) of Accomplishments and Contributions*, *Conference Proceedings*, *Proc. RMRS-P-30*, edited by M. P. McClaran, P. F. Folliott, and C. B. Edminster, pp. 125–129, For. Serv., U.S. Dep. of Agric., Washington, D.C.

Gauch, H. G., Jr. (1982), *Multivariate Analysis in Community Ecology*, 298 pp., Cambridge Univ. Press, Cambridge, U. K.

Gibbens, R. P., and R. F. Beck (1988), Changes in grass basal area and forb densities over a 64-year period on grassland types of the Jornada Experimental Range, *J. Range Manage.*, *41*, 186–192.

Gibbens, R. P., R. P. McNeely, K. M. Havstad, R. F. Beck, and B. Nolen (2005), Vegetation changes in the Jornada Basin from 1858 to 1998, *J. Arid Environ.*, *61*, 651–668.

Goodrich, D. C., T. O. Keefer, C. L. Unkrich, M. H. Nichols, H. B. Osborn, J. J. Stone, and J. R. Smith (2008), Long-term precipitation database, WGEW, Arizona, USA, *Water Resour. Res.*, doi:10.1029/2006WR005782, in press.

Goslee, S. C., K. M. Havstad, D. P. C. Peters, A. Rango, and W. H. Schlesinger (2003), High-resolution images reveal rate and pattern of shrub encroachment over six decades in New Mexico, U.S.A., *J. Arid Environ.*, *54*, 755–767.

Hastings, J. R., and R. M. Turner (1965), *The Changing Mile*, 317 pp., Univ. of Ariz. Press, Tucson, Ariz.

Houghton, R. A., J. L. Hackler, and K. T. Lawrence (1999), The U.S. carbon budget: contributions from land-use change, *Science*, *285*, 574–578.

Huete, A., K. Didan, T. Miura, E. P. Rodriguez, X. Gao, and L. G. Ferreira (2002), Overview of the radiometric and biophysical performance of the MODIS vegetation indices, *Remote Sens. Environ.*, *83*(1–2), 195–213.

Huxman, T. E., B. P. Wilcox, D. D. Breshears, R. L. Scott, K. A. Snyder, E. E. Small, K. Hultine, W. T. Pockman, and R. B. Jackson (2005), Ecohydrological implications of woody plant encroachment, *Ecology*, *86*, 308–319.

Johnson, A. R., S. J. Turner, W. G. Whitford, A. G. de Soyza, and J. W. Van Zee (2000), Multivariate characterization of perennial vegetation in the northern Chihuahuan desert, *J. Arid Environ.*, *44*, 305–325.

Justice, C. O., J. R. G. Townshend, E. F. Vermote, E. Masuoka, R. E. Wolfe, N. Saleous, D. P. Roy, and J. T. Morisette (2002), An overview of MODIS land data processing and product status, *Remote Sens. Environ.*, *83*, 3–15.

Khumalo, G., and J. Holechek (2005), Relationships between Chihuahuan desert perennial grass production and precipitation, *Rangeland Ecol. Manage.*, *58*(3), 239–246.

Martin, S. C. (1983), Responses of semidesert grasses and shrubs to fall burning, *J. Range Manage.*, *36*, 604–610.

McAuliffe, J. R. (1995), Landscape evolution, soil formation, and Arizona's desert grassland, in *The Desert Grassland*, edited by M. P. McClaran and T. R. Van Devender, pp. 100–129, Univ. of Ariz. Press, Tucson, Ariz.

McClaran, M. P. (1995), *Desert grasslands and grasses*, edited by M. P. McClaran and T. R. Van Devender, pp. 1–30, Univ. of Ariz. Press, Tucson, Ariz.

McClaran, M. P. (2003), A Century of vegetation change on the Santa Rita Experimental Range, in *Santa Rita Experimental Range: 100 Years (1903–2003) of Accomplishments and Contributions*, *Conference Proceedings*, *Proc. RMRS-P-30*, edited by M. P. McClaran, P. F. Folliott, and C. B. Edminster, pp. xx–xx, For. Serv., U. S. Dep. of Agric., Washington, D. C.

McCune, B., and J. B. Grace (2002), *Analysis of Ecological Communities*, 300 pp., MJM Software Design, Gleneden Beach, Oreg.

McCune, B., and M. J. Mefford (1999), PC-ORD multivariate analysis of ecological data, version 4.41, MJM Software, Gleneden Beach, Oreg.

McPhee, J., A. Comrie, and G. Garfin (2004), Drought and climate in Arizona: Top ten questions and answers, 24 pp., Clim. Assess. Proj. for the Southwest, Univ. of Ariz., Tucson, Ariz.

Menges, C. M., and P. A. Pearthree (1989), Late Cenozoic tectonism in Arizona and its impact on regional landscape evolution, in *Geologic Evolution of Arizona*, *Ariz. Geol. Soc. Dig.*, vol. 17, edited by J. P. Jenney and S. J. Reynolds, pp. 649–680, Ariz. Geol. Soc., Tucson, Ariz.

Minchin, P. R. (1987), An evaluation of relative robustness of techniques for ecological ordinations, *Vegetatio*, *71*, 145–156.

Moir, W. H., J. A. Ludwig, and R. T. Scholes (2000), Soil erosion and vegetation in grasslands of the Peloncillo Mountains, New Mexico, *Soil Sci. Soc. Am. J.*, *64*, 1055–1067.

Natural Resource Conservation Service (2003), Soil survey of Cochise County, Arizona: Douglas-Tombstone part, U.S. Dep. of Agric., Washington, D. C.

Neilson, R. P. (1986), High-resolution climatic analysis and Southwest biogeography, *Science*, *232*, 27–28.

Nichols, M. H., K. G. Renard, and H. B. Osborn (2002), Precipitation changes from 1956 to 1996 on the Walnut Gulch Experimental Watershed, *J. Am. Water Resour. Assoc.*, *38*(1), 161–172.

Peters, D. C., and R. P. Gibbens (2006), Plant communities in the Jornada basin: The dynamic landscape, in *Structure and Function of a Chihuahuan Desert Ecosystem: The Jornada Basin Long-Term Ecological Research Site*, edited by K. M. Havstad, L. Huenneke, and W. H. Schlesinger, pp. 211–231, Oxford Univ. Press, New York.

Peters, D. P. C., R. A. Pielke Sr., B. T. Bestelmeyer, C. D. Allen, S. Munson-McGee, and K. M. Havstad (2004), Cross-scale interactions, nonlinearities and forecasting catastrophic events, *Proc. Natl. Acad. Sci. U. S. A.*, *101*, 15,130–15,135.

Rango, A., L. Huenneke, M. Buonopane, J. E. Herrick, and K. M. Havstad (2005), Using historic data to assess effectiveness of shrub removal in southern New Mexico, *J. Arid Environ.*, *62*, 75–91.

Renard, K. G., M. H. Nichols, D. A. Woolhiser, and H. B. Osborn (2008), A brief background on the USDA Agricultural Research Service Walnut Gulch Experimental Watershed, *Water Resour. Res.*, doi:10.1029/2006WR005691, in press.

Rideout, S., B. P. Oswald, and M. H. Legg (2003), Ecological, political and social challenges of prescribed fire restoration in east Texas pineywoods ecosystems: A case study, *Forestry*, *76*(2), 261–269.

Schlesinger, W. H., J. F. Reynolds, G. L. Cunningham, L. F. Huenneke, W. M. Jarrell, R. A. Virginia, and W. G. Whitford (1990), Biological feedbacks in global desertification, *Science*, *247*, 1043–1048.

Skirvin, S., M. Kidwell, S. Biedenbender, D. King, S. Moran, and C. Holifield Collins (2008), Vegetation data, Walnut Gulch Experimental Watershed, Arizona, USA, *Water Resour. Res.*, doi:10.1029/2006WR005724, in press.

Stein, R. A., and J. A. Ludwig (1979), Vegetation and soil patterns on a Chihuahuan desert bajada, *Am. Midland Nat.*, *101*(1), 28–37.

Turner, R. M., R. H. Webb, J. E. Bowers and J. R. Hastings (2003), *The Changing Mile Revisited: An Ecological Study of Vegetation Change With Time in the Lower Mile of an Arid and Semiarid Region*, 334 pp., Univ. of Ariz. Press, Tucson, Ariz.

Van Auken, O. W. (2000), Shrub invasion of North American semiarid grasslands, *Annu. Rev. Ecol. Syst.*, *31*, 197–215.

Van Devender, T. R. (1995), Desert grassland history, in *The Desert Grassland*, edited by M. P. McClaran and T. R. Van Devender, pp. 68–99, Univ. of Ariz. Press, Tucson, Ariz.

Walton, M., J. E. Herrick, R. P. Gibbens, and M. D. Remmenga (2001), Persistence of municipal biosolids in a Chihuahuan desert rangeland 18 years after application, *Arid Land Res. Manage.*, *15*, 223–232.

S. H. Biedenbender, Coronado National Forest, Sierra Vista Ranger District, Forest Service, U.S. Department of Agriculture, 5590 S. Highway 92, Hereford, AZ 85746, USA.

A. Diaz-Gutierrez, Área de Producción Ecológica y Recursos Naturales, IFAPA, Centro IFAPA Alameda del Obispo, Av. Menéndez Pidal s/n, E-14080, Córdoba, Spain.

C. D. Holifield Collins, M. R. Kidwell, and M. S. Moran, Southwest Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, 2000 E. Allen Road, Tucson, AZ 85719, USA. (chandra.holifield@ars.usda.gov)

D. M. King, School of Natural Resources, University of Arizona, 325 Biological Sciences East, Tucson, AZ 85721, USA.

S. M. Skirvin, Department of Geography and Regional Development and Department of Mining and Geological Engineering, University of Arizona, 1103 E 2nd Street, Tucson, AZ 85721, USA.

M. A. Weltz, Exotic and Invasive Weeds Research Unit, Agricultural Research Service, U.S. Department of Agriculture, 920 Valley Road, Reno, NV 89512, USA.