Holocene environmental change and vegetation contraction in the Sonoran Desert

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Abstract

Two types of microtopographic features (plant scar mounds and plant scar depressions) on surfaces of barren desert pavements provide a unique record of the former presence of large perennial plants. Evidence of bioturbation by burrowing animals extends more than 1 m beneath each type of plant scar, indicating that both features originated as large bioturbation mounds. Formation of bioturbation mounds in desertsilv environments is generally restricted to areas beneath widely separated, large perennial plants. The contrasting forms of plant scars (mounds vs. depressions) represent time-dependent changes following disappearance of the large plants and eventual cessation of bioturbation. Plant scar mounds represent a geologically recent episode of plant mortality, whereas plant scar depressions represent the disappearance of plants at a considerably earlier time, possibly at the Pleistocene–Holocene transition. Contrasting spatial distributions of the two kinds of plant scars indicate that vegetation on alluvial fans has progressively contracted from a more diffuse, former vegetation cover, yielding the wide, barren pavement surfaces present today. In less arid portions of the Sonoran Desert, spatial distribution of recent plant mortality due to persistent, severe drought provides an analog of the progressive loss of plants from different parts of the landscape in the past.

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Introduction

Vegetation in extreme deserts is typically confined to a small fraction of the landscape that collects precipitation runoff from surrounding, completely barren areas (termed "contracted vegetation," Monod, 1954; Walter, 1973; McAuliffe, 1999; Fig. 1). Arid regions with contracted vegetation have experienced considerable variation in climate during the late Quaternary (Van Devender, 1990; Alsharhan et al., 1999) and probably supported denser and more diffuse vegetation during less arid climatic intervals. Fossil pollen records, plant macrofossil deposits, and stable isotope signatures in soils and fossil materials have been widely used to investigate late Quaternary vegetation changes in arid regions (Hall, 1985; Betancourt et al., 1990; Connin et al., 1998; Monger et al., 1998). However, no kind of paleoecological record has yet been identified that provides information about past spatial distributions of plants in arid environments where perennial vegetation is now largely absent.

In this paper, we investigate two kinds of distinct microtopographic features that commonly occur on broad, planar surfaces of barren desert pavements in some of the most arid parts of the Sonoran Desert. We designate these features as plant scar mounds and plant scar depressions. Evidence is presented in this paper that both features originated beneath widely spaced, long-lived perennial plants that have long since disappeared. We also present information on contrasting spatial distributions of the two kinds of plant scars and implications of these differences to interpretations regarding timing and causes of ecological change during the late Quaternary.

Study area and methods

Morphology, origin, and distribution of plant scar mounds and plant scar depressions on Quaternary alluvial fan deposits
Figure 1. Contracted vegetation on late Pleistocene alluvial fan deposits. Vegetation is limited to fluv es that have incised the dark, varnished pavement. Foothills paloverde trees (Cercidium microphyllum) are the largest plant canopies in the fluve in the foreground; the smallest shrubs are white bursage (Ambrosia dumosa), and the shrubs of intermediate size are creosotebush (Larrea tridentata). Prominent, light-colored plant scar mounds as well as fainter, slightly varnished plant scar depressions occur throughout the pavement surface. Width of the strip of pavement between the two sub-parallel fluv es in the center of the photograph is approximately 20 m. Surface elevation is approximately 150 m. Photo taken approximately 65 km east of Yuma, Arizona and 10 km north of the Gila River with a view to the southeast.

Road cuts across a terrace-like sequence of three Pleistocene fan surfaces (lower, middle, and upper terraces; Fig. 3) before it reaches the margin of Gould Wash. Investigations were concentrated on the middle terrace.

Elevational cross-sections through two representative plant scar mounds and one plant scar depression on the middle terrace were made by measuring the vertical deviation (to the nearest cm) at 20-cm horizontal intervals between a level line stretched above the center of each microtopographic feature and the soil surface. Two sets of these measurements were taken for each plant scar: one along the run of the slope and the other perpendicular to the slope. Each transect extended 1 m or more beyond the plant scar perimeter onto the flat surface of the surrounding desert pavement.

Size distributions of surface clasts were compiled from measurements (to nearest mm) of maximum diameters of clasts located directly beneath intersections of a wire grid (8 cm x 8 cm mesh size) with 32 grid intersections. The grid was placed on the surface at 5 locations within interiors of plant scars (one at center and four midway between the center and perimeter), yielding a total of 160 measurements. The grid was also positioned at four locations on the peripheral margin of each plant scar, and at four locations positioned 2 m beyond this margin on the surrounding pavement surface (128 measurements each). Total number of surface clasts composed of indurated pedogenic carbonate that fell below the grid intersections was recorded. For non-calcareous clasts falling beneath a portion of grid intersections (60 per plant scar interior, 40 per peripheral margin, 40 per surrounding

were studied on the US Army Yuma Proving Ground (YPG) northeast of Yuma, Arizona (Fig. 2). Mean annual precipitation measured at YPG headquarters is 92 mm (32.83 °N, 114.40 °W; elev. 98 m; period of record 1958–2002). Aerial reconnaissance by helicopter within an area 85 km to the north and 65 km east of Yuma, Arizona was conducted in April 1999 to assess the general distribution of plant scar features. Fieldwork on the ground (via helicopter in remote locations) and ground vehicle was conducted from 1999 to 2001. High-resolution aerial photographs (1:24,000 scale) were used to assess the general geographic occurrence of plant scar features within the YPG. USGS 1:24,000 orthophotoquads and on-line aerial imagery (http://terraserver.microsoft.com; 1:250,000 to 1:3000 scales) were used to inspect areas surrounding the YPG in southwestern Arizona.

Detailed fieldwork was conducted on Pleistocene alluvial fan deposits located immediately north of Gould Wash, 83 km N of Yuma, Arizona (Gould Wash study area, 33.4 °N, 114.5 °W; elev. 183–207 m; Fig. 2). Rhyolite is the principal lithology of the coarse gravelly to cobbly alluvium. Cibola

Figure 2. Geographical limit of the Sonoran Desert within Arizona. Open, numbered triangles indicate locations of the Gould Wash (1) and Organ Pipe Cactus National Monument (2) study sites. The 200- and 400-m contour intervals are shown for the area within the Sonoran Desert.
were confined to the portion of the middle terrace bounded by the broken line and the left and lower edges of the view. The western margin of view is dark pavement background. Width of the scene is 1.97 km.

Spatial analyses were confined to the portion of the middle terrace bounded by the broken line and the left and lower edges of the view. The western margin of view is 114.5259°W; the southern margin is 33.4206°N. The small rectangle is the area enlarged in B. (B) Enlarged view of part of middle terrace. White arrows indicate a pair of plant scar mounds; black arrows indicate two plant scar depressions.

Figure 3. (A) Aerial photograph of Pleistocene fan deposits north of Gould Wash showing the abundance of light-colored plant scar mounds against the dark pavement background. Width of the scene is 1.97 km. Spatial analyses were confined to the portion of the middle terrace bounded by the broken line and the left and lower edges of the view. The western margin of view is 114.5259°W; the southern margin is 33.4206°N. The small rectangle is the area enlarged in B. (B) Enlarged view of part of middle terrace. White arrows indicate a pair of plant scar mounds; black arrows indicate two plant scar depressions.

Soil profile characteristics on the middle terrace were studied along 7 trenches excavated through plant scars and extended into areas of intact pavement beyond peripheral margins of plant scars (average trench size ~1.5 m deep and 5-7 m long). Trench walls were examined for open and filled animal burrows, and soil morphology was described below the center of each mound or depression, below the outer scar margin, and below desert pavement surrounding the plant scars. Soils were described according to standard methods and nomenclature of the Soil Survey Staff (1993). Descriptions of degree of calcic horizon development follow the stages I–IV designations of Gile et al. (1966, 1981). Bulk soil samples were collected from each horizon and were analyzed in the DRI Soil Characterization and Quaternary Pedology Laboratory. All laboratory analyses were performed on the fine earth fraction (<2 mm). Laboratory measurements for particle-size determin-
from a well-developed, varnished stone pavement in the central interfluve area to peripheral areas lacking such pavement. One soil profile was described from a 1-m-deep trench located in the center of the pavement area; another profile description was made 1 m outside of the pavement boundary. Following a 52-mm precipitation event of 12–13 February, 2003, vertical depths of soil wetting fronts were measured to the nearest centimeter at 8 locations within the pavement area and 8 locations approximately 1 m beyond the pavement margin.

Results and discussion

Surface morphologies

Plant scar mounds consist of light-colored mounds that stand out prominently against the background of the surrounding, dark varnished pavement (Figs. 1, 3A, 4A). The approximately circular mounds generally range from 2 to 6 m in diameter, with centers elevated up to approximately 25 cm above the surrounding pavement (Figs. 4A, 5). A distinct feature of these mounds is the ubiquitous light surface color due to a lack of dark rock varnish on surface clasts, light-colored coatings of pedogenic carbonate on many non-calcareous clasts, and many clasts composed entirely of indurated pedogenic carbonate. Light-brown, fine-grained soil (surface particles ≤1 mm diameter) is exposed on 10–20% of the surfaces of mounds, whereas fine-grained soil is exposed on only 1.5–3% of surrounding desert pavements (Table 1A). Clasts on surfaces of mounds are well sorted in size and significantly smaller than clasts of the surrounding pavement (Table 1A). Perimeters of mounds typically contain a diffuse ring of clasts that are significantly larger than clasts in the central parts of mounds (Fig. 4A, Table 1A). Plants are generally absent from mounds with the exception of growth of ephemeral plants in years with abundant winter precipitation and occasionally, very small, young creosotebush plants (Larrea tridentata) that are probably at most a few decades old (Fig. 4A).

![Figure 4. (A) Light-colored plant scar mound with large clasts about the periphery. Small plant in center is a young creosotebush. Hat on right for scale. (B) Person is standing at the center of a plant scar depression.](image-url)
Plant scar depressions are very shallow, saucer-like depressions of the same diameter range as plant scar mounds. Centers of depressions are typically a few centimeters lower than the planar surface of the surrounding pavement (Figs. 4B, 5). These depressions have some morphological features in common with mounds. Like mounds, interiors of depressions contain well-sorted clasts of smaller average diameter than those constituting the surrounding desert pavement. Rim-like margins of depressions contain larger clasts than do depression interiors (Fig. 4B, Table 1A). In contrast to mounds, clasts on surfaces of depressions are tightly packed and form a stone pavement. Moreover, very little fine soil is exposed (<5%) and is not significantly different from the exposure of fine soil on surrounding areas of desert pavement (Table 1A). Surface clasts within depressions are lightly to moderately covered with rock varnish. However, these varnish coatings are neither as dark nor as thick as rock varnish on clasts of the surrounding pavement (Table 1A). This gives the depressions a somewhat lighter color against the darker background of surrounding pavement, making them faintly visible in aerial photographs.

Table 1
Surface characteristics and subsurface soil properties of a representative plant scar mound, plant scar depression, and surrounding stone pavements; middle terrace, Gould Wash study area, Yuma Proving Ground

(A) Surface characteristics. Arithmetic means in boldface; standard deviations in parentheses

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Plant scar mound CM-2</th>
<th>Plant scar depression CD-1</th>
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<tbody>
<tr>
<td></td>
<td>Interior</td>
<td>Margin</td>
</tr>
<tr>
<td>Mean clast diameter (mm)</td>
<td>13.0</td>
<td>30.8</td>
</tr>
<tr>
<td></td>
<td>(10.2)</td>
<td>(23.7)</td>
</tr>
<tr>
<td>Rock varnish development*</td>
<td>5.6</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>(1.0)</td>
<td>(1.0)</td>
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<tr>
<td>Pedogenic carbonate clasts (%)</td>
<td>52%</td>
<td>23%</td>
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<tr>
<td>Exposure of fine-grained soil (%)</td>
<td>11.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Elevation (cm)**</td>
<td>+15.0</td>
<td>–</td>
</tr>
<tr>
<td>Mound or depression diameter (m)</td>
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</table>

(B) Subsurface soil properties

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<tr>
<th>Characteristics</th>
<th>Plant scar mounds (Interiors)</th>
<th>Plant scar depressions (Interiors)</th>
<th>Surrounding pavements</th>
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</thead>
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<tr>
<td>Open faunal burrowsb</td>
<td>11</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Filled faunal burrows (krotavina)c</td>
<td>56</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Av horizon thickness (cm)</td>
<td>4</td>
<td>4</td>
<td>13.5</td>
</tr>
<tr>
<td>Av horizon silt +clay content (%)</td>
<td>52</td>
<td>66</td>
<td>80</td>
</tr>
<tr>
<td>Maximum soil reddening (Munsell)d</td>
<td>10YR7/3</td>
<td>10YR6/4</td>
<td>7.5YR5/6</td>
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<tr>
<td>Salinity: Wt EC</td>
<td>8584</td>
<td>9956</td>
<td>27,141</td>
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<tr>
<td>(mg/kg; upper 100 cm)</td>
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<td></td>
<td></td>
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<tr>
<td>CaCO3 content (% wt)</td>
<td>6.8</td>
<td>9.1</td>
<td>12.6</td>
</tr>
<tr>
<td>Calcic horizon stage</td>
<td>1</td>
<td>1−II</td>
<td>II−III</td>
</tr>
</tbody>
</table>

* Munsell color value of rock varnish coatings (carbonate coated surfaces excluded) of upper sides of clasts falling beneath intersections of sampling grid. Larger numbers reflect lighter color values.

b Elevation (positive value) or depression (negative value) with respect to surrounding, planar pavement surfaces.

c Number of burrow features exposed within an area of ca. 5.5 m² of a vertical exposure in trenches excavated through the centers of plant scar mounds, depressions, and surrounding pavement areas.

d Soil color of subsoil horizons with strongest degree of reddening.
Ambrosia dumosa

Distribution of bioturbation by rodents in desertscrub

Plant scar mounds and depressions are principally found on surfaces of older (i.e., Pleistocene) alluvial fans that have well-developed and varnished stone pavements. Although plant scar mounds are also found on more diffusely vegetated Holocene fan surfaces on the YPG, plant scar depressions are absent from these younger deposits and also from erosionally truncated surfaces of older deposits that lack well-formed pavements.

The light-colored plant scar mounds are clearly visible on 1:24,000-scale aerial photographs and black and white orthophotographs. Plant scar mounds occur in the most arid parts of the Sonoran Desert located along the lower Colorado and Gila rivers, within an approximately 150-km radius to the east, northeast, and north of Yuma, Arizona. Most of this area receives less than 100 mm average annual precipitation and lies below 200 m elevation (Fig. 2).

Distribution of bioturbation by rodents in desertscrub environments

Desertscrub vegetation has occupied the lower Colorado River Valley, including the elevation of the Gould Wash study area, during the late Wisconsin and throughout the Holocene (Cole, 1986; Van Devender, 1990). Plant macrofossils from ancient woodrat middens indicate that during the late Wisconsin, vegetation of this region contained creosotebush and other species that today are characteristic of modern-day Mojave desertscrub communities located 100–200 km to the northwest of the Gould Wash study area (Cole, 1986) and approximately 1000 m higher in elevation (personal observations). Widely spaced perennial plant canopies characterize those Mojave desertscrub communities.

Seed-eating kangaroo rats and pocket mice (family Heteromyidae) are the most abundant burrowing rodents in both Sonoran and Mojave desertscrub communities. Two species of burrowing ground squirrels are also common. Although some of these rodents, especially the relatively large-bodied kangaroo rats, forage for seeds extensively in open areas between shrubs (Reichman and Brown, 1983), their excavation of extensive burrow systems and formation of associated bioturbation mounds is concentrated in areas directly beneath large perennial plants. For example, at the Providence Mountains study area, average density of rodent burrow holes found beneath creosotebush canopies (0.68 holes/m²) was approximately 14 times the density of burrow holes in exposed areas lacking perennial canopy cover (0.05 holes/m²). Widely spaced canopies of creosotebush covered only 12% of the soil surface, yet 66% of all rodent burrow holes were located beneath those canopies. Although canopies of smaller perennial plant species (mainly white bursage, Ambrosia dumosa) covered 10% of the soil surface, only 6% of all rodent burrows were located beneath those smaller canopies. Rodent burrows were more likely to occur beneath large creosotebush plants than small ones. For creosotebush plants ≥1 m basal diameter, 10 of 11 (91%) had active rodent burrows beneath their canopies. However, active rodent burrows were found beneath only 12 of 43 (28%) of creosotebush plants less than 1 m basal diameter. Although occasional openings of rodent burrows occurred in exposed areas, elevated bioturbation mounds with multiple burrow openings were located only beneath canopies of large creosotebush plants and occasionally beneath other large shrubs such as Lycium andersonii. Reynolds (1958) observed a similar concentration of burrows of the Merriam kangaroo rat (Dipodomys merriami) beneath widely-spaced canopies of large woody plants at a site in southern Arizona. Within a 3-ha site, 93% of burrows were located beneath large shrubs and 3% were beneath smaller shrubs, but only 4% were located in the open.

Since desertscrub vegetation containing creosotebush probably was present at the Gould Wash study area during the late Wisconsin and throughout the Holocene, large creosotebush plants or other large, long-lived shrubs with similar architecture are the most probable candidates beneath which bioturbation mounds originally formed at the Gould Wash study area. Individual creosotebush plants can live for several thousand years (Vasek, 1980). Very old, large plants attain basal diameters of several meters (Vasek, 1980; McAuliffe, 1999); large individual plants cover roughly circular areas and are typically widely spaced, as are plant scars (Fig. 3). However, since woody remains (roots or stems of original plants) were not encountered in any of the trench excavations through plant scar mounds or depressions, a considerable amount of time must have elapsed since the plants died to allow for complete decay and disappearance of such remains.

Hypothesized origin of plant scars

We propose that plant scar mounds and plant scar depressions represent different temporal stages of change following disappearance of large perennial plants beneath which bioturbation mounds originally formed. Burrowing reduces total soil bulk density (due to open burrows, Table 1B; Whitford and Kay (1999)), and consequently increases soil volume and produces an elevated soil mound beneath large plants (Fig. 6A). Examinations of vertical exposures in trenches consistently revealed evidence of past bioturbation by rodents in the form of open animal burrows and krotovina (filled burrow tunnels) to depths exceeding 1 m below surfaces of plant scar mounds and plant scar depressions. In contrast, trench exposures in adjacent areas of desert pavements lacked any evidence of past bioturbation at any depth (Table 1B).

Death of plants long ago would have yielded bioturbation mounds that lacked protective plant canopies (Fig. 6B). Subsequent erosion by surface runoff and also possibly by eolian deflation would have selectively removed exposed fine soil particles from the mound, eventually concentrating a lag of small clasts on the surface (Fig. 6C). Within several meters directly downslope of plant scar mounds, pavement surfaces typically bear thin surface accumulations of light-colored, fine
Figure 6. Hypothesized developmental sequence of plant scar mounds and depressions. (A) Bioturbation mound beneath large, long-lived creosotebush plant. (B) Death of plant leads to selective erosion of fine soil mass. (C) Selective erosion yields a pavement-like lag of small surface clasts and bioturbation eventually ceases. (D) Settled soil mass produces a shallow depression and Av horizon develops beneath a pavement of small surface clasts.

soil materials, evidence of the transport of fine materials away from the mounds by water.

With the passage of time and cessation of bioturbation by rodents, settling and compaction would eventually yield a slight depression because part of the mound’s original fine soil mass was lost earlier to erosion. Lack of surface disturbance would permit formation of a surface pavement from the lag of small clasts and development of rock varnish on the tightly packed pavement clasts. Once a protective pavement forms, the depression would become a relatively persistent microtopographic feature on the pavement surface (Fig. 6D).

In the study area, active sub-canopy bioturbation mounds can be found on younger (Holocene) alluvial fans and erosional margins of older fans that lack well-formed pavements. Characteristics of active mounds provide evidence supporting the hypothesized origin of key features of plant scar mounds and depressions (Fig. 6). Burrowing rodents mechanically sort substrate materials within the mounds. Fine soil and small clasts up to approximately 2 cm diameter are retained in mounds, whereas rodents move slightly larger clasts to mound perimeters. Badgers (Taxidea taxus; body weight ~9 kg) commonly dig in mounds beneath large creosotebush plants in search of rodent prey. In doing so, badgers apparently face the bases of central creosotebush plants and push excavated materials, including large clasts, backwards towards the perimeters of mounds. Clasts measuring a maximum of 20 cm diameter and weighing up to 2.5 kg had been displaced by badgers in this manner to perimeters of sub-canopy bioturbation mounds beneath living creosotebush plants. Excavation and redistribution of coarse materials long ago by badgers
explains the observed scatter of larger clasts around perimeters of plant scar mounds (Fig. 4A); those larger clasts exceed a size that could plausibly be moved by small rodents. Clasts recently excavated by rodents and badgers in active bioturbation mounds are typically covered with rinds of pedogenic carbonate (indicating of their original subsoil location) and account for the origin the light-colored, carbonate-rich material on surfaces of plant scar mounds (Fig. 4A, Table 1A).

Contrasts in soil characteristics provide further evidence for different relative ages of plant scar mounds and depressions and the proposed developmental sequence (Fig. 6). Soil beneath plant scar mounds is weakly developed in comparison to soil beneath plant scar depressions, and soil beneath plant scar depressions is considerably less developed than soil beneath surrounding pavement surfaces (Table 1B). Time-dependent soil developmental characteristics (thickness and silt-clay content of the Av horizon, maximum reddening of subsoil horizons, salinity, carbonate content, and calcic horizon stage) are lowest beneath plant scar mounds, intermediate beneath plant scar depressions, and highest beneath the surrounding pavement (Table 1B). The greatly reduced occurrence of clasts composed of indurated pedogenic carbonate on surfaces of plant scar depressions compared to plant scar mounds indicates the passage of enough time to allow for dissolution of carbonate-rich materials from the surface (Table 1A). The increased carbonate content within soil beneath plant scar depressions (Table 1B) reflects time-dependent, sub-soil accumulation of carbonate dissolved and removed from the surface. The contrast in the degree of soil development underlying plant scar mounds and plant scar depressions suggests that at least a few thousand years would be required to account for these differences.

Relation between surface drainage and spatial distribution of plant scars

Plant scar mounds and depressions commonly co-occur on the same Pleistocene alluvial fan remnants. However, spatial distributions of the two in relation to on-fan drainages differ sharply. On the middle terrace, Gould Wash study area (Fig. 3), plant scar mounds are located closer to fluve margins, whereas plant scar depressions are located significantly further from fluvies and concentrated centrally in interfluve areas. Measurements from plant scar mounds peak sharply between 5 and 15 m from margins of fluvies, but 65% of all plant scar depressions are located from 20 to 40 m from the nearest fluve (Figs. 7A, C). Similar contrasts in the spatial distributions of plant scar mounds and depressions were observed in field reconnaissance in other areas on the YPG. Means of distance measurements for plant scar mounds and random points are nearly identical (Figs. 7A, B). However, the variance for the plant scar mound measurements is significantly less (i.e., a much narrower, peaked distribution) than the variance associated with distance measurements taken from random points (F test for equality of variances, $P<0.01$), indicating the non-random concentration of plant scar mounds in a rather narrow swath near fluve margins.

Figure 7. Distributions of distances measured to the margin of the nearest fluve for (A) plant scar mounds, (B) randomly distributed points, and (C) plant scar depressions.

Lateral positions of most active first- and second-order on-fan drainages on the middle terrace pavement (as well as the complementary location of interfluve areas where plant scar features are located) probably have changed little throughout the Holocene. The modern, spatial distribution of on-fan drainages on the pavement has apparently been inherited from a time (probably the late Wisconsin) when there was much greater runoff and stream discharge from the fan surface than during the more arid Holocene. Runoff generated by the very small drainage area (~1–2 km²) of the middle terrace study area during the Holocene has been relatively ineffective at incising and transporting the coarse materials originally emplaced during the Pleistocene by considerably larger flows derived from the entire Gould Wash drainage basin (119 km²). Consequently, weakly varnished pavements have re-formed over the surfaces of the headward-most sections of on-fan drainages (visible in aerial views; Fig. 1). Those re-formed pavements are commonly underlain by 20–50 cm of silt-rich, gravel-poor sand that lacks significant pedogenic modification. Accumulation of these fine-grained materials in
channels indicates a decrease in stream runon and corresponding stream competency during the Holocene and a resulting linear, downslope retraction of the headward limits of first-order channels. With the exceptions of plant scars and limited areas of linear, downslope retraction of first-order fluvies, broad interfluves are smooth, continuous, and very uniformly covered by dark varnished pavements, further indicating a lack of lateral migration of on-fan drainages during the Holocene. The modern main channel of Gould Wash is positioned 3–6 m below the Pleistocene fan surfaces. There is no evidence that any flows of Gould Wash have directly impacted these surfaces at any time during the Holocene. The only Holocene aggradation associated with Gould Wash is represented by a terrace remnant positioned 1–2 m above the active Gould Wash channel but well below the Pleistocene surfaces.

Contemporary drought and the spatial distribution of recent plant mortality

Recent mortality of creosotebush plants due to drought at the Growler Valley study area provides a modern proxy linking climate variation, landscape position, and the incipient creation of plant scars. Below-average annual precipitation was recorded at Organ Pipe Cactus National Monument headquarters in 4 of 5 yr from 1999 through 2003. The greatest precipitation shortage occurred in calendar year 2002, when only 22% (55 mm) of the annual average amount (245 mm) was received. A remote recording rain gauge located 1 km from the Growler Valley study area in the northwestern corner of the national monument also recorded the small precipitation input in 2002 (60 mm).

The Growler Valley study area (Fig. 8) is on alluvial fan deposits and contains a swath of desert pavement ranging from 15 m to over 25 m wide. Approximately 90% of the pavement surface is covered by tightly fitting, varnished pavement clasts. A fine-textured (loam), 2-cm-thick, calcic vesicular A (Avk) horizon underlies the pavement. The subsoil contains a Btk horizon and stage II carbonate accumulation. These soil characteristics indicate the alluvium on which the pavement formed is a late Pleistocene fan deposit and the degree of pavement and soil development is similar to those on Pleistocene fan remnants at the Gould Wash study area.

The desert pavement (Fig. 8) forms a very slightly convex surface and the peripheral areas that lack pavements on the north and south sides represent erosional margins of the fan remnant. In these peripheral areas only about 75% of the soil surface is covered by clasts; these clasts do not form a pavement. The Av horizon is thinner (1 cm) and coarser textured (sandy loam) than the Av horizon of the pavement area. Underlying horizons consist of a Bwk horizon and a stage I Bk horizon. Weaker soil development indicates that soil of the

Figure 8. Study plot at Organ Pipe Cactus National Monument; boundaries shown with broken line. All creosotebush plants (Larrea tridentata) within the plot are mapped. Dead plants are shown by solid black circles; live plants are the open white circles. Circle diameters indicate the basal stem crown diameter of plants.
peripheral areas has been truncated by erosion. A narrow, Holocene deposit is inset below the Pleistocene fan surface along the length of the large fluve to the north of the mapped area (cross-section: Fig. 8). The study plot did not include areas on this younger surface.

Dead plants were more common in the central pavement area than the peripheral areas. Within the central pavement area, 43% of 21 plants were dead in March 2004, whereas only 9% of 33 plants located beyond the pavement edge were dead (Fig. 8; chi-squared test of independence, $\chi^2 = 8.45, P < 0.005$). Six of the nine dead plants in the central pavement area died either in late 2002 or early 2003 following the most extreme year of drought. Dead and live creosotebush plants also significantly differed in their average distances to the nearest fluve. Minimum distance between the 12 dead plants and the nearest fluves averaged 13.62 m ($SD = 4.99$ m); minimum distances between the 42 live plants and nearest fluves averaged 8.23 m ($SD = 5.76$ m) (two-sample t test, unequal sample size; $t = 2.94, P < 0.005$).

Higher mortality of creosotebush in the pavement area is in part a consequence of a more xeric soil moisture environment due to the restriction of infiltration by the pavement and underlying Av horizon. Recent studies have demonstrated that infiltration dramatically decreases with increasing development of desert pavement and the associated Av horizon (McDonald et al., 1996; Young et al., 2004). The relatively impermeable soils of the pavement generate runoff that is received and more readily absorbed by more permeable soils beyond the pavement margin, thereby creating more favorable soil moisture environments in the peripheral areas.

Measurements of the depth of infiltration associated with a recent large winter storm demonstrated the relation between landscape position and depth of soil moisture penetration. On 12–13 February 2003, 52 mm precipitation was measured at the gauge located 1 km from the site. Wetting fronts measured on 21 February showed the difference in infiltration and redistribution of soil moisture beneath pavements versus the non-paved periphery. The depth of the wetting front in the central pavement area (mean = 13.9 cm, $SD = 1.5$ cm) was only half that measured just outside the pavement margin (mean = 27.1 cm, $SD = 8.2$ cm) ($t$ test for samples with unequal variance, $t = 4.49, P < 0.005$). Density of creosotebush is lower and plants are smaller in the central pavement area than in peripheral areas (Fig. 8), reflecting the inhibition of infiltration on the pavement surface by the fine-textured Av horizon.

**Linkages between late Quaternary climate changes and formation of plant scars**

Before the occurrence of plant mortality that eventually yielded the plant scar depressions, large perennial plants were more diffusely distributed over the entire landscape at the Gould Wash study area. Plants that survived this earlier episode of mortality were located closer to fluves (represented by modern-day plant scar mounds, Fig. 7A). The more recent loss of those survivors led to even further vegetation contraction, giving rise to the wide, barren pavement surfaces present today.

At the less arid Growler Valley study area, the spatial distribution of mortality among creosotebush plants in response to recent, severe drought provides a modern-day analog of the temporal progression of plant mortality over the landscape that occurred long ago in more arid areas. Plant death was more common in the more xeric soil environments of central interfluve areas than peripheral areas where the soil is more permeable and also receives runoff delivered from interfluve pavements.

The widespread occurrence and relatively uniform morphology of plant scar mounds on pavements in the more arid parts of the study region suggest that shrub mortality was widespread and probably triggered by climate change. At the Gould Wash study area, absence of any large woody remains on or beneath the surfaces of plant scar mounds suggests that the large plants beneath which the mounds originally formed died at least many centuries ago, given the persistence of hard woody materials in this extremely arid zone where decomposition is extremely slow. For example, fragments of buried creosotebush wood exceeding 700 yr of age (calibrated $^{14}$C dates) have been recovered near the bases of large, old plants at a site in the Mojave Desert that receives over 130 mm annual precipitation (Vasek, 1980). The plant mortality that gave rise to plant scar mounds is probably a late Holocene phenomenon and may represent a response to increased aridity in the last several thousand years (Van Devendor, 1990; McAuliffe and Van Devendor, 1998). More recent, minor climate fluctuations, for example, increases in flood-generating storms across the southwestern US between about A.D. 1600 and 1900 (Ely et al., 1993; Redmond et al., 2002) may have occasionally fostered relatively short-lived re-occupancy of the mounds by plants. If so, those plants likely never attained large size or great age, given the absence of any woody remains.

Plant mortality that gave rise to plant scar depressions was probably triggered by considerably earlier climate change. The light to moderate coatings of rock varnish on surfaces of pavement clasts within depressions are very similar to the degree of varnish formation on clasts of gravelly alluvial fans deposited 8,000–12,000 yr ago at a site in the Mojave Desert, California (McDonald et al., 2003). Given this evidence, plant scar depressions may reflect shrub mortality that occurred at the time of the Pleistocene–Holocene transition.

Although the plant mortality that eventually yielded the plant scars was probably associated with periods of increased climatic aridity, lack of soil moisture per se may not be the sole cause of the loss of plants. Soils beneath desert pavements on Pleistocene fan deposits in the lower Colorado River Valley are strongly saline to within approximately 5 cm of the soil surface (Ligurta and Cristobal soil series, Barmore, 1980; Table 1B). Atmospheric deposition (in dust and precipitation) is the principal source of salts in soils of these upland environments (McFadden et al., 1987; McDonald et al., 2003). However, during the late Pleistocene, with more effective precipitation and greater leaching depths, these soils
would have been considerably less saline (McDonald et al., 1996). The relatively impermeable silt- and clay-rich A v horizon beneath surface pavements (Table 1B) combined with reduced effective precipitation following the Pleistocene–Holocene transition probably led to rapid, shallow accumulation of salts and loss of salt-intolerant plants. Further, slight decreases in precipitation during the Holocene could have led to further salinity increases, even in areas nearer fluvus where the most recent wave of mortality occurred. It is likely that both mechanisms (climatic drought and shallow salt accumulation) acted in concert to cause the loss of plants that eventually yielded plant scar mounds and plant scar depressions. The spatial magnitude of vegetation contraction, especially the widespread and geologically recent disappearance of plants from what are now plant scar mounds, indicates that relatively small climate changes such as those in the mid–late Holocene can ultimately have large and widespread ecological consequences in these extremely arid regions.

Arid regions that receive <100 mm average annual precipitation are even more commonplace in several other desert regions of the globe, including the Sahara and Arabian Deserts, and the coastal deserts of Peru, Chile, and Namibia. These other desert regions may also contain geomorphic surfaces such as gravelly fan deposits where similar microtopographic traces of the former presence of large perennial plants could provide unique records of past environmental changes.

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