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THE LASTING EFFECTS OF TANK MANEUVERS ON DESERT SOILS AND INTERSHRUB FLORA

By Douglas V. Prose and Howard G. Wilshire

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II LASTING EFFECTS OF TANK MANEUVERS ON THE DESERT

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS

For readers who prefer to use inch-pound units, conversion factors for the terms in this report are listed below:

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.2818	foot (ft)
square meter (m^2)	10.76	square foot (ft^2)
cubic meter (m^3)	35.31	cubic foot (ft^3)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
cubic meter per second(m^3/s)	35.31	cubic foot per second (ft^3/s)
gram (g)	0.03527	ounce avoirdupois (ozavdp)
kilogram (kg)	2.205	pound avoirdupois (lbavdp)
megagram (Mg)	1.102	tons, short (2,000 pounds)

The Lasting Effects of Tank Maneuvers on Desert Soils and Intershrub Flora

By Douglas V. Prose and Howard G. Wilshire

Abstract

Mojave Desert soils and intershrub flora sustained lasting disturbances during military training maneuvers initiated by General George Patton, Jr. in the 1940s, and during Operation Desert Strike in 1964. At six sites, mean desert pavement clast size was significantly smaller by 15% to 50% in single tank tracks compared to undisturbed surfaces. The finer-grained tracks yielded significantly higher surface reflectance values at two of three sites. At one site, Patton era tank tracks cross centuries-old "intaglios" and there was no significant difference in clast size between the disturbances. Full recovery of pavement surfaces may require a change in climate since pavements formed in Pleistocene times under climatic conditions that no longer exist.

Tank tracks of both ages exhibited significant levels of soil compaction, as indicated by penetrometer resistance values that were 51% to 120% greater than those in undisturbed soils to 0.3 m depth. Soil bulk density in tracks was 4% to 6% higher than in undisturbed soils. Soil compaction lowered infiltration rates in tank tracks by 24% to 55% in comparison to undisturbed soils.

Compaction has prevented the intershrub flora from recovering in tank tracks. Annual and herbaceous perennial plant density was higher by 13% to 56% in tank tracks than in undisturbed soils, but compaction has restricted the growth of individual plants. This was reflected in plant cover values, which were 3% to 16% lower in tank tracks than in undisturbed soils. Soil compaction also altered the species composition. Species with long taproots, such as *Chaenactis fremontii*, were reduced in density and cover in tank tracks, whereas grass species with shallow, fibrous root systems had large density increases in tracks.

Another important element of the intershrub flora, cryptobiotic crust, exhibited a low rate of recovery from the impact of tank travel at one site. The cover of the most well-developed component of the crusts, growing on delicate soil pedicels in undisturbed soils, was reduced by 50% in tank tracks because of destruction and compaction of the uppermost soil layers. Full

INTRODUCTION

Military ground-training maneuvers are a major land use in deserts of the American southwest, and they are known to cause disturbances to desert soils and vegetation that persist for decades to centuries (Rowlands, 1980; Webb and Wilshire, 1983; Lovich and Bainbridge, 1999). During World War II, maneuvers involving over one million troops and thousands of tanks and other off-road vehicles were staged over $5 \cdot 10^6$ ha of essentially roadless desert wilderness in California, Arizona, and Nevada (Figure 1). The U.S. Army War Department called the training area, which was established by General George Patton, Jr., in April 1942, the Desert Training Center (DTC) (Meller, 1946; Bischoff, 2000). The DTC operated year-round through April 1944. In May 1964, another

Figure 1.Tanks maneuvering at Desert Training Center, circa 1942-1944.

massive exercise, called Operation Desert Strike, was staged for two weeks over 200,000 ha of the central Mojave Desert (U.S. Army, 1964). Much of this maneuver took place within the former boundary of the DTC (Figure 2).

These historical activities provided a unique opportunity to analyze the long-term effects of tank maneuvers on a variety of desert soils and vegetation and to assess their prospects for recovery from military maneuvers and similar kinds of disturbances. This information has implications for land use practices at active military armored division training bases in arid lands of the southwestern United States. Two bases are located in the Mojave Desert: the U.S. Army National Training Center at Fort Irwin, California, and the Twenty Nine Palms Marine Corps Base. This information is also useful in assessing the long-term effects of temporary, non-military activities that have impacts on desert soils and vegetation similar to those of military maneuvers. These include recreational off-road vehicle use and road construction associated with resource prospecting and extraction and utility corridors.

Relevant research

A number of studies have documented the effects of military and non-military off-road vehicle travel on desert pavement surfaces in the southwest U.S. Pavement surfaces are highly stable under natural conditions (Dregne, 1976) but have been found to be easily disturbed by off-road vehicles (Wilshire and Nakata, 1976; Elvidge and Iverson, 1983; Wilshire, 1983). Analysis of fresh tank tracks at Fort Irwin shows that surface stones are broken and ground into the soil at the time of impact, leaving a mixture of overturned pebbles and stones with broken surfaces, as well as unvarnished pebbles churned up from the subsurface (Kryszik, 1985). The new surface is lighter in color and contrasts sharply with the original surface, and the disturbance remains visible for many decades. Seventy-year old ruts left by the wagons of settlers were visible in the Mojave Desert (Hunt and Mabey, 1966; Hunt *et al.*, 1966). Of even greater antiquity are designs known as “intaglios,” which were created by indigenous people several hundreds to thousands of years ago simply by

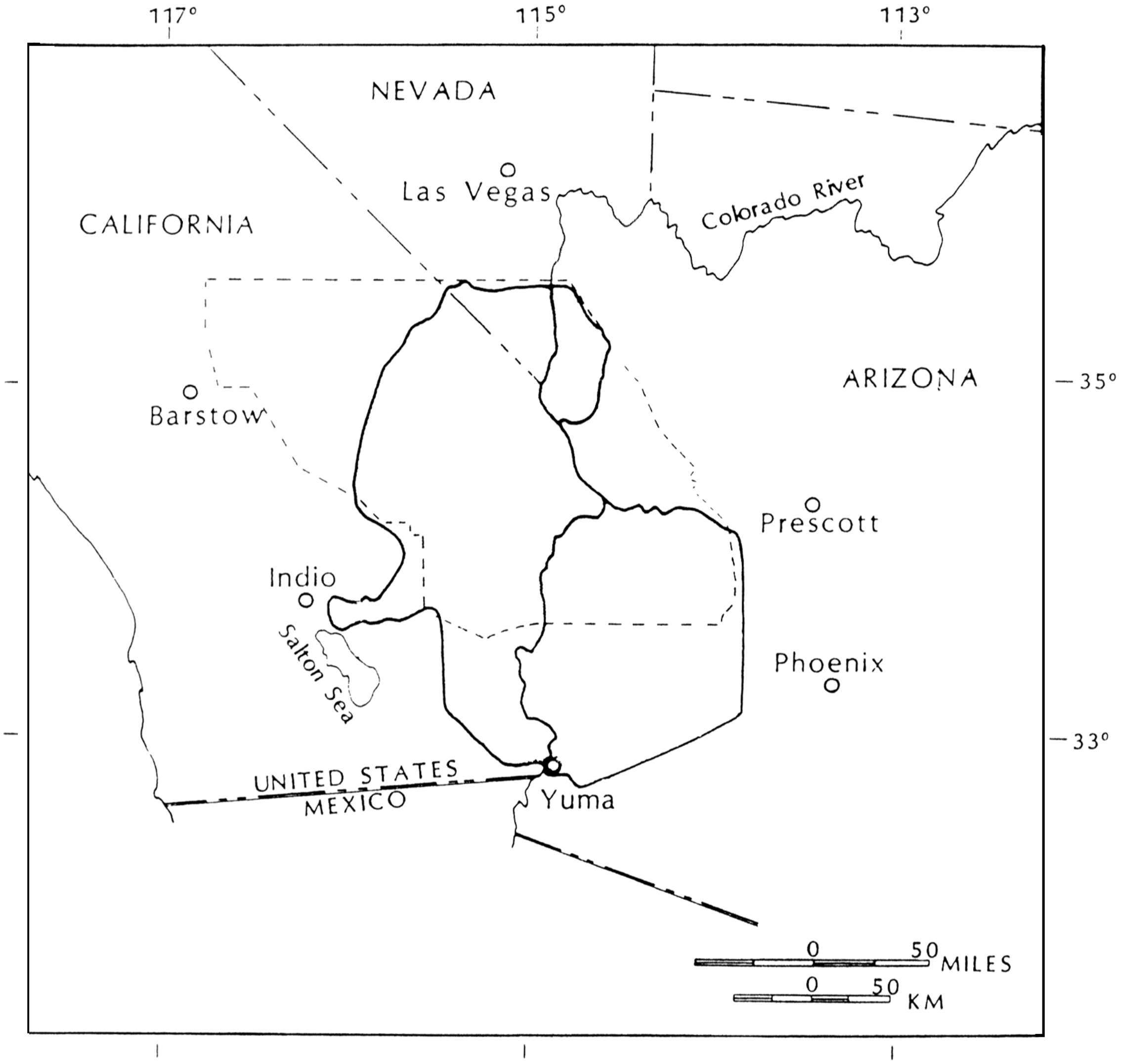


Figure 2. Desert Training Center (DTC) and Operation Desert Strike maneuver areas. Dark outline was DTC boundary; dashed outline was Desert Strike boundary.

scraping aside loose surface stones (Davis and Winslow, 1966; U.S. Heritage Conservation and Recreation Service, 1982). Intaglios are found throughout the Mojave Desert and have been damaged during military maneuvers. This has afforded an opportunity to compare the characteristics of pavements disturbed at different time periods and to assess their rate of recovery.

Studies that have assessed soil compaction and vegetation disturbances caused by military maneuvers are relevant to this study. Soils throughout Patton's Desert Training Center remained significantly compacted after 40 years as a result of troop activities at base camps (Prose, 1985; Prose and Metzger, 1985). Soil compaction in the camps' tent sites, parking lots, and dirt roads was cited as a major cause of reductions in the cover of long-lived shrub species such as *Larrea tridentata* (creosote bush) (Iwasiuk, 1979; Lathrop, 1983; Prose and Metzger, 1985; Prose *et al.*, 1987). In Arizona's Dutch Flat valley, where patches of ground were bulldozed and used for aerial gunnery practice at the DTC, the long-lived species *Larrea tridentata*, *Yucca brevefolia* (Joshua tree), *Fouquieria splendens* (ocotillo), *Cercidium floridum* (paloverde), and species of *Opuntia* (cacti) have not returned after 60 years.

Cryptobiotic crusts, a vital component of the intershrub spaces in the desert, are very slow to heal after being damaged by maneuvering tanks. At a Mojave Desert site used for maneuvers in the 1940s, only six percent of the crusts in tank tracks had re-colonized to pre-disturbance levels (J. Belnap, written communication, 1999).

Soil compaction caused by recreational off-road vehicles in the Mojave Desert is well documented and this information is relevant to this study (Wilshire and Nakata, 1976; Webb *et al.*, 1978; Sheridan, 1979; Adams *et al.*, 1982; Webb, 1982; Webb, 1983). Also relevant are studies of soil compaction and(or) incomplete recovery of long-lived shrub species in mining town roads and home sites abandoned for 30-78 years in Nevada and California (Wells, 1961; Webb and Wilshire, 1980; Webb *et al.*, 1986; Webb *et al.*, 1987; Knapp, 1992); agricultural fields abandoned for 65-70 years in California (Carpenter *et al.*, 1986); and 30-year old pipeline corridors in California (Vasek *et al.*, 1975). Another by-product of soil compaction is a lowering of the infiltration rate of rainwater, which can lead to accelerated soil erosion (Hinckley *et al.*, 1983) and restriction of plant root growth (Taylor and Gardner, 1963; Adams *et al.*, 1982).

Most of the studies cited above made estimates of the recovery of disturbed soils and vegetation to pre-disturbance conditions. For military impacts, Lathrop (1983) estimated a recovery time of 75 years for perennial vegetation in tank tracks to reach control density and cover. Prose and Metzger (1985) estimated that it takes from 48 to 152 years for the density of creosote bush to recover in moderately compacted military camp tent sites, depending on soil texture and the degree of soil compaction, and 75-540 years, if at all, for creosote bush in heavily compacted dirt roads and parking lots to recover to pre-disturbance densities. Cryptobiotic crusts measured in Patton's tank tracks may require as long as 2,000 years before cyanobacteria fully recolonize intershrub areas (J. Belnap, writ. comm., 1999). The average recovery rate for cryptobiotic crusts was estimated at 220 years, because crusts below shrubs recover faster as they benefit from more shade, moisture, and protection from disturbance.

Recovery of compacted soils in abandoned ghost towns in the Mojave and Great Basin Deserts was estimated to take 70-680 years (Webb and Wilshire, 1980; Webb and Newman, 1982; Webb *et al.*, 1986; Knapp, 1992). At least a century is estimated for compacted soils in off-road vehicle recreation sites to recover (Webb *et al.*, 1983). Recovery of vegetation communities to pre-disturbance conditions can take a few centuries in pipeline and powerline corridors (Vasek *et al.*, 1975a, b; Lathrop and Archbold, 1980) to over a millennia in ghost towns (Webb and Newman, 1982).

STUDY AREA

From 1984-1986, nine study sites were established in the California desert on public lands administered by the Bureau of Land Management (BLM). Some of these sites fell within the boundaries of newly-designated wilderness areas established by the California Desert Protection Act of 1994. Camps Granite and Ibis were base camps of the Desert Training Center from 1942-1944. All except two of the sites (Pilot Knob Mesa and Piute Valley) were impacted by both the WWII-era maneuvers and Operation Desert Strike in 1964. None of the sites appeared to have been disturbed by human activities since the maneuvers, though light cattle grazing occurs in Ward Valley and may have occasionally impacted that site.

Elevations at the nine sites range from 200 m to 790 m. Mean January and July temperatures at Needles, California are 11° and 35°C, respectively. Rainfall is bimodal and variable year to year, with a yearly average of 112 mm at Needles and 79 mm at Iron Mountain, California, from 1940-1984 (National Climatic Center, written communication, 1985). Rainfall during the two-year period of the Patton era exercises was normal and no rain fell during the two-week exercise period in May 1964.

Soils and geomorphic surfaces

Soils at all study sites are classified as Calciorthids, mixed, thermic, and calcareous. Soils at the Camp Granite and Ward Valley sites were formed in granitic alluvium, and soils at the other sites were formed in volcanic, granitic, igneous, and metamorphic sediments.

The study sites were located on gently-sloping alluvial fans, on two distinct geomorphic surfaces. One type of surface studied was relatively flat, of late Pleistocene age, and mantled with a desert pavement. The pavement stones range in size up to 0.2 m and cover 80-100% of the ground. Varnish on the stones is well-developed. The surface stones rest loosely on a vesicular, silty A horizon that is 20-40 mm thick. The B horizon of cobbly sand extends below the A horizon to 0.2-0.3 m depth, where it grades abruptly to a cemented Bk or k horizon. The B horizon is moderately oxidized and shows stage II-III calcium carbonate development (for definitions of soil carbonate stages, see Gile *et al.*, 1966). The pavement surfaces are largely devoid of vegetation except for isolated perennial shrubs and brief displays of annual plants that appear in disturbed areas when climatic conditions are favorable.

The other type of surface studied was located between pavement surfaces but not in active washes. These surfaces are Holocene in age. Stones and gravel up to 0.1 m in diameter occupy 20 to 50% of these surfaces, and the rest of the space is occupied by shrubs, plants, and cryptobiotic crust. Soils consist of a silty-sandy, vesicular A horizon 10-30 mm thick, grading to a moderately-oxidized B horizon of gravelly sand. Both horizons are weakly layered and are calcareous (stage I $CaCO_3$ development). The B horizon grades to a Bk horizon at 0.3-0.8 m depth. Soil textures in the 0.0-0.3 m depth range are gravelly sands at the Piute Valley, Skeleton Pass, and Camp Granite sites, and loamy sand at the Ward Valley site. Moisture content of these soils was low at the time of measurement, ranging from 0.4% to 1.1% by weight to 0.3 m depth.

These two geomorphic surfaces were chosen for study because they were the most common surfaces impacted during the 1940s and 1964 maneuvers. Active weathering processes on surfaces such as sand dune fields, playas, and wash channels have made it difficult to identify vehicle tracks accurately enough for the purposes of this study, so these surfaces were not measured. This study design therefore focuses on surfaces that recover slowest from tank impacts, at least visually. However, the surfaces studied are the most common Mojave Desert surfaces impacted during the 1940s and 1964 maneuvers.

Intershrub flora

Annuals and herbaceous perennials were measured in the spring of 1985 at the Ward Valley and Skeleton Pass sites. The dominant annuals at both sites were *Chaenactis fremontii* (pincushion) and *Plantago insularis* (woolly plantain), both native species.

Cryptobiotic crusts, consisting of a stable, intertwining mat of cyanobacteria, algae, lichens, fungi, mosses, and fine soil particles (Johansen, 1993), were measured at Camp Granite. The species of lichen crust is *Heppia lutosa* (identified by H.D. Thiers, San Francisco State University). Cryptobiotic crusts were particularly well-developed at this site, occupying approximately 55-60% of the undisturbed intershrub spaces.

The perennial vegetation at all three sites where intershrub ground cover was measured is dominated by *Larrea tridentata* (creosote bush) and *Ambrosia dumosa* (white bursage). The plant series measured were creosote bush series and creosote bush-white bursage series (Sawyer and Keeler-Wolf, 1995). *Opuntia ramosissima*, *Yucca shidigera*, *Encelia farinosa*, *Krameria parvifolia* and several short-lived species were infrequently found. Seven of the nine sites established for this study have Mojave Desert vegetation communities and two sites, Chemehuevi Valley and Pilot Knob Mesa, are located in Colorado Desert communities.

METHODS

This study assesses the recovery of desert soils and plants where impacted by a single pass of a military tank during the 1940s and 1964 maneuvers. Tank tracks studied were produced in 1942-1944 by the M3 Grant or M4 Sherman tanks, the most commonly used vehicles in the training exercises (Meller, 1946). In this report, these tracks are referred to as “Patton” tracks. These tanks had an individual track width of 0.42 m and a total vehicle width of 2.45 m. They weighed 35,000 kg and had a standing ground pressure of 0.95 bars. Tank tracks produced during Operation Desert Strike in 1964 were made by the bigger and heavier M60 tank, which had an individual track width of 0.58 m and a total vehicle width of 3.6 m. These tracks are referred to as “Desert Strike” tracks. The M60 weighed 51,000 kg and had a standing ground pressure of 0.78 bars.

Tank tracks are easily distinguishable from four-wheeled military or non-military vehicles because of their large dimensions and because a tank leaves two tracks when making a turn as opposed to a four-wheeled vehicle which leaves four tracks. Measurements in tracks were made on straight segments of track, though disturbances to the ground surface were generally more severe where the tanks made turns. It was not possible to determine whether the soils were wet or dry when the Patton era tanks traversed them in 1942-1944. Maneuvers took place year round. The soils were dry in May 1964 when Operation Desert Strike occurred, as no rain fell during the maneuvers and for at least two weeks prior to them.

Desert pavement measurements

The clast size of surface stones was measured in and out of Patton and Desert Strike tank tracks to test whether maneuvering tanks created lasting disturbances to Pleistocene-aged pavements. At the Pilot Knob Mesa site, measurements were made in intaglio designs and in Patton tracks that crossed over them. Clast size measurements were made by placing a 50 m fiber tape along the ground and averaging the long and short axes dimensions of each clast resting beneath 1 m marks on the tape. Within tracks the tape was placed in a zig-zag pattern in order to randomly sample the entire width of the impacted zone. Out-of-track measurements were made as close as possible to tank tracks.

Surface reflectance was measured in and out of Patton and Desert Strike tracks on pavement surfaces to test whether visually lighter and smoother surfaces within tank tracks created an increased albedo effect. Reflectance was measured with a device consisting of a 0.19 m high by 0.16 m wide cylinder, which was open-ended at the bottom and fitted with a strobe light and reflective light meter at the top. The instrument was randomly placed on the ground such that no light entered the cylinder, then a beam of light of constant energy was directed at the surface. The light meter recorded the reflected light in units of foot-lamberts (candles per square foot). A total of 25-40 measurements each were made in, and adjacent to, tank tracks.

Soil compaction measurements

Soil compaction in tank tracks on Holocene soils was measured with a recording penetrometer to a depth of 0.3 m (Carter, 1967). The penetrometer was fitted with a 30° conical tip and had a maximum obtainable resistance of 70 bars. At each Holocene soil site, 70-125 readings were randomly taken each in Patton and Desert Strike tracks, and in adjacent undisturbed soils. An exception was the Piute Valley site, where only

Table 1. Comparison of pavement surface clast size in and out of tank tracks and an intaglio site.

SITE	UNDISTURBED		DESERT STRIKE		PATTON		INTAGLIO	
	Mean (mm)	S.D. (mm)	Mean (mm)	S.D. (mm)	Mean (mm)	S.D. (mm)	Mean (mm)	S.D. (mm)
Camp Ibis	14.8	14.5	7.6*	7.8	8.1*	11.4	n.m.	n.m.
Clipper Valley	28.8	39.0	24.5	36.0	18.8**	24.7	n.m.	n.m.
Marble Valley	18.4	27.0	10.7*	17.0	10.5*	13.7	n.m.	n.m.
Chemehuevi Valley	14.4	13.6	6.0*	5.9	8.6*	12.0	n.m.	n.m.
Skeleton Pass	16.9	15.9	12.4*	14.2	11.9*	16.9	n.m.	n.m.
Pilot Knob Mesa	12.3	10.6	n.m.	n.m.	7.2*	6.7	6.2*	7.8

n.m. - not measured
* - denotes significantly different from undisturbed at probability, $p<0.05$
**- denotes significantly different from undisturbed and Desert Strike at $p<0.05$

Patton tracks were measured. Where the penetrometer tip encountered a rock when being pushed into the soil, the attempt was abandoned and tried in a different location.

Bulk density of tracked and undisturbed Holocene soils was also measured (Blake, 1965) as an indicator of compaction. At each site, 10 paired samples were taken with a 0.1 m long, 224 cm^3 piston-driven cylinder at the 0.0-0.1 m, 0.1-0.2 m, and 0.2-0.3 m depth intervals. The samples were oven dried at 105°C for 24 hours to correct for water content (weight percent). Two undisturbed soil samples from each site were analyzed for particle-size distribution with the hydrometer method (Day, 1965).

Infiltration rates were measured in three Holocene soils using the method of Constantz (1984). Infiltration rates were measured by placing a capped, double-ring infiltrometer with inner ring diameter of 0.15 m and outer ring diameter of 0.35 m into the soil, and delivering water to the inner ring with a constant-head delivery system. The volume of water infiltrating under steady-state flow conditions was measured at two-minute intervals until terminal velocity was attained for 20 consecutive readings. Six tests each in and adjacent to tracks were made at each site.

Intershrub flora measurements

Measurements of the effects of tank travel on desert annual and herbaceous perennials were made in April 1985 at the Ward Valley and Skeleton Pass sites. Measurements were made in tracks and adjacent undisturbed soils using the Daubenmire method (Daubenmire, 1968). A 0.1 m^2 (0.2 m x 0.5 m) frame was placed randomly along transect lines of 40 measurements each. Two transects each in and out of tracks were measured at both sites. Daubenmire cover classes and plant density were determined for plants in each category.

Cryptobiotic crusts were measured in and out of tank tracks at the Camp Granite site, where crust cover is exceptionally well-developed on the granitic, gravelly sand soils. Crusts were measured along with the other elements of the intershrub ground cover with a 0.1 m^2 frame and classified in terms of per cent cover according to Daubenmire cover classes. Crust cover was characterized in two ways: “pedicelled” crust, which was black in color and growing on raised soil pedicels, and “flat” crust, which was light grey in color and grew flat on the ground. The other elements of ground cover measured were “plants,” which were mostly annuals, “gravel,” and “bare ground.” Twenty plots were randomly measured each in tank tracks and in adjacent undisturbed soils.

Statistical analyses

To analyze for differences between undisturbed and impacted soils and intershrub flora, results were analyzed statistically with appropriate paired-sample t-tests at the 95% confidence level (Sokal and Rohlf, 1969). Cover values for annuals and herbaceous perennials were transformed for analyses.

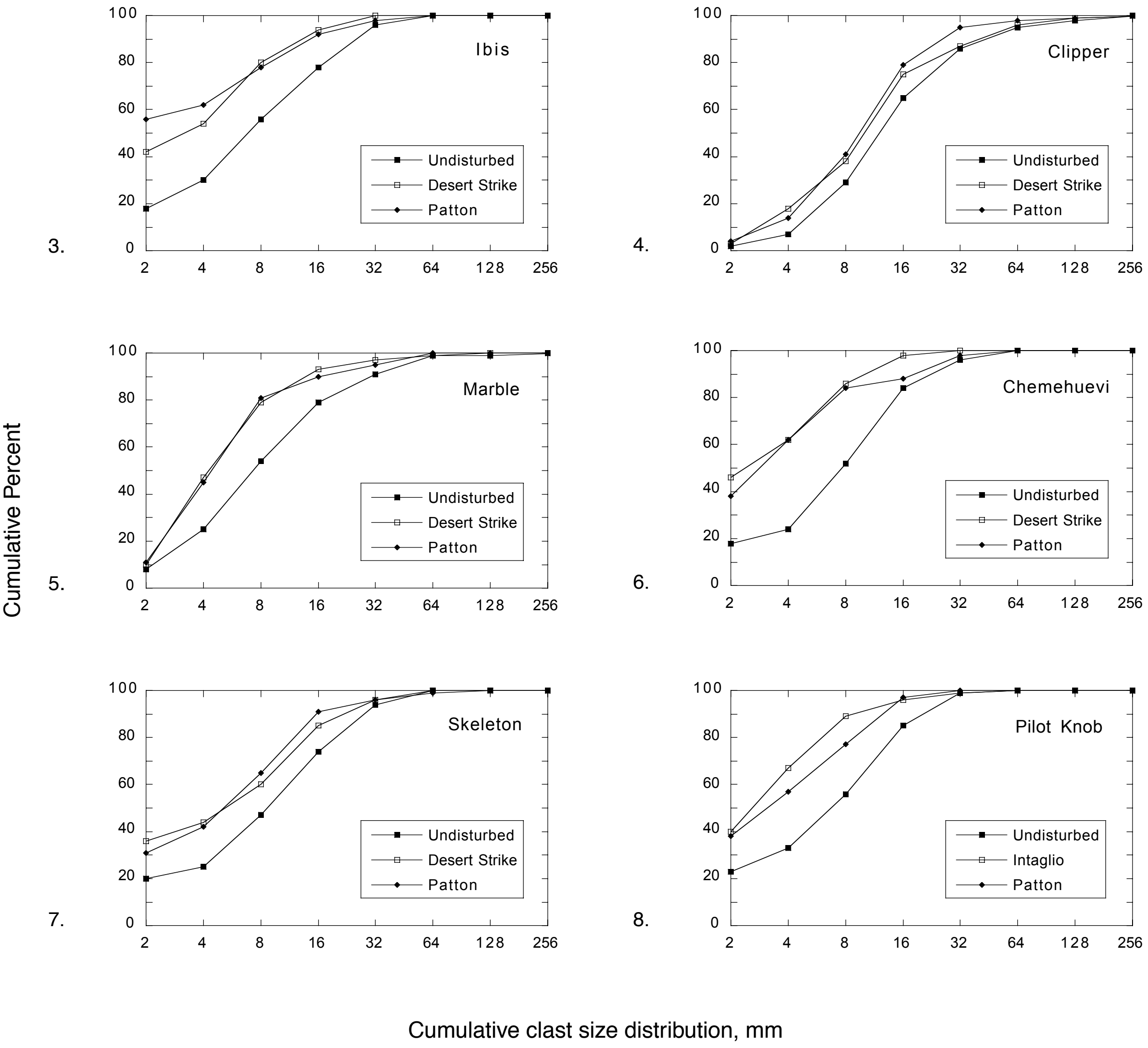
RESULTS

Desert pavement measurements

Mean clast sizes of undisturbed surfaces ranged from about 12 mm at Pilot Knob Mesa to 29 mm at Clipper Valley (Table 1). Within tank tracks, mean clast sizes were smaller by 15% to 50% than on undisturbed surfaces. These were all statistically significant differences, except between the undisturbed surface and Desert Strike tank tracks at Clipper Valley. The Patton tracks at Clipper Valley had a significantly finer surface than the Desert Strike tracks. At the other four sites where both Desert Strike and Patton tracks occurred, there was no significant difference in the mean clast size between these two kinds of tracks.

At the Pilot Knob Mesa site, intaglios and Patton tracks had a significantly finer surface than the undisturbed surface. There was no significant difference in mean clast size between intaglios and Patton tracks. Desert Strike tracks were not found here because Operation Desert Strike did not take place in this area.

There were marked differences in the cumulative clast-size distribution of surface stones between disturbed and undisturbed surfaces at all six sites (Figures 3-8). Disturbed surfaces had a



Figures 3 - 8. Pavement surface clast size in and out of tank tracks.

higher percentage of fine clasts than undisturbed surfaces, and this is probably a principal cause of the conspicuous difference of appearance for tank tracks (Figure 9).

Surface reflectance

Surface reflectance was measured in Patton tracks and on adjacent undisturbed surfaces at three pavemented sites, and also in Desert Strike tracks at the Marble Valley site (Table 2). Surface reflectance in Patton tracks was significantly increased at two of three sites. Reflectance in Desert Strike tracks at Marble Valley was significantly higher than the undisturbed surface, and was also significantly higher than in Patton tracks.

Soil compaction measurements

At the four Holocene soils sites measured, recording penetrometer values in Patton tracks are 51% to 120% higher than in undisturbed soils in the upper 0.3 m soil profile (Figures 10-13). The highest compaction levels in Patton tracks were recorded at the 50 mm depth, where values were

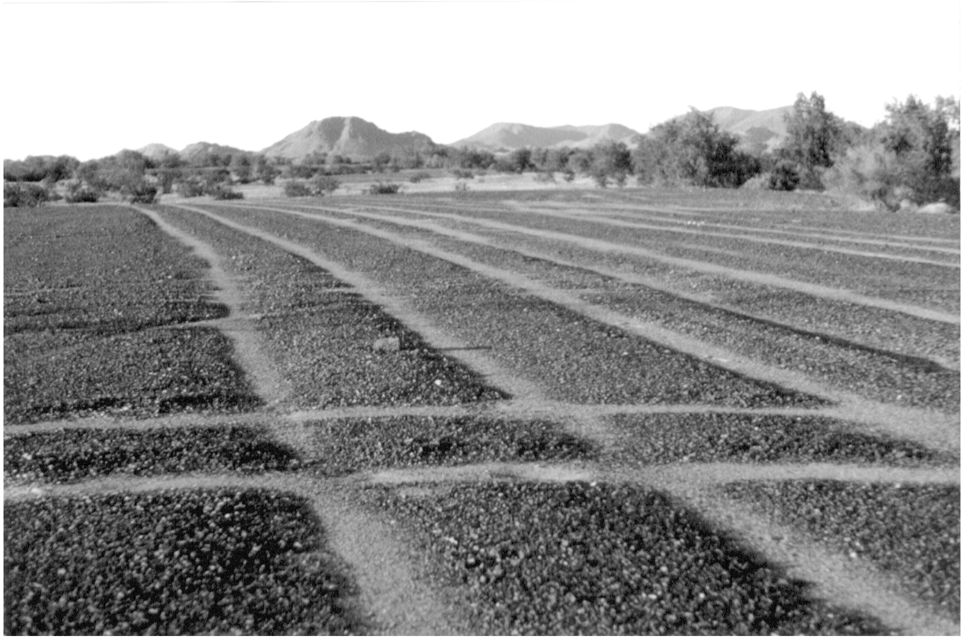


Figure 9. Patton tank tracks on a surface with significant desert pavement.

Table 2. Surface reflectance in and out of tank tracks.

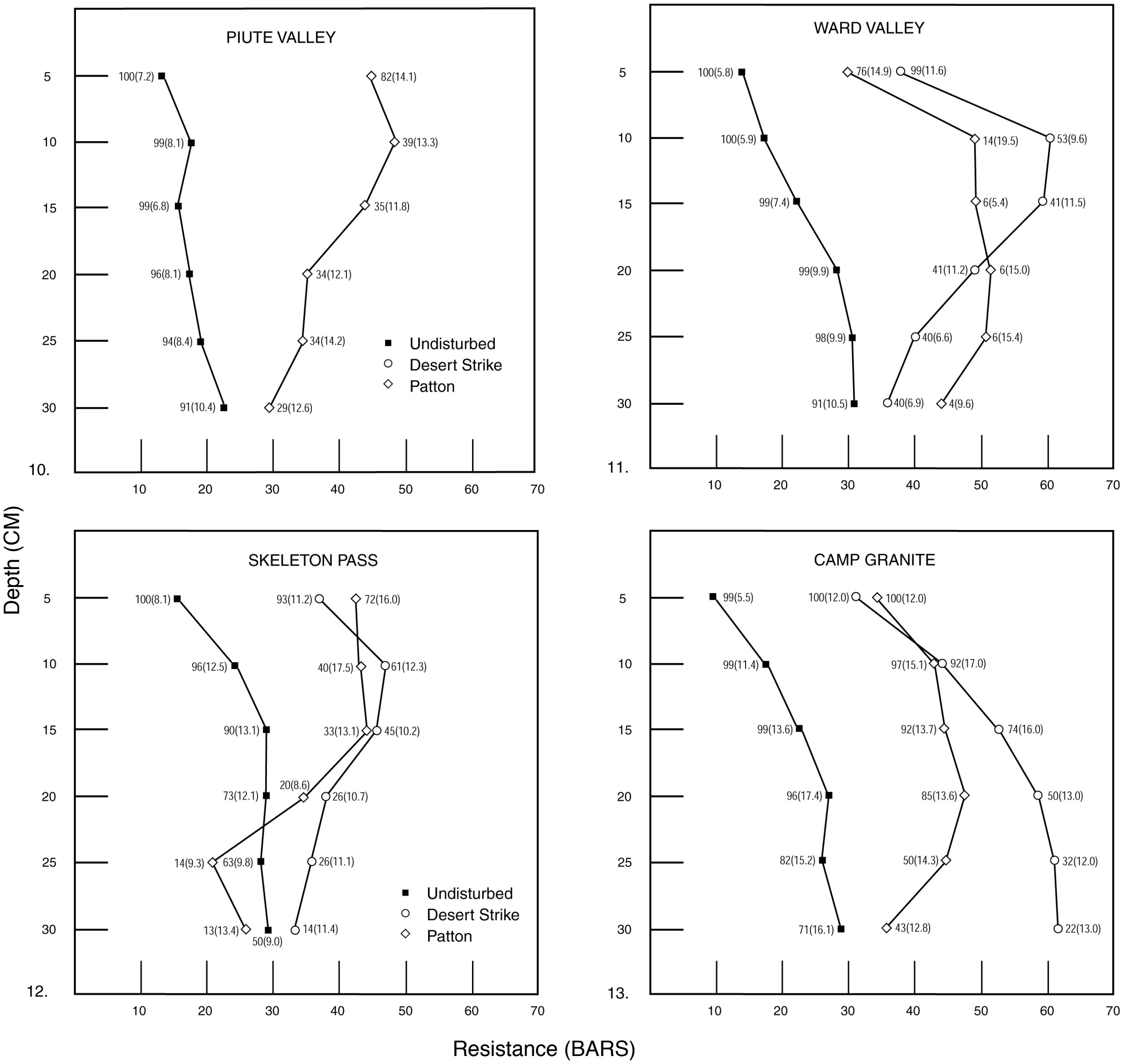
SITE	SURFACE REFLECTANCE (foot-lamberts or candles/ft^2)					
	UNDISTURBED		DESERT STRIKE		PATTON	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Camp Ibis	25.4	2.3			25.7	1.6
Marble Valley	30.4	0.8	33.1*	1.2	31.7**	1.3
Skeleton Pass	26.7	1.1			28.1*	1.1

Each mean = 25 to 40 measurements
* - denotes significantly different from undisturbed at probability, $p<0.05$
**- denotes significantly different from undisturbed and Desert Strike at $p<0.05$

123% to 273% greater than undisturbed soils. In over half the attempted penetrations in tank tracks, the penetrometer encountered soil compacted beyond the maximum resistance value of 70 bars before reaching the 0.15 m depth. In contrast, 90% to 95% of attempted penetrations reached the 0.15 m depth in undisturbed soil. At the Ward Valley site, the soil was so compacted in Patton tracks by the 0.1 m depth that the penetrometer penetrated that deep only 14% of the time.

Younger Desert Strike tracks also show high levels of compaction at the three sites where they were measured. Penetrometer values follow the same general trends with depth as those recorded in older Patton tracks.

In comparing results between Patton and Desert Strike tracks, consistent trends do not emerge. At the Ward Valley site, readings in Desert Strike tracks are significantly higher than in Patton tracks at the 50 mm, 0.1 m, and 015 m depth intervals, though it is questionable whether soils in the Desert Strike tracks are actually more compacted than in Patton tracks, on average, because a much lower percentage of readings penetrated deeper than 50 mm in the Patton tracks. Compaction in Desert Strike tracks is significantly less than in Patton



Figures 10 - 13. Penetrometer resistance in and out of tank tracks. Numbers in graphs are percent of measurements reaching corresponding depths and (standard deviation in parenthesis).

tracks at the 50 mm depth at Skeleton Pass and Camp Granite, but at greater depths compaction in Desert Strike tracks becomes comparable to, and then surpasses, that in Patton tracks. Combining readings for the 50 mm to 0.3 m depths at each site, there are no significant differences in compaction levels in Desert Strike and Patton tracks at Ward Valley and Skeleton Pass. At Camp Granite, Desert Strike tracks are significantly more compacted than Patton tracks in this comparison, but only because compaction is greater in the 0.15 to 0.3 m depth range.

Soil bulk density

Soil bulk density measurements for the 0.0-0.3 m depth range record significant levels of soil compaction in both Patton and Desert Strike tracks at all sites measured (Table 3). Trends follow those for penetrometer readings, though increases in bulk

Table 3. Soil bulk density in and out of tank tracks.

	SOIL BULK DENSITY (g/cm^3)					
SITE	UNDISTURBED		DESERT STRIKE		PATTON	
	Undisturbed mean	S.D.	Desert Strike mean	S.D.	Patton mean	S.D.
PIUTE VALLEY						
0.0-0.1 m depth	1.65	0.06	n.m.	n.m.	1.72*	0.03
0.1-0.2 m depth	1.68	0.02	n.m.	n.m.	1.77*	0.02
0.2-0.3 m depth	1.69	0.04	n.m.	n.m.	1.73*	0.04
SKELETON PASS						
0.0-0.1 m depth	1.61	0.06	1.69*	0.05	1.74**	0.05
0.1-0.2 m depth	1.66	0.07	1.72*	0.06	1.75*	0.06
0.2-0.3 m depth	1.67	0.05	1.67	0.08	1.70	0.09
WARD VALLEY						
0.0-0.1 m depth	1.58	0.07	1.69*	0.03	1.69*	0.03
0.1-0.2 m depth	1.67	0.05	1.75*	0.05	1.78*	0.04
0.2-0.3 m depth	1.69	0.03	1.70	0.06	1.74**	0.03
CAMP GRANITE						
0.0-0.1 m depth	1.54	0.05	1.68*	0.06	1.63*	0.07
0.1-0.2 m depth	1.63	0.05	1.71*	0.07	1.68*	0.05
0.2-0.3 m depth	1.64	0.07	1.69*	0.05	1.67	0.08

n.m. - not measured

density in disturbed soils are not as profound as those seen in penetrometer results. For instance, Patton tracks have bulk densities that are 4% to 6% higher than undisturbed soils in the 0.0-0.3 m depth range, compared to a 51% to 120% difference in penetrometer resistance in the same comparison.

Bulk density in tank tracks is highest in the upper 0.2 m. At 0.2-0.3 m depth, bulk densities in tank tracks are significantly different from undisturbed soils at only half the sites.

Comparing values between Patton and Desert Strike tracks, soils under Patton tracks are significantly denser than Desert Strike tracks in the 0.0-0.3 m depth range at Skeleton Pass and Ward Valley. At Camp Granite, soils under Desert Strike tracks are significantly denser than Patton tracks.

Infiltration rates

Infiltration rates were lowest in the stiff, rocky soils at Skeleton Pass and highest in the loose, loamy sands at Ward Valley (Table 4). The variability of infiltration rates in undisturbed soils was high, which rendered differences in mean infiltration values between undisturbed and tracked soils statistically insignificant in some cases. Variability of infiltration rates within compacted tank tracks was much lower than in undisturbed soils.

At the Ward Valley site, infiltration rates were 55% lower in Patton tracks compared to undisturbed soil (significantly different at $p<0.05$) due to high levels of persisting soil compaction. Infiltration rates in Patton tracks at Skeleton Pass were significantly reduced by the same percentage:

Table 4. Steady-state infiltration rates in and out of tank tracks.

SITE	INFILTRATION RATE (mm/hr) UNDISTURBED Mean	UNDISTURBED S.D.	DESERT STRIKE Mean	DESERT STRIKE S.D.	PATTON Mean	PATTON S.D.
Ward Valley	436	122	320*	94	196**	76
Skeleton Pass	132	59	87	29	59**	23
Camp Granite	249	62	220	95	190	43

Each mean represents six measurements.
* - denotes significantly different from undisturbed at $p<0.05$
**- denotes significantly different from undisturbed and Desert Strike at $p<0.05$

55%. At Camp Granite, the mean infiltration rates in Patton tracks was 24% lower than in undisturbed soil. However, one of the measurements in undisturbed soil had a very high infiltration rate, which made the standard deviation of the mean sufficiently high to narrowly render it insignificantly different from the rate in tracked soils.

Infiltration rates in Desert Strike tracks were not as low as in Patton tracks. At Ward Valley, a 27% reduction was measured in Desert Strike tracks compared to undisturbed soils (significantly different at $p<0.05$), which is a significantly greater difference than the rates in Patton tracks. At Skeleton Pass, the rates in Desert Strike tracks were 34% lower than in undisturbed soils, but this was not statistically different. The Desert Strike infiltration rates were, however, statistically higher than rates in Patton tracks at this site. At Camp Granite, the rates in Desert Strike tracks were not statistically different from either the undisturbed soils or the Patton tracks rates.

The higher infiltration rates found in Desert Strike tracks compared to Patton tracks at the Ward Valley and Skeleton Pass sites correlate with bulk density measurements, which show that soil compaction in the 0.0-0.3 m depth range was significantly lower in Desert Strike tracks than in Patton tracks at these two sites.

Intershrub flora measurements

Annuals and herbaceous perennials were measured at two sites: Ward Valley and Skeleton Pass (Table 5). The Ward Valley site had a higher total cover and density of plants and a greater number of species, apparently because its soils were considerably looser and finer grained. The results show that intershrub plant cover and density have been altered in tank tracks. The overall general effect was to lower the total plant cover and increase total plant density in tank tracks. Cover decreased because individual plants in tank tracks were considerably smaller in size. These alterations contribute to an increased visual contrast between tracked and undisturbed surfaces (Figure 14).

At the Ward Valley site, total cover was 14% lower in Patton tracks than in undisturbed adjacent areas, while density was 66% higher in the tracks. The total number of species decreased from 14 in undisturbed areas to 11 in Patton tracks. At Skeleton Pass, cover was 16% lower in Patton tracks compared to undisturbed areas, and density was 13% higher. The same number of species (10) was in both the tracked and untracked areas. In Desert Strike tracks at Ward Valley, total plant cover was reduced 7% from undisturbed values.

Total plant density increased 54% in Desert Strike tracks, a comparable amount to the density increase in Patton tracks. At Skeleton Pass, total cover in Desert Strike tracks was about equal to that in undisturbed areas, but total density increased by 56%. The total number of species declined from 13 in undisturbed areas to 12 in Desert Strike tracks at Ward Valley. One more species (eight total) was found in Desert Strike tracks than in undisturbed areas at Skeleton Pass.

In terms of individual species changes, the biggest trends in Patton and Desert Strike tank

Table 5. Cover and density of intershrub plants in and out of tank tracks.

	WARD VALLEY								SKELETON PASS							
	% Cover				Individuals per m^2				% Cover				Individuals per m^2			
	Undis-turbed	Patton Camp	Undis-turbed	Desert Strike	Undist-turbed	Patton Camp	Undist-turbed	Desert Strike	Undist-turbed	Patton Camp	Undist-turbed	Des. Strike	Undist-turbed	Patton Camp	Undist-turbed	Desert Strike
Annuals																
Chaenactis fremontii	6.6	1.8	5.8	1.4	14.3	6.5	6.8	3.3	6.3	1.7	12.5	8.5	14.0	8.0	28.8	30.5
Plantago insularis	6.4	7.5	6.9	5.3	78.5	175.3	60.3	90.3	2.8	2.6	7.2	9.2	28.2	27.3	46.3	80.5
Manoptilon bellioides	-	-	-	-	-	-	-	-	0.5	0.4	0.2	0.1	2.0	1.8	0.8	1.3
Langloisia punctata	0.1	-	0.3	0.3	0.3	-	1.3	1.3	0.1	0.1	0.1	0.1	0.2	0.1	0.3	0.5
Pectocarya platycarpa	2.6	1.5	5.4	2.6	8.3	4.0	15.3	11.0	5.6	5.4	-	0.1	22.7	20.0	-	0.5
Erioneuron pulchellus	-	-	-	-	-	-	-	-	3.5	6.0	0.9	0.8	9.2	27.2	2.5	6.0
Chorizanthe brevicornu	0.4	-	0.1	0.4	0.5	-	0.5	0.5	1.0	0.1	-	-	1.8	1.3	-	-
Oenothera decorticans	0.1	0.2	0.1	-	0.8	1.0	0.5	-	0.1	0.3	-	-	0.5	2.5	-	-
Cryptantha nevadensis	1.4	1.1	0.9	0.8	3.5	4.3	5.5	3.8	0.6	0.3	-	-	2.3	1.8	-	-
Eriophyllum wallacei	1.3	0.8	0.9	1.9	8.3	5.3	8.3	23.8	-	-	-	-	-	-	-	-
Astragalus sp.	0.6	0.4	3.9	5.8	1.8	3.3	15.8	32.8	-	-	-	-	-	-	-	-
Malacorthrix glabrata	1.6	1.4	6.8	4.0	6.0	5.3	14.0	12.5	-	-	-	-	-	-	-	-
Cryptantha micrantha	1.5	0.5	1.7	2.1	10.3	3.0	20.3	28.3	-	-	-	-	-	-	-	-
Phacelia crenulata	0.1	-	-	-	0.3	-	-	-	-	-	-	-	-	-	-	-
Herbaceous Perennials																
Euphorbia polycarpa	8.4	9.3	8.5	12.3	20.5	25.0	15.3	25.8	2.3	2.2	0.3	1.8	4.7	6.3	1.0	5.0
Tridens pulchellus	2.1	4.1	9.1	9.9	15.0	47.3	83.5	146.8	-	-	0.1	0.1	-	-	0.3	0.5
TOTALS	33.2	28.6	50.4	46.8	168.4	280.3	247.4	380.2	22.8	19.1	21.3	20.7	85.6	96.3	80.0	124.8
% change from undisturbed		-13.9		-7.1		66.4		53.7		-16.2		-2.8		12.5		56.0
No. of species present	14	11	13	12					10	10	7	8				

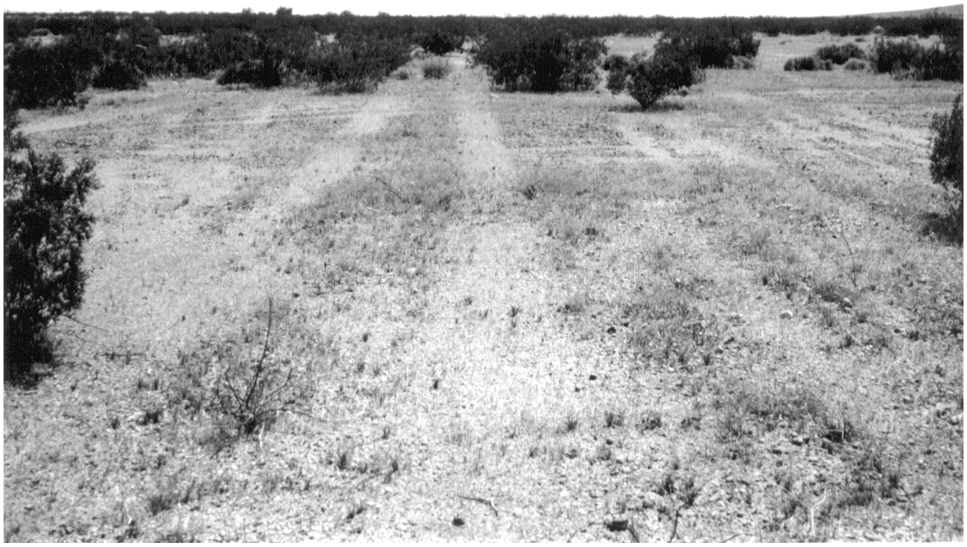


Figure 14. Patton tracks where they modified annual and herbaceous perennial plant growth in Ward Valley.

tracks are: (1) decreases in cover and density occurred in the annuals *Chaenactis fremontii* and *Pectocarya platycarpa*, and (2) increases in density (but not always cover) were measured for *Plantago insularis*, *Erioneuron pulchellus* and the herbaceous perennials *Euphorbia polycarpa* and *Tridens pulchellus*.

Cryptobiotic crusts

At Camp Granite, tanks had a significant effect on cryptobiotic crust growth (Table 6). Well-developed crusts are black and grey in color and grow on hummocky, delicate soil pedicels of silt and clay. In tank tracks, the crust is mostly flat and light grey in color, which combines with an increased percentage of gravel and bare ground patches to make the tracks highly visible (Figure 15).

In undisturbed soils, pedicelled crusts are the dominant intershrub feature at Camp Granite, and they occupy 38% of the ground surface. In Patton tank tracks, pedicelled crusts occupy only 19% of the surface, a 50% reduction. The dominant surface feature in Patton tracks is bare ground (30%), followed by gravel (24%), flat crust (18%), and annuals (6%). A similar trend was measured in Desert Strike tracks, though there was a higher percentage of flat crust (25%) and less gravel (24%) compared to Patton tracks.

At Camp Granite, the upper layer of unconsolidated silt underneath well-developed crusts had an average thickness of 51 mm. Underneath Patton and Desert Strike tracks, it was only 29 mm and 17 mm thick, respectively. In the highly compacted tank parking lot of the camp, the silt layer was only 11 mm thick. There, raised and flat crusts combined occupied only 17% of the intershrub surface, and bare ground and gravel occupied the remainder.

DISCUSSION

Pavement surfaces with a range of mean clast sizes had significantly finer-grained clasts in tank tracks than on undisturbed surfaces. At all but one site (Clipper Valley), there were no significant differences in clast size means between 40-year-old Patton and 20-year-old Desert Strike tracks, despite a twenty year difference in age. Nor was the mean clast size in Patton tracks significantly different than the clast size in centuries-old intaglio figures. These results suggest that pavement surfaces disturbed by tanks are reworked within two decades by wind and runoff, which blow and wash finer-grained gravels into the tracks. This new surface,

Table 6. Cryptobiotic crust percent cover in and out of tank tracks, Camp Granite.

SITE	PERCENT COVER OF GROUND COVER COMPONENTS					
	UNDISTURBED		DESERT STRIKE		PATTON	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Pedicelled crust	38.0	15.4	17.6	11.1	18.7	12.0
Flat crust	19.8	14.3	25.2	13.5	17.5	12.9
Plants	5.6	5.5	3.1	2.8	5.6	5.5
Gravel	21.7	10.6	20.6	10.0	24.1	13.8
Bare ground	8.1	6.4	27.5	20.4	29.9	18.8

which has a markedly finer clast-size distribution than the original surface, itself becomes very stable. Continued recovery of this new surface to a pre-disturbance state is dependent upon pavement formation processes that must move larger stones into disturbed zones to mask the disturbance.

Pavement formation involves one or more processes of surface deflation, erosion of fine-grained material, upward migration of stones from lower soil layers, and colluviation of clasts from topographic highs into depressions (Springer, 1958; Cooke, 1970; Ritter, 1986; McFadden *et al.*, 1987). Pavements in the Mojave Desert took many thousands of year to develop and have remained stable since their formation in Pleistocene times (Bull, 1974; Wells *et al.*, 1985, 1995). Pleistocene pavements have also been cited as a relic of a wetter climate, forming under conditions that do not presently exist (Wells *et al.*, 1995). Therefore, present-day geomorphic processes are probably not capable of reworking tracked surfaces to pre-disturbance conditions, and it will require a climatic shift to wetter conditions to initiate surficial processes that are vigorous enough to heal the disturbances.

Varnish development on the gravel and stones within tank tracks is another process that may mask the scars over time. However, there was no discernible varnish development on stones within tank tracks or centuries-old intaglios. Engel and Sharp (1958) reported that a scraped roadbed in Death valley developed a varnished stone surface like that of the original pavement after 25 years, but this anonymously fast varnish regeneration rate was found to be in error by Elvidge (1982). Archaeological evidence shows that varnish formation on pavement stones is an exceedingly slow process, taking as long as 3,000-5,000 years to form a visible veneer and 10,000 to form dark coatings (Clements and Clements, 1953; Hunt and Mabey, 1966; Hayden, 1976). Varnish re-development will therefore not be a factor in the recovery of tank tracks on pavement surfaces.

The finer-grained, brighter surfaces in tank tracks yield higher reflectance values than the original pavement. Changes in reflectance can have implications for desert flora and fauna, since reflectance affects the temperature of the soil and air at ground level (Belnap, 1995). Small desert animals burrow under surface stones, and changes in surficial stone structure and soil microclimate may directly affect their survival (Larmuth, 1978).

On a macro scale, sustained military maneuvers destroy large areas of pavement surfaces, eliminating dark varnished stones and exposing light colored, finer-grained materials over hundreds of acres. At the Fort Irwin and Twenty Nine Palms Marine Corps training bases in the Mojave Desert, where year-round maneuvers have been taking place for many years, highly degraded maneuver areas occupy entire valleys and their brighter appearance is plainly observed in satellite images. The extent to which these impacts have affected the albedo of the bases, and in turn the flora and fauna, may be substantial but has not been assessed.

Soil compaction in Holocene-aged soils persists at significant levels in both Patton and Desert Strike tank tracks, as shown by recording penetrometer, bulk density, and infiltration measurements. Similar levels of compaction were found in Patton tank tracks at numerous Mojave Desert sites (Prose, 1985). As in the Prose (1985)

Figure 15. Desert Strike tracks where they traverse cryptobiotic crust at Camp Granite.

study, penetrometer measurements in this study showed greater levels of compaction than did bulk density. Bulk density is not considered as sensitive an indicator of soil compaction as penetrometer resistance (Voorhees *et al.*, 1978), but the method is useful because it provides results where extreme compaction prevents the use of the recording penetrometer. The method is also valuable for analyzing soil-plant interactions and for comparing results with those of other researchers who used bulk density to measure compaction.

Patton era tank tracks are more compacted than Desert Strike tracks at two of three sites, despite being 20 years older and thus having had more time to be loosened. One reason for this finding could be tank design. The World War II era M3 and M4 tanks were lighter but exerted a greater static load to the soil, 0.95 bars, than the M60 tanks used in 1964, 0.78 bars, due to narrower treads on the M3 and M4. On the other hand, the much heavier M60 tank exerted greater shear stress to the soil as it moved, and shear stress can cause soil density to increase by one-third that caused by normal (static) stress alone (Bodman and Rubin, 1948; Taylor and Vandenberg, 1966). Soil-vehicle relationships are complex even for a vehicle at rest (Garber and Wong, 1981), let alone for a tank bouncing across rough desert terrain during maneuvers.

Another factor that may have caused compaction to be greater in the older Patton tracks is soil moisture content at the time of impact (Soane *et al.*, 1980). Soils may have been wet when some of the Patton tracks were produced in the 1940's, since maneuvers took place year-round for a two-year period. Wet soils would have produced greater soil compaction than if soils were dry (Adams *et al.*, 1982; Webb, 1982). Soils were dry when Desert Strike tracks were produced in 1964, as no rain fell during and several weeks before the maneuvers.

In a study that demonstrates the effect of moisture content on compaction of desert soils by off-road vehicles, Adams *et al.* (1982) measured compaction caused by a four-wheel drive Ford Bronco truck when soils were both wet and dry. When soils were wet at the time of impact, compaction caused by a single truck pass reached levels comparable to those measured in Patton and Desert Strike tank tracks. Five or more truck passes on dry soils were required to reach these same levels of compaction. It is interesting to note that a four-wheel pickup truck can have a standing ground pressure up to four times greater than that of a Patton era M3 or M4 tank, because a tank's long, wide treads distribute the vehicle's weight over a much larger area than the four tires of a truck. A truck, then, may produce greater compaction of the soil than a tank when the vehicles are standing still.

Regardless of whether soils were dry or wet at the time of impact, the results of this study show that compaction caused by tanks remains significant for at least four decades. It is not known how much loosening of the soil occurred since impact, and how much longer it will take for soils to recover fully, because the level of compaction produced at the time of impact is unknown. Controlled studies that measure the amount of compaction caused by military tanks at the time of impact would help resolve this question. Nonetheless, compaction levels are not widely different between 40-year-old Patton era tracks, 20-year-old Desert Strike tracks, and fresh truck tracks, indicating that Mojave Desert soils undergo little recovery from compaction in 40 years and will remain significantly compacted for many more decades, and probably for centuries.

Soil compaction in tanks tracks has caused a lowering of water infiltration rates at the three sites where infiltration was measured. Increases in soil bulk density come at the expense of the destruction of large pores, which results in lower infiltration rates because infiltration is dependent on the presence and interconnectedness of these pores (Iverson *et al.*, 1981; Webb, 1982). The high degree of variability in infiltration measurements is typical for layered, gravelly desert soils, which often have a more complex interstitial pore space structure than homogenous, loamy soils found in more temperate regions (Eckert *et al.*, 1979; Webb, 1982; Liddle, 1997). The process of infiltrometer ring emplacement may also affect the variability of measurements (Webb, written communication, 2000).

A reduction in infiltration rates has implications for the erodability of the soil, especially on sloping terrain (Iverson, 1980; Webb and Wilshire, 1983). Normally infiltration rates of Mojave Desert soils are so high that surface runoff, and subsequent soil erosion, only occurs on the order of decades (Iverson *et al.*, 1981). Compaction greatly accelerates this process. In compacted off-road vehicle trails, Hinckley *et al.* (1983) found that erosion rates were increased by 10 to 20 times over natural rates. Accelerated soil erosion has not been studied on desert lands used for military maneuvers, but the abundance of eroded scars in Patton and Desert Strike tank tracks throughout the former maneuver areas indicates that erosion is a significant by-product of military maneuvers in desert terrain.

Soil compaction appears to play a major role in preventing intershrub flora from returning to pre-disturbance conditions in tank tracks. Overall annual and herbaceous perennial plant density is substantially increased in tank tracks, compared to undisturbed soils, while cover has decreased. It appears that plants can take hold relatively easily in the tank tracks because of the presence of a thin layer of loose, wind-blown sand built up in the tracks' depression. Once established though, the roots of the plants may have a difficult time penetrating the extremely compacted soil beneath the loose top layer, which possibly restricts the size of individual plants.

The results of this study are consistent with those found in a controlled study of the effects of compaction by off-road vehicle travel in the Mojave Desert (Adams *et al.*, 1982). Annual cover was reduced in that study, but not density, in as little as one pass of a truck and 20 passes of a motorcycle on loamy sands. They attribute these changes to soil compaction. Compaction was also cited as the primary cause of reductions in the growth of desert annuals in a separate off-road vehicle study in the Mojave Desert (U.S. Bureau of Land Management, 1980).

Not only are plant density and cover altered by soil compaction, but individual species respond to compaction in different ways. Of particular interest in this study are the responses of common annual species such as *Chaenactis fremontii*, *Plantago insularis*, and the grass species *Tridens pulchellus* at Ward Valley and *Erioneuron pulchellus* at Skeleton Pass. *Chaenactis* generally experienced large reductions in density and cover in tank tracks, whereas the grass species had large increases in density. Similar results were presented in Adams *et al.* (1982), where *Chaenactis* was reduced in cover and density in off-road vehicle tracks, while a non-native grass species, *Schismus barbatus*, increased in cover and density. *Chaenactis* is a relatively large annual with a long taproot, and it cannot penetrate compacted soils easily, whereas species with fibrous, laterally-spreading root systems, such as grasses, are better able to adapt (Adams *et al.*, 1982).

Plantago insularis was found to be the most abundant species in terms of density, both in and out of tank tracks. In tank tracks, its density increased markedly compared to undisturbed areas but its cover was similar because of the smaller size of individual plants, indicating that *Plantago* adapts well to compacted soils. This annual is common throughout the desert and it is very hardy, able to survive when other species die out under stressful conditions (Tevis, 1958a, b).

Another important component of the intershrub flora — cryptobiotic crust — was significantly altered in Patton and Desert Strike tank tracks at Camp Granite. There was a substantial reduction in cover of the black, pedicelled portion of the crust in the tracks. The mature, pedicelled crust is associated with a sufficiently deep and loose, silty A horizon that permits cyanobacterial sheath materials to accumulate and support the growth of lichen and moss, whereas the flat, light-grey crust growing in tank tracks is an immature one that lacks many of the lichen and cyanobacteria species of a fully-developed crust (Campbell *et al.*, 1989; Belnap, 1995).

The silt layer under the crust, which is approximately 50 mm thick at Camp Granite, is comprised of wind and water borne deposits that formed with the aid of cryptobiotic crusts over many centuries of surface aggradation and degradation (Wilshire, 1983). Off-road vehicles such as tanks easily break up and flatten the pedicelled crusts and expose the underlying silty soils to sheet erosion, which quickly washes away the fine materials and leaves a smooth, compacted layer that is difficult for crusts to grow in (Wilshire, 1983; Belnap *et al.*, 1994; Belnap, 1995). It probably will not be possible for the crusts in tank tracks to re-develop to full maturity until a silty A horizon accumulates to sufficient thickness to permit the formation of soil pedicels.

The intershrub areas in general are harsh microhabitats for crusts to live in, compared to the space underneath shrubs, and several species of lichen have recovered only 3-6% in Patton tracks in the intershrub spaces after 55 years, with full recovery estimated to require almost 2,000 years (J. Belnap, written communication, 1999).

Since cryptobiotic crusts are a vital part of the desert flora where they occur, modifications to them have consequences for the rest of the ecosystem (Wilshire, 1983; Evans and Ehlringer, 1993; Belnap, 1995). Reductions in developed crust cover expose the surface to increased erosion, which removes organic matter, nutrients, and microbial populations. Crusts are important sources of nitrogen and fixed carbon in the desert and disturbance to crusts leads to reductions in these nutrients, which adversely affects the seedling establishment and survival of some vascular plant species (Maryland and McIntosh, 1966; Harper and Pendleton, 1993; Belnap *et al.*, 1994; Belnap and Harper, 1995).

CONCLUSION

This report documents the long-lasting nature of some of the disturbances to Mojave Desert soils and vegetation caused by military vehicles. How long will these disturbances persist before natural processes heal them? This question has increasing significance because of the rapidly rising demand to use the arid lands of the southwest U.S. for expanded military maneuvers and related temporary, non-military activities. Year-round military training maneuvers can put enormous pressures on arid lands, degrading them to the point where surfaces become stripped of stable pavements and protective vegetation, exposing them to rapid erosion and the chronic generation of dust, which interfere with training operations (U.S. Bureau of Land Management, 1996).

Another activity that degrades large areas of desert land in much the same way as military maneuvers is off-road vehicle recreation. This land use is expanding rapidly throughout the American deserts and is impacting some of the most remote corners of public lands.

There are other human activities occurring in the desert that are temporary in nature and that create long-lasting disturbances to the land, particularly activities that involve the construction of dirt roads that are eventually abandoned. These land uses include prospecting for and extracting resources such as oil, gas, and other minerals, and the construction of pipelines and transmission tower corridors that traverse desert lands. The soils of abandoned roads will remain highly compacted and hostile environments for desert vegetation for centuries if left to recover by natural processes

(Webb *et al.*, 1988). Rehabilitation of roads immediately after abandonment is logistically feasible and will reduce the amount of time required for recovery, but the rehabilitation of arid lands is a relatively new and expensive enterprise with no guarantee of success (Bainbridge *et al.*, 1995a, b).

Rehabilitation of large expanses of desert land degraded by recurring military maneuvers and off-road vehicle recreation is an exceedingly expensive, unlikely proposition (Lovich and Bainbridge, 1999). Most abandoned areas will be left to recover by natural processes. For disturbed pavement surfaces, the climatic conditions necessary to re-generate a new pavement ceased to exist at the close of the last Ice Age some 11,000 years ago (Wells *et al.*, 1995). The current Holocene climate will probably have to change to a wetter one to eliminate disturbances on pavements; therefore, disturbances created by tanks and other off-road vehicles can be considered to be permanent.

From the results of this study it is difficult to estimate the length of time required for Holocene-aged soils to recover from soil compaction caused by military maneuvers, since the level of compaction created at the time of impact is unknown. Little recovery seems to have occurred in four decades, though other researchers have found that compacted Mojave Desert soils are capable of being loosened over time. Recovery estimates are highly variable, ranging from 70 to 680 years, and are dependent on the severity of compaction and the vigor of natural processes that operate locally to alleviate compaction (Webb *et al.*, 1986). The main processes operating in desert lands are: repeated wetting and drying of soils, expansion of clay particles in the soil, seasonal freezing and thawing, and biological activity in the soil (Webb *et al.*, 1986, 1988). The sites in this study were all located in the low, dry, sparsely-vegetated valleys of the Mojave Desert, where compaction alleviation processes are the least vigorous, so recovery of these soils from compaction is probably on the order of centuries. Recovery of the intershrub plants and cryptobiotic crusts is closely linked to recovery of soils from compaction and can be also be expected to take centuries.

This study only assessed impacts caused by a single pass of a tank, but the larger scars of multiple passes of tanks and other military off-road vehicles are common throughout the former maneuver areas. Disturbances to soils and vegetation are much more severe in those areas and recovery will be much slower.

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