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Recovery of Severely Compacted Soils in the Mojave Desert, California, USA

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Often as a result of large-scale military maneuvers in the past, many soils in the Mojave Desert are highly vulnerable to soil compaction, particularly when wet. Previous studies indicate that natural recovery of severely compacted desert soils is extremely slow, and some researchers have suggested that subsurface compaction may not recover. Poorly sorted soils, particularly those with a loamy sand texture, are most vulnerable to soil compaction, and these soils are the most common in alluvial fans of the Mojave Desert. Recovery of compacted soil is expected to vary as a function of precipitation amounts, wetting-and-drying cycles, freeze-thaw cycles, and bioturbation, particularly root growth. Compaction recovery, as estimated using penetration depth and bulk density, was measured at 19 sites with 32 site-time combinations, including the former World War II Army sites of Camps Ibis, Granite, Iron Mountain, Clipper, and Essex. Although compaction at these sites was caused by a wide variety of forces, ranging from human trampling to tank traffic, the data do not allow segregation of differences in recovery rates for different compaction forces. The recovery rate appears to be logarithmic, with the highest rate of change occurring in the first few decades following abandonment. Some higher-elevation sites have completely recovered from soil compaction after 70 years. Using a linear model of recovery, the full recovery time ranges from 92 to 100 years; using a logarithmic model, which asymptotically approaches full recovery, the time required for 85% recovery ranges from 105–124 years.

Keywords desert soils, disturbance recovery, military effects, soil bulk density, penetration resistance

Severe soil compaction results from various land uses in the Mojave Desert (Lovich & Bainbridge, 1999), particularly military exercises involving widespread vehicle use (Prose & Wilshire, 2000). Training exercises cause considerable ecosystem disruption (Krzysik, 1985), and management of military lands is a major concern of the U.S. Department of Defense. The disturbance legacy of military exercises during World War II and in 1964 is still evident in the Mojave Desert (Prose, 1985; Prose & Metzger, 1985; Steiger & Webb, 2000), with individual tank tracks still visible 50–60 years after the original disturbance (Prose & Wilshire, 2000; Belnap & Warren, 2002). Active rehabilitation of severely compacted soils is expensive and usually

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requires ripping with heavy equipment. As a result, most sites with severely compacted soils typically are abandoned without active restoration.

Other land uses that may significantly compact desert soils include off-road vehicle (ORV) use, livestock grazing, and construction of utility corridors. Off-road vehicles cause significant compaction with as few as 1 to 10 passes (Davidson & Fox, 1974; Vollmer et al., 1976; Wilshire & Nakata, 1976; Webb, 1982, 1983). As noted by Prose & Wilshire (2000), compaction under recreational vehicles may be greater than under tracked vehicles, such as tanks, owing to the higher ground pressures under conventional tires. Grazing by domestic livestock causes severe compaction, which can be especially high near watering areas (Webb & Stielstra, 1979). Heavy vehicles compact soils in right-of-ways and access roads during the construction of utility corridors (Vasek et al., 1975a,b).

Abandoned military camps and mining towns with minimal subsequent disturbance provide evidence documenting the recovery rates of severely compacted soils in the Mojave Desert (Webb & Wilshire, 1980; Prose & Metzger, 1985; Webb et al., 1988; Knapp, 1992; Prose & Wilshire, 2000). This study examines compaction recovery in military training camps, built during World War II in the Mojave and Sonoran Deserts in response to anticipated desert warfare in North Africa and then abandoned in 1944, and ghost towns, built in the late nineteenth and early twentieth century in response to discovery of precious-metal ore bodies, and abandoned when ores could not be profitably mined or production ceased in the early 1900s. The purpose of this study is to provide quantitative estimates of the natural recovery of severely compacted soils in the Mojave Desert, updating and expanding on the work of Webb et al. (1986) and Webb & Thomas (in press). The results provide land managers with information to make a choice between expensive restoration measures and a ''leave-alone'' strategy of ecosystem restoration.

The Compaction Process

Effects of Soil Compaction

Soil compaction has significant effects on ecosystem restoration following severe disturbances. Roads are a major source of fugitive dust (Campbell, 1972), and water erosion can be 10–20 times higher on slopes (Iverson, 1980; Iverson et al., 1981). Because soil compaction significantly reduces infiltration rates, recovery of compacted soil is of primary concern to erosion control. Soil compaction may retard the establishment of desert plants (Adams et al., 1982; Prose et al., 1987; Webb et al., 1988; Prose & Wilshire, 2000). Revegetation of abandoned sites is slow (Webb & Wilshire, 1980; Webb et al., 1988), but significant recovery can occur in as little as a half century, and the role of residual compaction in the recovery of perennial vegetation is unclear (Webb et al., 1988).

Vulnerability of Soils to Compaction

Soil compaction is, by definition, the decrease in pore volume within a soil mass, resulting in an increase in bulk density (Johnson & Sallberg, 1960). The density increase caused by soil compaction changes other soil properties, most notably the size distribution and continuity of pores and strength characteristics. Decreases in the sizes of pores, particularly macropores, decreases infiltration rates but may increase water-holding capacity, depending on the amount of compaction and the soil particle-size distribution. Increases in soil strength affect root elongation and propagation into compacted soils, which may affect seedling establishment and restoration of vegetation cover. Subsequent growth rates of plants may also be limited because the compaction may limit access to both water and nutrients. In seasonally inundated soils (e.g., playas), compaction can also affect plant growth by reducing oxygen availability to roots.

In its simplest sense, compaction results from the application of normal stress to the soil surface. In reality, vehicles impart a complex, three-dimensional stress field on soil, resulting in a normal stress that compacts soil but also in shear stresses that cause dilation of soil (Webb, 1982). Depending upon the magnitude of the normal stress, compaction typically occurs between 0.05 and 0.30 m depth, with dilation occurring at very shallow depths. Most heavily-used dirt roads have a thin, loose layer of soil over a densely compacted layer, which complicates measurement of the amount of compaction. Most laboratory compaction tests, which attempt to eliminate shear while applying normal stress, cannot account for this complexity, creating a dichotomy in the interpretation of some analyses.

The amount of compaction that a soil can sustain is a function of particle-size distribution, structure, and water content at the time of compaction (Webb, 1983). Poorly sorted soils, such as loamy sands and sandy loams, compact more readily than well sorted soils, such as eolian sand or playa surfaces. Gravel may increase compaction over what would occur with the <2 mm fraction alone (Webb, 1983); large amounts of gravel may inhibit compaction, as particle-to-particle contacts in gravel may absorb stress that might otherwise decrease soil unit volume. Soils compact the most when stresses are applied at water contents slightly less than field capacity, the water content that a soil drains to about 24 hours after rainfall (Webb, unpublished data). At low water contents, pore-water pressures are high, increasing the resistance to applied pressure (Greacen, 1960). At water contents near saturation, volume decreases can be attained only by removal of water, and, therefore, the rate of drainage while pressure is applied is an over-riding consideration. Poorly drained soils are seldom present in desert areas, except in some playas and riparian areas.

Bulk density is difficult to measure in gravelly soils typical of the Mojave Desert. Infiltration rates and soil strength are sensitive indicators of soil compaction, prompting some researchers (Prose, 1985) to prefer these measurements to the more fundamental property of bulk density. Soil strength, typically measured with a penetrometer, is strongly dependent on water content (Greacen, 1960), and water content should be reported for all penetration-resistance data to allow comparability with other studies.

Processes of Recovery from Soil Compaction

Amelioration of soil compaction is a complex process, and several factors affect the recovery rate. Water erosion, which may accelerate in compacted soils on slopes, greatly increases the ecosystem recovery time because rates of soil formation in arid regions are extremely slow; however, compacted zones are partially or totally removed from the soil. In contrast, deposition of new eolian or alluvial sediments over a compacted soil, which has occurred in the Patton encampments (Prose & Metzger, 1985), may effectively eliminate compacted soil as a problem for reestablishing plants. The following discussion applies to relatively stable surfaces that are relatively unaffected by accelerated soil erosion or subsequent deposition.

The most important soil factor affecting compaction recovery rates is the magnitude of the increase in bulk density as a function of depth. The magnitude of compaction is very important because some lightly compacted soils may not recover (Heinonen, 1977) or may recover at an imperceptible rate. Highly compacted soils loosen after disturbance ceases, and the recovery rates are faster at the surface than in the subsurface (Thorud & Frissel, 1976) because the surface receives the greatest weathering and environmental extremes. Webb (1982) notes that most compaction occurs at 0.0–0.1 m depths in desert soils.

Compaction amelioration results from clay-mineral expansion during wetting-and-drying, freeze-thaw heaving, and bioturbation. Clay-mineral expansion, or shrink-swell, is most prevalent in soils containing expansive clays such as smectite. The rate of loosening is dependent on the clay content, clay mineralogy, the depth of water penetration, the frequency of wetting and drying cycles, and the depth of the compaction in the soil. In areas with winter-dominated precipitation and cool weather, the frequency of wetting-and-drying cycles is relatively low because the soil tends to remain moist throughout the winter and early spring. However, soils in areas with a summer-dominated rainfall have frequent wetting-and-drying cycles as a result of recurring thunderstorms and subsequent hot weather.

Freeze-thaw cycles reduce compaction in regions where severe freezing occurs (Orr, 1975), although the loosening may occur only above 0.2 m (Blake et al., 1976; Larson & Allmaras, 1971; van Ouwerkerk, 1968). The effectiveness of freeze-thaw loosening depends on soil-water content, texture, rate of frost penetration, and depth of compaction. Frost-heaving effects are inseparable from wetting and drying because the freezing of water in the soil includes a desiccation of clay minerals (Larson & Allmaras, 1971). Freeze-thaw loosening may be most effective in deserts with cold winters (e.g., Great Basin Desert), as opposed to deserts that experience only periodic frost (e.g., Sonoran Desert).

In a laboratory experiment, Akram & Kemper (1979) applied both wetting-and-drying and freeze-thaw cycles to compacted soils with textures ranging from silty clay to loamy sand. They found that most of the change in infiltration rate, which is indicative of soil compaction, occurred during the first three cycles although the resulting infiltration rates were still below the undisturbed rates. The data of Akram & Kemper (1979) indicate that an exponential-decay model may be appropriate in empirically describing compaction amelioration. Both freeze-thaw and wetting-and-drying cycles were most effective in clay-rich soils; compacted loamy sand changed little during four cycles.

Bioturbation may be more important than physical processes in loosening compacted, coarse-grained desert soils. Rodent-burrowing activity is very important, especially at depth, although reestablishment of animal populations may be dependent on the rate of plant succession. Roots penetrating the soil cause volume expansion near the soil surface (Larson & Allmaras, 1971), and small channels left in the soil after the root dies create macroporosity. Soil loosening is most effective by plants with diffuse root systems, as opposed to plants with central taproots, because the small diffuse roots displace less of the high-strength, compacted soil per root while penetrating the soil with more roots per unit volume. Agricultural studies that indicate monocots, usually annuals and perennial grasses, may have a greater ability to colonize compacted soils than dicots (Lathrop & Rowlands, 1983). Annuals with diffuse root systems would loosen soil only over a small depth range, however, without affecting compaction at depths greater than 0.1 m. Annual monocots are usually the first to colonize compacted soils in the Mojave Desert (Lathrop & Rowlands, 1983; Prose & Wilshire, 2000).

In regions of greater than 500 mm yr^{-1} of rainfall and frequent freeze-thaw cycling, estimates of recovery time range from less than 10 years to 84 years, depending on the various factors that affect compaction recovery (Webb & Thomas, 2001). In the Mojave Desert, one study suggests a high variability in the recovery times for compacted soils, positing that recovery below a depth of 0.3 m may be much slower than at shallower depths (Prose & Wilshire, 2000), if at all. Bolling & Walker (2000) concluded that spatial heterogeneity in abandoned roads in southern Nevada obscured any significant recovery trends, but their study site included lumped measurements over a complicated array of geomorphic surfaces, which may respond differently to both the initial disturbance and subsequent recovery. Webb et al. (1986) concluded that compaction recovery in the Mojave Desert requires 80–140 years. Knapp (1992) similarly concluded that complete recovery from compaction requires 100–130 years in ghost towns in the northern Great Basin Desert. Both studies assumed that a linear-recovery model is an appropriate empirical description of compaction recovery and concluded that compaction amelioration is faster at higher-elevation sites where freeze-thaw and wetting-and-drying cycles are frequent.

Methods

Measurements of compaction recovery were made in 19 sites in the Mojave Desert with 32 site-time combinations (Figure 1, Table 1). The sites included the five abandoned World War II sites of Camps Ibis, Granite, Iron Mountain, Clipper, and Essex described by Howard (1985) and Bischoff (2000). Soil compaction in these sites was originally measured by Prose & Metzger (1985). In addition, soil compaction was measured in seven ghost towns and another more recently

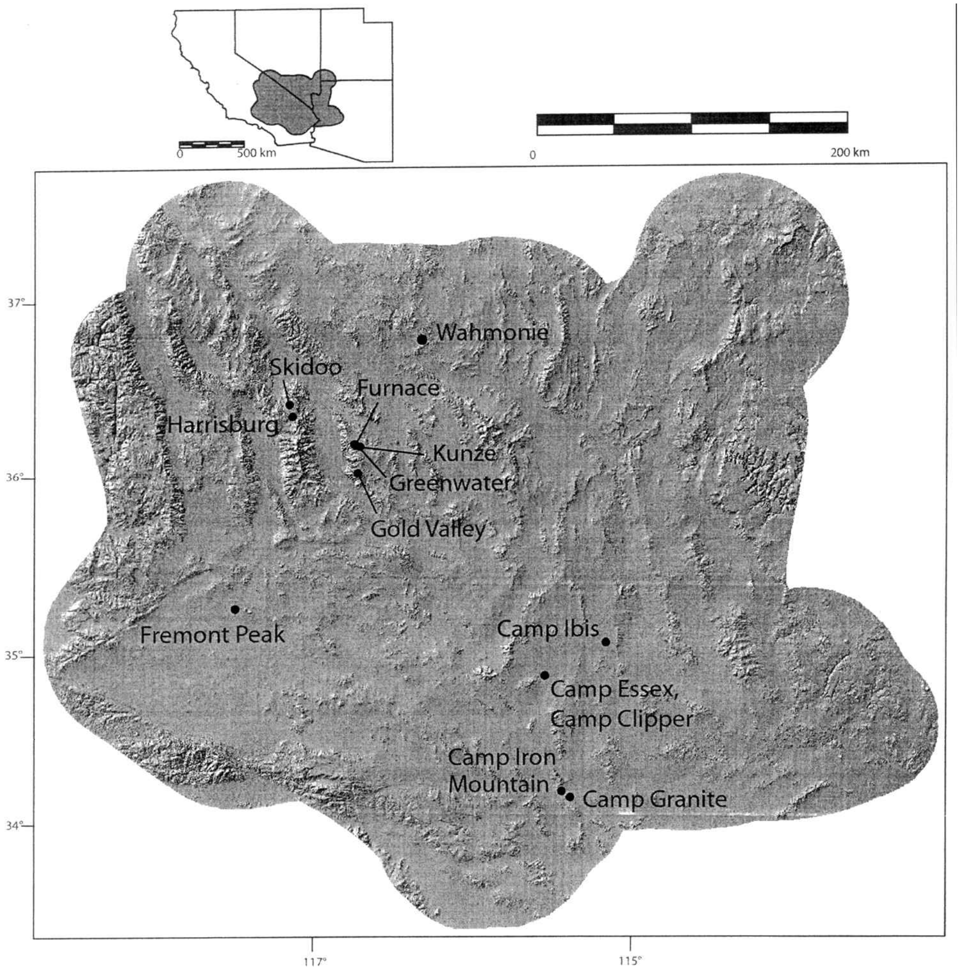

FIGURE 1 Shaded relief map of the Mojave Desert showing the locations of compaction-recovery sites.

TABLE 1 Characteristics of Disturbed Sites Reported in this Study

Site	Subsite	Elevation (m)	Age of geomorphic surface[1]	Year abandoned	Year(s) compaction measured
Fremont Peak	200 pass	893	Holocene	1979	1980, 1999
Camp Iron Mountain[2]	parking lot	388	Holocene	1944	1984, 2000
Camp Granite[2]	parking lot	367	Holocene	1944	1984
Camp Clipper[3]	parking lot	571	Holocene	1944	1984
Camp Essex[3]	parking lot	571	late Holocene	1944	1984, 2000
Camp Ibis[2]	parking lot	550	late Pleistocene	1944	1984
Gold Valley	west	1310	latest Pleistocene	1908	1982, 1999
Wahmonie	old road	1320	latest Pleistocene	1960	1978, 1999
Wahmonie	townsite	1320	latest Pleistocene	1928	1978, 1999
Greenwater	Road	1340	Holocene	1907	1981, 1998
Greenwater	site C	1340	late Pleistocene	1907	1981, 1998
Greenwater	site G	1340	late Pleistocene	1907	1981, 1998
Furnace	Road	1430	latest Pleistocene	1985?	1998
Furnace	Main Street	1430	latest Pleistocene	1907	1981, 1998
Kunze	townsite	1430	Holocene	1906	1998
Harrisburg	townsite	1640	middle Holocene	1907	1985, 1999
Skidoo	Downtown	1730	early Holocene	1916	1981, 1999
Skidoo	Montgomery Street	1730	early Holocene	1907	1981, 1999
Skidoo	Old road	1740	early Holocene	1916	1981, 1999

[1] Ages of geomorphic surfaces from Webb and others (1988) or inferred from a combination of Prose and Metzger (1985) soil data and site inspection.

[2] Desert Training Center – Patton encampment originally studied by Prose and Metzger (1985).

[3] Bishoff (2000). Prose and Metzger (1985) refer to these camps variously as "Camp Clipper old" (=Camp Clipper) and "Camp new Clipper" and "Camp Clipper new" (=Camp Essex).

abandoned site with known dates of abandonment (Table 1). The townsites are Harrisburg and Skidoo in the Panamint Mountains of Death Valley National Park; Gold Valley, Furnace, Kunze, and Greenwater in the Black Mountains of Death Valley National Park; and Wahmonie on the Nevada Test Site in southern Nevada (Webb & Wilshire, 1980; Webb et al., 1988). The Fremont Peak site in the western Mojave Desert was originally used to study compaction under motorcycle traffic (Webb, 1982).

Dates of abandonment and other site-specific information are given in Webb & Wilshire (1980), Webb et al. (1983, 1988), and Prose & Metzger (1985) and are repeated in Table 1. The recovery times, or the elapsed time between abandonment and measurement, ranged from 1 to 91 years. Visitation to these sites is light, with the highest visitation at the World War II encampments owing to roadside markers. None of the camps or townsites were recently grazed by domestic livestock; although sheep herds once grazed seasonally near Fremont Peak, no evidence of livestock use during the 20 years of abandonment was observed. Feral burros grazed lightly at Skidoo and Harrisburg before their removal in the mid-1980s. Although wild horse herds roam parts of the Nevada Test Site, no evidence remains of their presence at Wahmonie.

Annual precipitation at the World War II encampments probably ranges from 100 to 150 mm with less than five days yr^{-1} with freezing temperatures. Annual precipitation at the ghost towns ranges from about 150 to 185 mm, with mean January temperatures ranging from 3.9°C at low elevations to 1.1°C at high elevations (Webb et al., 1986). The number of days yr^{-1} with freezing temperatures is difficult to estimate for these sites, but nearby climate stations at about the same elevations have 50 to 75 freezing days yr^{-1}. Therefore, comparison of compaction recovery in the World War II encampments with ghost towns may yield information on the efficacy of wetting-and-drying and freeze-thaw loosening.

All of the soils studied were Entisols or Aridisols, depending upon age of geomorphic surface (Table 1), in the suborders Torrifluvents and Orthids (Soil Survey Staff, 1975). Ages of geomorphic surfaces are presented in Webb and Colleagues (1988) or were inferred from descriptions given in Prose & Metzger (1985). None of the undisturbed soils studied had significant desert pavements or A_v horizons. Soil textures at depths of 0 to 0.1 m varied from sandy loam in granitic soils, to gravelly loamy sand, to sandy loam on volcanic substrate. The gravel content ranges from 4 to 32%, and sand contents ranged from 52 to 86%, indicating that these soils are poorly sorted and typical of common Mojave Desert soils. Clay content is between 3 and 6% in all soils studied (Table 2).

Laboratory Measurements

Bulk soil samples were collected from 0–6 cm depth at all sites except Camp Clipper, which was on the same geomorphic surface as Camp Essex. Proctor compaction curves (Felt, 1965) were run on each sample using the standard method as specified in the ASTM standards (ASTM D 698-91). A minimum of four water contents were analyzed, with some samples requiring 6–8 points for adequate representation of the relation between water content and maximum bulk density.

Field Measurements

Subsites were selected to represent highly compacted areas abandoned and allowed to recover naturally with little subsequent disturbance (Table 1). At all subsites, undisturbed (control), abandoned, and active road sites were chosen for measurement to allow estimation of an indexed recovery percentage.

TABLE 2 Physical Properties of Sites Reported in this Study

Site	Particle size distribution[1]				Undisturbed bulk density[3] (Mg m^{-3})	Maximum bulk density[4] (Mg m^{-3})	Bulk density in active road (Mg m^{-3})	Water content[5] (kg kg^{-1})
	Gravel (%)	Sand (%)	Silt (%)	Clay (%)				
Camp Clipper[2]	4	82	8	6	1.55	1.88	1.81	0.008
Camp Iron Mountain	22.2	71.8	4.2	1.8	1.68	1.98	1.93	0.003
Camp Granite[6]	26.8	52.1	18.9	2.2	1.54	1.87	n.m.	0.004
Camp Essex	10.0	76.6	7.9	5.5	1.57	1.88	1.81	0.007
Camp Ibis[6]	8.8	86.3	4.0	0.9	1.65	2.12	n.m.	0.011
Fremont Peak	8.7	65.3	21.2	4.7	1.46	2.07	1.79	0.065
Furnace	26.8	63.9	7.9	1.3	n.m.	1.85	n.m.	0.023
Gold Valley	23.1	62.7	13.0	1.2	1.29	1.95	1.49	0.074
Greenwater	31.8	60.0	7.0	1.3	n.m.	1.89	n.m.	0.047
Harrisburg	13.6	65.3	18.8	2.2	1.43	1.99	1.71	0.023
Kunze	24.2	66.7	7.6	1.6	n.m.	1.90	n.m.	0.039
Skidoo	8.1	65.1	24.5	2.3	1.54	1.97	1.72	0.022
Wahmonie	8.0	79.6	10.7	1.7	1.40	1.96	1.60	0.064

[1] Determined using sieve analyses for gravel and sand and hydrometer analyses for silt and clay.
[2] Particle size from Prose and Metzger (1985, p. 66).
[3] For 0–30 mm soil depth.
[4] Determined using laboratory Proctor compaction tests.
[5] Moisture content at the time of penetrometer measurements.
[6] For 0–10 mm soil depth.
n.m., not measured because of high gravel contents.

Penetration depth, a common index of compaction, is the mean depth to which an operator (weight = 85 kg) can push a 30°, 920-mm^2 cone into the soil surface (Wilshire & Nakata, 1976). The normal force exerted on the penetrometer at insertion beyond the cone is 910 kN m^{-2}. Penetration depth is the measurement of compaction that is least sensitive to soil gravel content (Webb, 1983; Webb et al., 1986), and indexing penetration depth to the active road minimizes the variables of operator weight and water content. For each treatment, 70 penetration depths were averaged. Penetration depth was measured in townsites, undisturbed soil, and active roads at 19 sites over several years to form 31 estimates of compaction recovery.

Soil bulk density in the 0–60 mm depth was measured using a 57-mm diameter coring device designed to collect intact samples. The recovered soil was dried in a drying oven at about 60°C for 48 h; the lower temperatures were used to minimize ''baking'' of clay minerals and a loss of structural water from clay minerals. At each site, 10 bulk density samples each were collected from active roads, the abandoned areas, and undisturbed areas. I include bulk density measurements taken by Prose and Metzger (1985), who sampled a slightly deeper depth range of 0–100 mm. Because Prose and Metzger (1985) did not collect samples from active roads, the maximum bulk density measured using the Proctor test was substituted for this value at camps not measured in 2000, and the active road bulk density measured in 2000 was substituted for the active road bulk density in 1984 for sites measured in common (Table 1).

We assumed soils were compacted fully and abandoned with no subsequent disturbance. The index of recovery, I_R, is:

$$I_R = (P_d - P_a)/(P_u - P_a), \tag{1}$$

where P = mean soil parameter (density or penetration depth), P_d = historically disturbed soils, P_u = undisturbed soils, and P_a = soil in active roads (representing high current compaction). The amount of time estimated for full recovery, T_F, is calculated by:

$$T_F = T_R/I_R, \tag{2}$$

where T_R = recovery time (yrs). Indexing of soil properties using Eq. (1) removes the influence of soil-water content at the time of measurement, which is particularly important for penetration depth and allows comparison among sites.

Results

Proctor Compaction Curves

The Proctor compaction analysis indicates that the soils in the World War II camps and ghost towns are highly vulnerable to soil compaction. Maximum bulk densities ranged from 1.85 to 2.12 Mg m^{-3}, and the average difference between the undisturbed bulk densities measured in the field and the maximum densities was 0.456 Mg fm^{-3}. Similarly, the difference between maximum Proctor bulk density and the bulk density in active roads was 0.23 Mg m^{-3}, due at least in part to the zone of dilation on the surface of active roads.

The compaction curves for the World War II encampments (Figure 2a) have important differences from the curves for the ghost towns (Figure 2b). The peak in the compaction curves for the World War II encampments is relatively sharp, and most curves fall off at a water content of about 0.15 kg kg^{-1}, suggesting that the

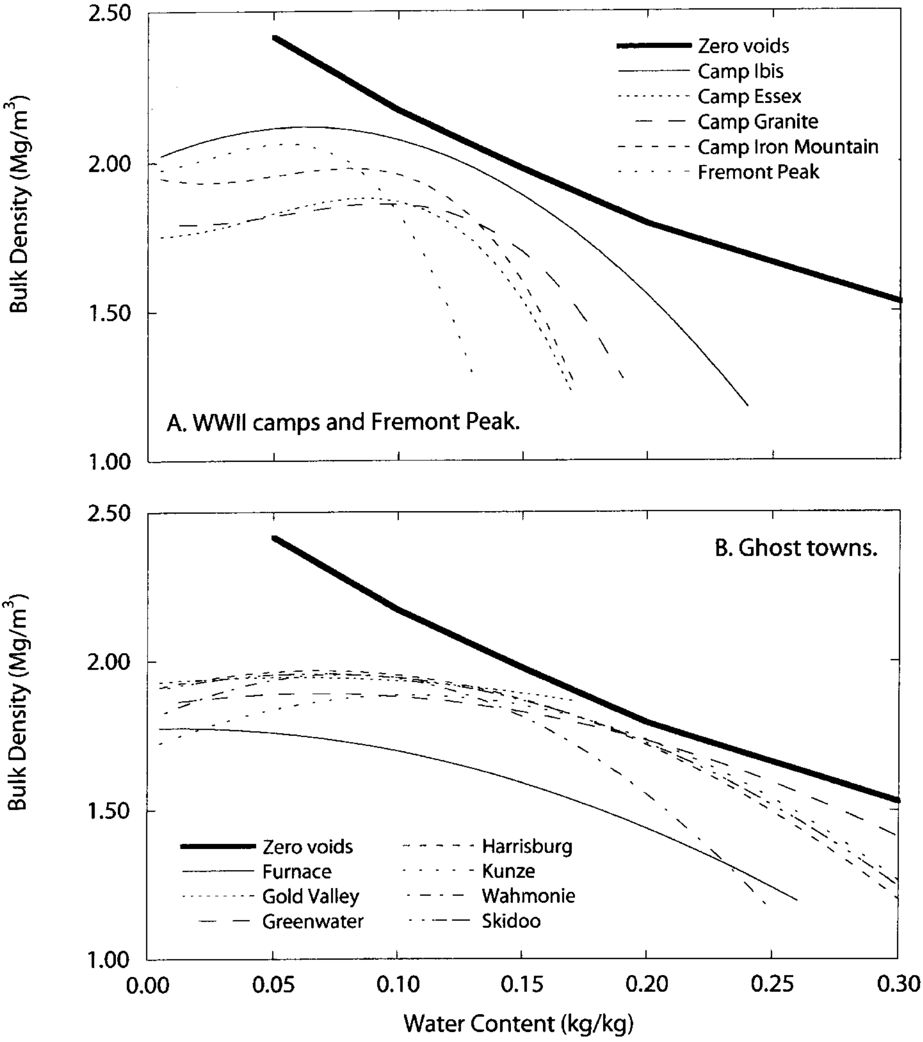

FIGURE 2 Proctor compaction curves for soils at compaction-recovery sites. (A. World War II encampments and the Fremont Peak site. B. Ghost towns.)

water-holding capacity of these soils is relatively low. The compaction curves for the ghost towns are flatter, indicating that compaction vulnerability remains high at higher water contents than for the encampments. The difference may be related to the fact that the soils in the World War II camps are better sorted than the soils in the ghost towns, particularly with respect to the amount of gravel versus sand (Table 2). For the World War II camps, the maximum bulk density occurred at a water content of 0.74 $kg\,kg^{-1}$; for the ghost towns, the water content was 0.072 $kg\,kg^{-1}$.

Compaction Recovery: Penetration Depth

Most compacted soils have not recovered, even after recovery periods of up to 91 years since abandonment. Compacted soils, as measured with penetration depth, had fully recovered in only 2 of 31 comparisons, in both cases after 70 years of abandonment. The average penetration depths were 35 mm for active roads, 88 mm for recovering site, and 111 mm for undisturbed soil; water content at the time of the penetration depth measurements ranged from 0.3 to 7.4% (Table 2). Using eq. (2), the full recovery time ranged from $27 \leq T_F \leq 154$ for the 31 measurements. Using linear regression, force-fit to $I_R = 0$ at $T_A = 0$, yields an estimated index of recovery, I_{Re}, as

$$I_{Re} = 1.001 \cdot T_R \quad (r = 0.578). \tag{3}$$

This linear model predicts complete recovery in 100 years. The data suggest that a linear model of recovery is inappropriate; indeed, such a model force-fit to recovery of 0% at $T_R = 0$ falls under the data points for abandonment times of $T_R < 40$ years (Figure 3a).

A better representation of compaction recovery is a logarithmic function of the form:

$$I_{Re} = -36.39 + 59.65 \cdot (\log(T_R + 4)), \quad (r = 0.652). \tag{4}$$

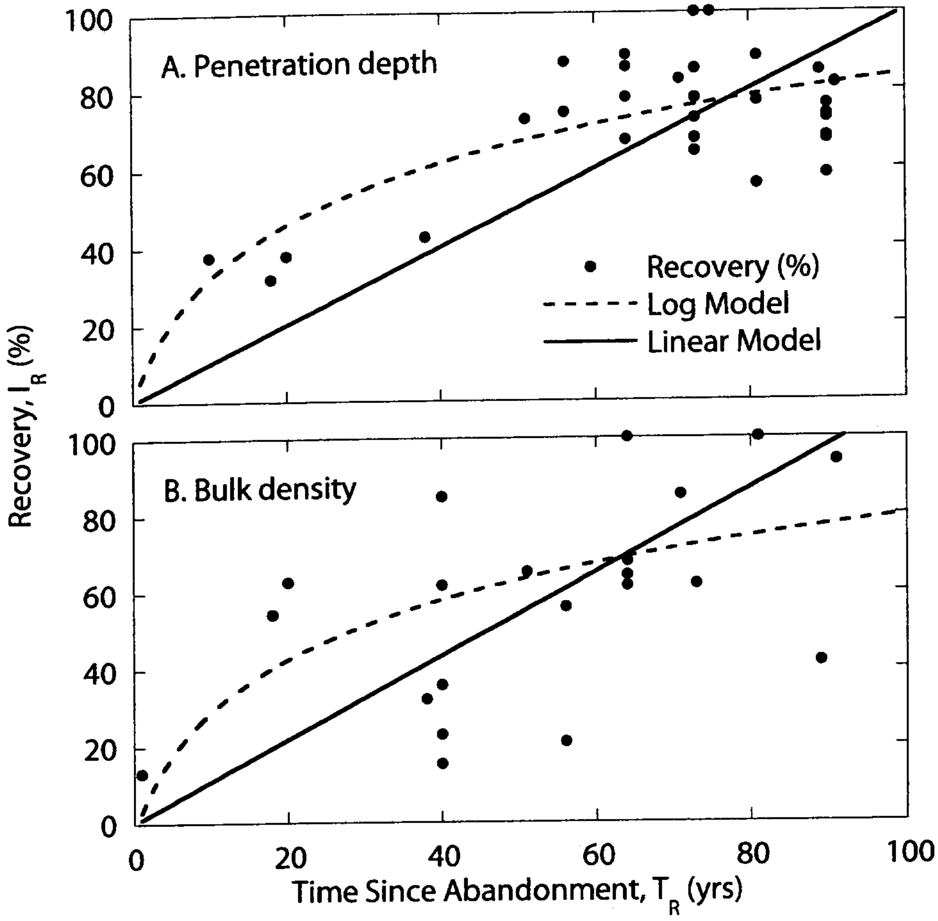

FIGURE 3 Compaction recovery for abandoned sites in the Mojave Desert. (A. Penetration depth. B. Bulk density.)

Because of its logarithmic form, Eq. (4) has the disadvantage of being unrealistically asymptotic at large T_R (Figure 3a). Eq. (2) does not reach $I_{Re} = 100\%$ until $T_R = 190$ yrs. Partial recovery times provide more realistic measures of recovery (Webb & Wilshire, 1980). Using this approach, $T_R = 105$ years for $I_{Re} = 85\%$ recovery. From the linear and logarithmic models, severe soil compaction as measured with penetration depth requires about 70–105 years for recovery in the Mojave Desert.

Compaction Recovery: Bulk Density

Using bulk density, compacted soils had fully recovered in 3 of 22 measurements, all with $T_R > 64$ years. Using Eq. (2), the full recovery time ranged from $8 \leq T_F \leq 269$ years, reflecting the large amount of variability in the data. Using linear regression, force-fit to $R = 0$ at $T_A = 0$, yields:

$$I_{Re} = 1.087 \cdot T_R \quad (r = 0.566). \tag{5}$$

This linear model predicts complete recovery in 92 years (Figure 3b). The logarithmic function is:

$$I_{Re} = -38.01 + 58.41 \cdot (\log(T_R + 4)), \quad (r = 0.509). \tag{6}$$

The logarithmic relation (Eq. 6) does not reach $I_{Re} = 100\%$ until $T_R = 227$ years, and $T_R = 124$ years for $I_{Re} = 85\%$ recovery. Neither model appears clearly better than the other, and for $T_R < 50$, five points are above each curve and four points are beneath. Of the four lower points, three were measured by Prose & Metzger (1985) at the lower elevation sites. From the linear and logarithmic models, recovery measured in terms of bulk density requires 92–124 years.

Compaction Recovery: Effect of Elevation

Site elevation is a proxy for the amount of wetting-and-drying and freeze-thaw loosening that a site might undergo in the Mojave Desert, owing to the strong vertical precipitation and thermal gradients in this region. Using either penetration depth or bulk density, the recovery times are significantly related to elevation. Using multiple linear regression, with $I_{Re} = 0$ at $T_R = 0$, the recovery relation for penetration depth is:

$$I_{Re} = 0.018 \cdot E + 0.659 \cdot T_R (r = 0.974), \tag{7}$$

where E = elevation (m). For bulk density, the recovery relation is:

$$I_{Re} = 0.026 \cdot E + 0.578 \cdot T_R (r = 0.936). \tag{8}$$

The coefficients for E and T_R are significant at $P < 0.05$.

Compaction Recovery: Other Factors

Other factors that might affect amelioration of soil compaction did not significantly explain any of the variability in recovery as shown in Figure 3. The recovery time of individual sites was highly variable and did not discriminate among young versus old geomorphic surfaces (e.g., Holocene versus Pleistocene surfaces). Gravel content explained more variance ($r = 0.269$) than did sand, silt, or clay content, and none of the results were statistically significant at $P < 0.05$. Given the specific sites that are available for measurement in the Mojave Desert, elevation of the site appears to be the only variable that explains a significant amount of variance in compaction recovery.

Discussion and Conclusions

Recovery of severely disturbed desert soils and vegetation, as measured with penetration resistance and bulk density, requires approximately a century in the Mojave Desert. Full recovery times range from 100–190 years and 92–227 years on the basis of full recovery times estimated from penetration-depth and bulk-density measurements, respectively. By using the linear-model estimates of full recovery and the logarithmic-model estimates of 85% recovery (more realistic), I conclude that soil compaction at 0–6 cm requires 92–124 years to recover in the Mojave Desert. These results are in agreement with previous studies (Webb et al., 1986; Knapp, 1992).

Owing to the large variability in recovery (Figure 3), it is difficult to conclude whether the path of recovery is linear or logarithmic. The difference is crucial to land management. A logarithmic recovery path would indicate that initial recovery is fast, and the potential recovery might be the difference between initiating artificial reclamation or allowing natural recovery. For penetration depth, the logarithmic curve appears to best represent the early course of recovery (Figure 3a). For bulk density, the more fundamental soil property, the results are more equivocal, with five points above and four points below both curves (Figure 3b). However, three of the four lower points are from the World War II encampments, and the low recovery rate may be due in large part to the use of Prose & Metzger's (1985) data.

Prose & Metzger (1985) did not index recovery to nearby active roads, and I either used values I measured in active roads, or in two cases (Camps Clipper and Granite), I substituted the maximum bulk density obtained from the Proctor compaction tests for the bulk density in an active road as part of my analysis. Because the average difference between the Proctor maximum bulk density and the density in the active roads was $0.23\,\mathrm{Mg\,m^{-3}}$, this procedure increased the amount of recovery estimated using Eq. (1). In addition, the lowest points at $T_R = 40$ and 56 years were measured at Camp Essex, suggesting the possibility of additional disturbance after abandonment, as originally discussed by Prose & Metzger (1985).

Recovery of soil compaction is significantly related to elevation, indicating that a complex interaction among the recovery mechanisms of wetting-and-drying cycles, freeze-thaw cycles, and bioturbation is responsible. Both wetting-and-drying and freeze-thaw cycles increase with elevation, and the importance of each variable cannot be quantitatively separated in this empirical study. Freeze-thaw loosening may be the more important process in Harrisburg and Skidoo than in the lower elevation townsites, and particularly the World War II encampments. The frequency of wetting-and-drying cycles is probably not very different among the townsites, despite differences in mean annual precipitation, whereas the frequency of freeze-thaw cycles probably is greater at higher elevations. Laboratory compaction-recovery tests will be required to separate out the efficacy of these two processes.

References

Adams, J. A., L. H. Stolzy, A. S. Endo, P. G. Rowlands, and H. B. Johnson. 1982. Desert soil compaction reduces annual plant cover. *California Agriculture* 36:6–7.

Akram, M., and W. D. Kemper. 1979. Infiltration of soils as affected by the pressure and water content at the time of compaction. *Soil Science Society of America Journal* 43:1080–1086.

Belnap, J., and S. Warren. 2002. Patton's tracks in the Mojave Desert, USA: An ecological legacy. *Arid Land Research and Management* 16: (this issue).

Bischoff, M. C. 2000. *The Desert Training Center/California-Arizona maneuver area, 1942–1944*. Technical Series 75, Statistical Research, Inc., Tucson, Arizona.

Blake, G. R., W. W. Nelson, and R. R. Allmaras. 1976. Persistence of subsoil compaction in a mollisol. *Soil Science Society of America Journal* 40:943–948.

Bolling, J. D., and L. R. Walker. 2000. Plant and soil recovery along a series of abandoned desert roads. *Journal of Arid Environments* 46:1–24.

Campbell, C. E. 1972. Some environmental effects of rural subdividing in an arid area: A case study in Arizona. *Journal of Geography* 71:147–154.

Davidson, E., and M. Fox. 1974. Effects of off-road motorcycle activity on Mojave Desert vegetation and soil. *Madroño* 22(8):381–412.

Felt, E. J. 1965. Compactibility, pp. 400–412 in C. A. Black, ed., *Methods of Soil Analysis*, Part 1. Monograph No. 9, American Society of Agronomy, Madison, Wisconsin.

Greacen, E. L. 1960. Water content and soil strength. *Journal of Soil Science* 11(2):313–333.

Heinonen, R. 1977. Towards "normal" soil bulk density. *Soil Science Society of America Journal* 41:1214–1215.

Howard, G. W. 1985. The Desert Training Center/California-Arizona maneuver area. *Journal of Arizona History* 26(3):273–294.

Iverson, R. M. 1980. Processes of accelerated pluvial erosion on desert hill slopes modified by vehicular traffic. *Earth Surface Processes* 5:369–388.

Iverson, R. M., B. S. Hinckley, R. H. Webb, and B. Hallet. 1981. Physical effects of vehicular disturbances on arid landscapes. *Science* 212:915–917.

Johnson, A. W., and J. R. Sallberg. 1960. *Factors that influence field compaction of soils*. Highway Research Board Bulletin 272, Department of Transportation, Washington, D.C.

Knapp, P. A. 1992. Soil loosening processes following the abandonment of two arid western Nevada townsites. *Great Basin Naturalist* 52(2):149–154.

Krzysik, A. J. 1985. *Ecological assessment of the effects of army training activities on a desert ecosystem: National Training Center, Fort Irwin, California*. Technical Report N-85/13, U.S. Army Corps of Engineers, Champaign, Illinois.

Larson, W. E., and R. R. Allmaras. 1971. Management factors and natural forces as related to compaction, pp. 367–427 in K. K. Barnes, W. M. Carleton, H. M. Taylor, R. I. Throckmorton, and G. E. VandenBerg, eds., *Compaction of agricultural soils*. American Society of Agricultural Engineers Monograph, St. Joseph, Michigan, USA.

Lathrop, W. E., and P. G. Rowlands. 1983. Plant ecology in deserts: An overview, pp. 113–152, in R. H. Webb and H. G. Wilshire, eds. *Environmental effects of off-road vehicles*. Springer-Verlag, New York.

Lovich, J. E., and D. Bainbridge. 1999. Anthropogenic degradation of the southern California desert ecosystem and prospects for natural recovery and restoration. *Environmental Management* 24(3):309–326.

Orr, H. K. 1975. Recovery from soil compaction on bluegrass range in the Black Hills. *Transactions of the American Society of Agricultural Engineering* 18(6):1076–1081.

Prose, D. V. 1985. Persisting effects of armored military maneuvers on some soils of the Mojave Desert. *Environmental Geology and Water Science* 7(3):163–170.

Prose, D. V., and S. K. Metzger. 1985. Recovery of soils and vegetation in World War II military base camps, Mojave Desert. *U.S. Geological Survey Open-file Report 85-234*, Menlo Park, California.

Prose, D. V., and H. G. Wilshire. 2000. The lasting effects of tank maneuvers on desert soils and intershrub flora. *U.S. Geological Survey Open-file Report OF 00–512*, (http://geology.usgs.gov/open-file).

Prose, D. V., S. K. Metzger, and H. G. Wilshire. 1987. Effects of substrate disturbance on secondary plant succession; Mojave Desert, California. *Journal of Applied Ecology* 24:305–313.

Soil Survey Staff. 1975. *Soil taxonomy*. Agriculture Handbook No. 436, Soil Conservation Service, Department of Agriculture, Washington, D.C.

Steiger, J. W., and R. H. Webb. 2000. Recovery of perennial vegetation in military target sites in the eastern Mojave Desert, Arizona. *U.S. Geological Survey Open-file Report OF 00-355*, (http://geology.usgs.gov/open-file).

Thorud, D. B., and S. S. Frissell, Jr. 1976. Time changes in soil density following compaction under an oak forest. *Minnesota Forestry Research Notes No. 257*, St. Paul, Minnesota.

van Ouwerkerk, C. 1968. Two model experiments on the durability of subsoil compaction. *Netherlands Journal of Agricultural Science* 16:204–210.

Vasek, F. C., H. B. Johnson, and D. H. Eslinger. 1975a. Effects of pipeline construction on creosote bush scrub vegetation of the Mojave Desert. *Madroño* 23(1):1–13.

Vasek, F. C., H. B. Johnson, and G. D. Brum. 1975b. Effects of power transmission lines on vegetation of the Mojave Desert. *Madroño* 23(3):114–130.

Vollmer, A. T., B. G. Maza, P. A. Medica, F. B. Turner, and S. A. Bamberg. 1976. The impact of off-road vehicles on a desert ecosystem. *Environmental Management* 1(2):115–129.

Vorhees, W. B., C. G. Senst, and W. W. Nelson. 1978. Compaction and soil structure modification by wheel traffic in the northern corn belt. *Soil Science Society of America Journal* 42:344–349.

Webb, R. H. 1982. Off-road motorcycle effects on a desert soil. *Environmental Conservation* 9(3):197–208.

Webb, R. H. 1983. Compaction of desert soils by off-road vehicles, pp. 51–79, in R. H. Webb and H. G. Wilshire, eds. *Environmental effects of off-road vehicles*. Springer-Verlag, New York.

Webb, R. H., and S. S. Stielstra. 1979. Sheep grazing effects on Mojave Desert vegetation and soils. *Environmental Management* 3:517–529.

Webb, R. H., and H. G. Wilshire. 1980. Recovery of soils and vegetation in a Mojave Desert ghost town, Nevada, U.S.A. *Journal of Arid Environment* 3:291–303.

Webb, R. H., and K. A. Thomas. in press. Recoverability of severely disturbed soils and vegetation in the Mojave Desert, California, USA, in *Proceedings of the 2000 Dubai Conference on Desertification*, Dubai, United Arab Emirates.

Webb, R. H., H. G. Wilshire, and M. A. Henry. 1983. Natural recovery of soil and vegetation following human disturbance, pp. 279–302 in R. H. Webb and H. G. Wilshire, eds., *Environmental effects of off-road vehicles*. Springer-Verlag Publishers, New York.

Webb, R. H., J. W. Steiger, and H. G. Wilshire. 1986. Recovery of compacted soils in Mojave Desert ghost towns. *Soil Science Society of America Journal* 50:1341–1344.

Webb, R. H., J. W. Steiger, and E. B. Newman. 1988. The effects of disturbance on desert vegetation in Death Valley National Monument, California. *U.S. Geological Survey Bulletin 1793*, Denver, Colorado.

Wilshire, H. G., and J. K. Nakata. 1976. Off-road vehicle effects on California's Mojave Desert. *California Geology* 29:123–132.