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Patton's Tracks in the Mojave Desert, USA: An Ecological Legacy

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Recovery of soil properties from World War II-era military training exercises in the Mojave Desert was measured approximately 55 years following disturbance. Tracks from military vehicles were still visible, particularly in areas of desert pavement. Soil penetrability was much lower in visible tracks than outside the tracks. Soils in tracks had fewer rocks in the top 10 cm of the soil profile than adjacent untracked soils. Larger particles (> 4.8 mm) formed a moderately well-developed pavement outside of the tracks, while smaller, loose particles (≤4.8 mm) dominated the surface of the tracks. The time required to restore the desert pavement is likely to be measured in centuries. Based on biomass estimates, the cyanobacterial component of biological soil crusts had recovered 46–65% in tracks, compared to outside the tracks. Overall recovery of lichen cover has been much slower. Under plant canopies, cover of Collema tenax was not significantly different between areas inside and outside the tracks; however, recovery of Catapyrenium squamulosum was only 36%. In plant interspaces with less favorable moisture and temperature conditions, C. tenax showed a 6% recovery and C. squamulosum a 3% recovery. Assuming recovery of the biological soil crust is linear, and complete only when the most sensitive species (C. squamulosum) has fully recovered in the most limiting microhabitats (plant interspaces), it may require almost two millennia for full recovery of these areas.

Keywords biological soil crusts, arid lands, disturbance, recovery, microbiotic crusts, cryptobiotic crusts

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Human perceptions of desert ecosystems have changed dramatically over the past 50 years. Once thought to be barren wastelands where impacts were of little concern, scientific understanding and aesthetic appreciation of desert ecosystems has forced a reexamination of this belief system. Many impacts once considered short-lived are now seen to have long-term consequences. Unassisted recovery of soils and vascular and non-vascular plants often fails to result in similar plant community structure, although many of the original species are often present (Wells, 1961; Vasek, 1980; Webb & Wilshire, 1980; Lathrop & Rowlands, 1983; Prose & Metzger, 1985; Prose et al., 1987; Prose & Wilshire, 2000; Steiger & Webb, 2000; although see Knapp, 1991). This may be a result of several factors, including little or no orderly succession of species in these environments (Shreve, 1942; MacMahon, 1987; Lathrop & Rowlands, 1983), change in climate or habitat conditions since the initial establishment of the original community (Webb et al., 1987; Webb & Bowers, 1993, Steiger & Webb, 2000), and/or time frames for succession that are longer than observation periods (Wells, 1961; Beatley, 1980; Vasek, 1980; Cole, 1985; Webb et al., 1987; Webb et al., 1988; Bowers et al., 1995).

Studies have shown that soils and vegetation are heavily impacted by the compression and shear forces generated by off-road wheeled and tracked vehicles. Documented effects have included increased quantity and frequency of water runoff, accelerated soil loss from wind and water erosion, decreased soil porosity and water infiltration, decreased hydraulic resistance to overland flow and decreased cover of soil stabilizers such as vegetation, rocks, or biological soil crusts (Luckenbach, 1975; Vollmer et al., 1976; Eckert et al.,1979; Webb & Wilshire, 1980; Iverson et al., 1981; Webb, 1982, 1983; Hinckley et al., 1983; Lathrop, 1983; Nakata, 1983; Webb & Wilshire, 1983; Wilshire, 1983; Webb et al., 1986, 1988; Belnap & Gillette 1997, 1998; Belnap & Lange, 2001).

Recovery rates of desert soil structure appear to be dependent on many factors. Studies of ghost towns and dated disturbances in the Mojave Desert indicate that recovery from soil compaction, in terms of soil strength and infiltration, may require 70–680 years (Iverson et al., 1981; Webb et al., 1986, 1988; Prose & Wilshire, 2000). Compaction also affects vascular plant establishment (Webb & Wilshire, 1980; Adams et al., 1982), and recovery of the original vascular plant species has been slow at these sites, with recovery estimates of 75–540 years, if at all (Vasek, 1980; Webb & Wilshire, 1980; Webb & Neuman, 1982; Lathrop & Rowlands, 1983; Prose & Metzger, 1985; Prose & Wilshire, 2000; Steiger & Webb, 2000). The ecological roles of biological soil crusts that can be found in all deserts (Belnap 2001a) have only recently received attention, and are now known to be a critical component of semiarid and arid ecosystems (Belnap & Lange, 2001). They are essential in stabilizing soil surfaces from both wind and water erosion (reviewed by Belnap, 2001b; Warren, 2001). They are important in contributing nitrogen and carbon to desert ecosystems and influencing the nutrient content of vascular plants (reviewed by Belnap et al., 2001b). They also influence rainfall infiltration and runoff (Warren, 2001) and soil albedo (Belnap,1995).

Soil surface disturbances have repeatedly been shown to impact biological soil crusts negatively, either through mortality or reduced physiological functioning (reviewed by Harper & Marble, 1988; Johansen, 1993; Belnap & Eldridge, 2001). Disturbance of these crusts can also result in increased soil erosion (reviewed by Belnap, 2001b; Warren, 2001). The type, timing, and extent of disturbance, as well as site climatic factors, can greatly influence recovery time. In addition, the evolutionary disturbance history of sites may play a role in recovery rates (Belnap & Eldridge, 2001). Recovery of soil crusts may require up to 250 years or more on the Colorado Plateau of North America (Belnap 1993, 1995), while shorter recovery times (approx. 50 years) are estimated for areas with greater effective precipitation, such as the northern Great Basin and Chihuahuan deserts of North America (Belnap et al., 1994; Belnap & Eldridge, 2001). However, only a few studies have addressed recovery times of soil crusts in hot deserts such as the Mojave (Webb et al., 1988; Prose & Wilshire, 2000).

Between 1942 and 1944, many areas of the Mojave Desert were used for military training activities (Figure 1; Prose & Wilshire, 2000). The impacts of these exercises can still be seen, particularly in areas covered by moderate to well-developed desert pavement. This study examined recovery of soil structure and biological soil crusts in a training area near Needles, California about 50 years following disturbance.

Methods

Site Selection and Characterization

Data were collected in April 1995, approximately 55 years after the area had been used for military exercises. Tracks from military vehicles were located in the Chemehuevi Valley, 19 km SW of Needles, California (34° 70′ N, 114° 70 E). Mean annual precipitation recorded at the nearby Needles airport between 1948 and 2000 was 116 mm. The mean maximum temperature recorded over the same time period was 30°C; mean minimum temperature was 15.8°C. Highest monthly mean temperatures were recorded in July (42.5°C); lowest monthly mean temperatures occurred in January (5.3°C). Locations were selected where parallel tracks indicated that a vehicle had passed. Tracks were mostly visible where soils were covered by

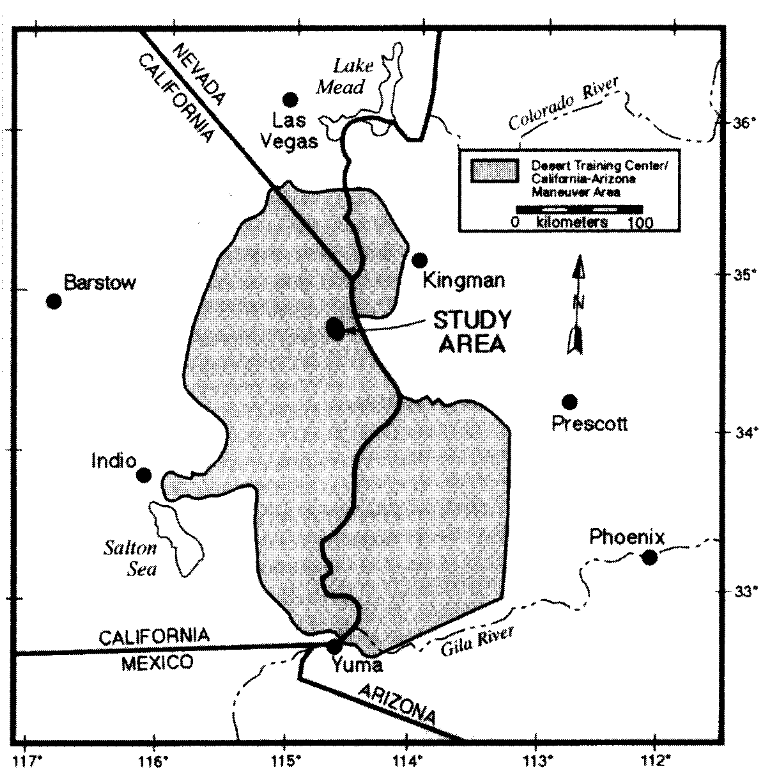

FIGURE 1 Location of military maneuvers in the Mojave Desert during 1942–1945. The dark shaded area shows the location of this study.

moderately well-developed desert pavements that characterized the general area. Based on the width of individual tracks and the distance between parallel tracks, we selected tracks most likely created by M3/M4 Sherman tanks and M2 light tractors (Caterpillar-type tractors converted to military use as artillery tow vehicles).

The total surface area covered by tracks was estimated using two randomly placed step-point transects (Evans & Love, 1957), each approximately 0.8 km long. Every fourth step was labeled either "track" or "not track" based on the presence or absence of a track at the toe of the observer's boot. "Track" was recorded only when two parallel tracks could clearly be distinguished. There were many areas where it appeared that a vehicle had passed by, but only one track could be distinguished. These were not counted as they could not be unquestionably identified as evidence of a tracked vehicle.

Vegetation and Soil Sampling

Vegetative cover was estimated using four randomly placed 100 m line intercept transects (Canfield, 1941). Thirty cores of the top 10 cm of soil were randomly collected throughout the study site and composited for chemistry and texture analyses. A recording soil penetrometer was used at five locations to estimate the resistance of the air-dry soils to penetration (Carter, 1967), with seven to 10 paired measurements made per location. Outside the tracks, soils could be penetrated with the instrument and mean values were obtained at 5–35 cm. Inside the tracks, however, the soil was so compacted below 5–10 cm that it exceeded the maximum pressure recorded by the instrument (70 kg cm^{-2}). Consequently, values for tracks could only be calculated for the 5 cm and 10 cm depths. Values for the 5 cm depth seldom exceeded the maximum, and thus could be directly measured. At 10 cm, some values were measurable while most exceeded the limits of the instrument. For those that exceeded the maximum, 70 kg cm^{-2} was used as a minimum estimate of penetration resistance for calculating the mean resistance at that depth. Because the penetrometer could not go below 10 cm in the tracks, no values could be calculated for greater depths.

Data on soil particle size distribution were collected inside and outside the tracks at three of the five locations. Using a 100 cm^2 surface area, soils were collected in 2 cm increments to a depth of 10 cm. The size distribution of coarser particles (>0.05 mm) was determined using a standard set of stacking sieves. Size classes included very fine sand (0.05–0.15 mm), fine sand (0.15–0.30 mm), medium sand (0.30–0.85 mm), coarse sand (0.85–1.4 mm), very coarse sand (1.4–4.8 mm), fine gravel (4.8–19 mm), and coarse gravel (>19 mm). Particles collected on each sieve were weighed, and results reported in grams.

Biological Soil Crusts

Nitrogenase activity: Twenty 5.1 cm^2 × 3 cm deep, paired samples of the soil surface were randomly collected within and adjacent to three tracks. If rocks were encountered during the random placement of sampling tubes, the rocks were moved aside and soils collected beneath them. Samples were placed in clear, gas-tight tubes and the surface wetted with distilled water. Tubes were then injected with enough acetylene to create a 10% acetylene atmosphere. After injection, samples were incubated for four hours at 26°C in a chamber lighted with Chromo50 (5000 K) and cool white fluorescent bulbs. Subsamples (0.25 mL) of the head space within the tubes were then analyzed for acetylene and ethylene content on a Carle FID gas chromatograph equipped with a 2.43 m, 8% NaCl on alumina column, using helium as the carrier gas (30 mL min^{-1}). Calibrations with ethylene standards were done at the time of observations. Results were reported in nmol C_2H_2 m^{-2} h^{-1}.

Cyanobacterial biomass. Chlorophyll *a* concentration was used to estimate cyanobacterial biomass. Fifteen 2.6 cm^2 × 1 cm deep samples of the soil surface were collected from each track and from the adjacent untracked areas in the same manner as nitrogenase samples (30 samples total per site). Samples were extracted immediately with dimethyl sulfoxide (DMSO) in the dark for 45 minutes at 65°C (Ronen & Galun, 1984). Samples were then shaken and centrifuged. Absorption spectra were measured in a Hewlett-Packard diode array spectrophotometer, after calibration with a DMSO blank. Measurements were made at 398 nm (Belnap, 1995).

Lichen cover. Lichen cover was estimated by species in the center of each track and in an adjacent area 1 m outside the track. Quadrats (0.1 m^2) were read every 25 cm for 7 m. Quadrats were recorded as to whether they were in the plant interspace or under the canopy of a plant. When results were tallied, cover of lichens in the interspace outside and inside the tracks was compared separately from cover of lichens under plant canopies. The lichen cover in the different microhabitats was also multiplied by the percentage of landscape represented by each category, and obtained values then totaled to estimate an "average" recovery rate for each landscape unit.

Statistics

Results between tracked and untracked samples for nitrogenase activity, chlorophyll *a*, and lichen cover were compared using a Student's *t*-test (SPSS, 1999). The recording penetrometer readings were compared using a paired *t*-test for the average reading at each depth. Particle size distribution measurements were not statistically compared.

Results and Discussion

Site Characteristics

Outside the tracks, the study sites were characterized by a moderately-developed desert pavement, underlain by an Av horizon of medium thickness. Surface rocks lacked heavy varnishing. There was no pavement visible within the tracks, and the Av horizon was either absent or weakly developed. Perennial vascular plant cover was dominated by the overstory shrub *Larrea tridentata* (Sessé & Moc. ex DC.) Coville (15% canopy cover) and the understory shrub *Ambrosia dumosa* (Gray) Payne (25% canopy cover). Soils were an unclassified gravelly-pavement, and the texture was a sandy loam. Soil chemical and physical properties are presented in Table 1.

Tracks were found to cover approximately 12% of the study area. This is a conservative measurement, as we did not count tracks when both tracks were not plainly visible. In addition, visible tracks occurred only on patches of desert pavement (which represented 60% of the surface), although the tanks obviously had to drive between these patches.

Soil Resistance to Penetration

Figure 2 presents penetration resistance of the soils inside and outside of the tracks. At 5 and 10 cm, penetration resistance was significantly higher inside the track than outside the track ($P < 0.01$). Because the penetrometer was stopped at 10 cm by the resistance of the soil, no measurement was possible below this depth. Small soil pits that were dug confirmed that soil density, not rocks, precluded penetration of the soil.

TABLE 1 Soil Characteristics at the Study Site (For Chemical Components Values Shown in mg kg^{-1} Soil)

pH	8.3
Sand%	77
Silt%	15
Clay%	8
CEC $cmol_c$ kg^{-1}	9.6
Organic Matter%	.04
NO_3-N	.08
P	6.3
Available K	145
Exchangeable K	162
Zn	.03
Fe	1.5
Mn	3.2
Cu	.04
Exchangeable Ca	5790
Exchangeable Mg	135
Exchangeable Na	9.7

Similar to our results, Prose (1985) and Prose & Wilshire (2000) also found significantly higher soil penetration resistance in tank tracks compared to adjacent untracked areas at multiple sites in the Mojave Desert. In addition, other studies in the Mojave Desert have shown that vehicular traffic (both tanks and wheeled vehicles) results in long-lasting compaction of soils (Snyder et al., 1976; Iverson et al., 1981; Webb, 1982, 1983; Webb et al., 1986). The degree of soil compaction resulting from traffic is dependent on soil texture and structure, soil moisture content, and ground pressure of the vehicle. Well-aggregated soils with a wide range of soil particle sizes tend to compact more readily than soils with a uniform particle size and/or poor aggregation. The soil at our study site was a sandy loam (Table 1), which is among the most compactible of all soil types (Bodman & Constantin, 1965). The potential for soil compaction increases with soil moisture content up to a point where the majority of the pores are filled with water. It is impossible to ascertain the soil moisture conditions at the time the study site was tracked. In addition, as a general rule, the degree of soil compaction increases as the ground pressure of the vehicle increases, although this may be affected by the speed of the passing vehicle. Standing ground pressure of the M3/M4 Sherman tanks of the Patton era was approximately 0.9 kg cm^{-2}, while the ground pressure of the M2 light tractor was approximately 0.4 kg cm^{-2} (Hoffschmidt & Tantum, 1970). By contrast, cattle and pickup trucks have ground pressures of approximately 1.7 and 3.5 kg cm^{-2}, respectively (Lull, 1959). The difference is due to the larger surface area of the tracks over which the weight of the tracked vehicles is spread. On the other hand, tanks generate greater shear forces than other off-road vehicles (Prose & Wilshire, 2000).

Recovery of soils that have been compacted results from a combination of processes including expansion of clay minerals during wetting, freeze-thaw heaving, and biological activity (Webb et al., 1986). Because these processes occur with a lower degree of frequency and/or intensity in hot deserts such as the Mojave, recovery from soil compaction in these areas is naturally slower than in more mesic environments. Webb et al. (1986) measured soil compaction in seven ghost towns in the Mojave Desert 64 to 71 years after abandonment, and projected full recovery between 80 and 140 years. Remeasurement at three of these sites indicates that recovery time for soils is more likely 80 to 120 years (Webb, pers comm). At the Wahmonie townsite in Nevada, Webb et al. (1983) measured soil compaction from

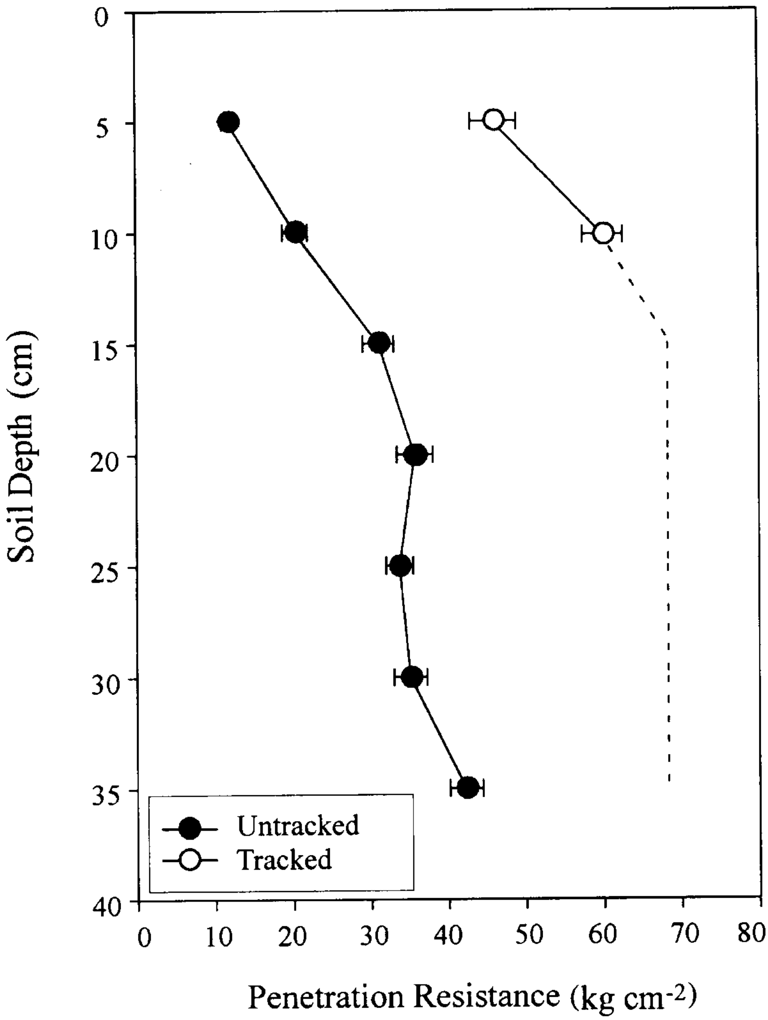

FIGURE 2 Profiles of soil resistance to penetration in untracked areas (solid circles) and in tank tracks (open circles). At the 10 cm depth, many values were greater than 70 kg cm^{-2}, the maximum value the penetrometer could record. To calculate the 10 cm value, either the true value ($<$70 kg cm^{-2}) or the maximum value (70 kg cm^{-2}) was used. Below this depth, no measurement was possible. For illustration purposes, the maximum recordable value of the penetrometer is represented by the dashed line.

three sites that were abandoned at different times over 51 years and predicted recovery times of 70 to 680 years.

Compaction and concomitant increases in soil bulk density cause decreased water infiltration, increased runoff, and increased soil erosion in desert ecosystems (Iverson et al., 1981; Snyder et al., 1976; Webb, 1982). Consequently, remnant military tracks can be expected to generate more water runoff than adjacent untracked areas. Where the tracks run parallel to the slope, these linear features can exacerbate soil erosion by increasing the volume and velocity, and thus the sediment transport capacity of the runoff. As the formation of a mature Aridisol may require 10,000 years or more (Dregne, 1983), loss of this resource can be considered irretrievable on a human time-scale.

Vertical Soil Particle Size Class Distribution

The vertical distribution of soil particle size classes was measured in three of the five study areas. Overall, soil outside the tracks was characterized by more gravel-sized particles (>4.8 mm) near the surface (Figure 3), which is consistent with the presence of an intact desert pavement. In contrast, the tracks had no coarse gravel on the surface; the concentration of coarse gravel peaked at a depth of 2–4 cm. We suspect the abundance of larger fragments at the 2–4 cm depth is likely the result of tanks pushing the desert pavement downward. This has been seen at Ft. Irwin with fresh tank tracks (Prose & Wilshire, 2000). We also suggest that the rut formed by the tracks has subsequently and gradually filled with smaller soil particles, hence the relatively greater concentration of smaller particles at and near the surface (Figure 3). This is supported by the observation that most of the small particles on the soil surface were not cemented in place, but instead were lying loose on the soil surface.

The disruption of the desert pavement surface has significant implications for the ecological stability of the site. Larger mineral fragments are better able to protect soil surfaces from both wind and water erosion. The increased surface roughness creates a thicker boundary layer of still air that shields the soil surface from erosive winds (Gillette et al., 1980). In addition, concentration of large fragments at the surface protects the soil from raindrop splash erosion and creates a more tortuous path for runoff, thus reducing sheet erosion. Desert pavement results from the concentration of large mineral fragments on the soil surface, and is now believed by many to be a process of inflation where coarse mineral fragments are pushed to the surface by the shrinking and swelling action of clay minerals that may either occur naturally at a site or are blown in and subsequently filter into the soil profile via cracks. The process can span millennia (Wells et al., 1995) or may require climatic conditions that are not currently present, thus precluding recovery (Prose & Wilshire, 2000).

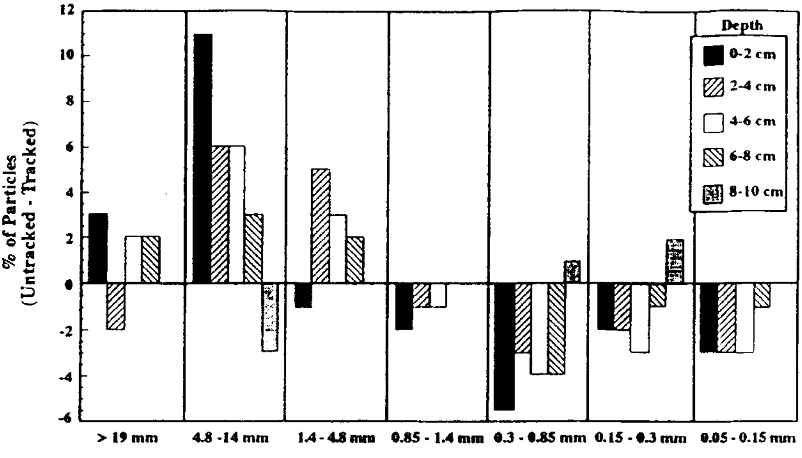

FIGURE 3 Distribution of particle size classes at different depths. Values represent the difference between the percentage of particles of a given size class inside and outside of the tracks. Positive values indicate that more particles of a given size class occurred outside of the tracks, while negative values indicate more of that size class occurred in the tracks. Note that larger particles were more common outside of the tracks, while the tracks were dominated by smaller particles.

Biological Soil Crusts

Combining data from the interspaces and under plant canopies, cyanobacterial biomass outside the tracks was twice that inside the tracks (0.13 vs 0.06 mg chl *a* g^{-1} dry soil; $P < 0.01$). Nitrogenase activity in the combined interspace and plant canopy samples showed a similar pattern, with activity in the untracked area approximately twice that seen in the tracks (13.6 vs 8.8 nmol C_2H_2 h^{-1}; $P < 0.01$). Two species of lichens were present at the site, *Collema tenax* (Sw.) Ach. and *Catapyrenium squamulosum* (Ach.) Breuss. Under plant canopies, *C. tenax* cover inside the tracks tended to be lower than outside the tracks, but differences were not significant (4.1 vs 6.0%; Figure 4a). *C. squamulosum* covered 1.9% of the surface in the tracks, compared to 5.3% ($P < 0.05$) in the untracked areas. In the interspaces between

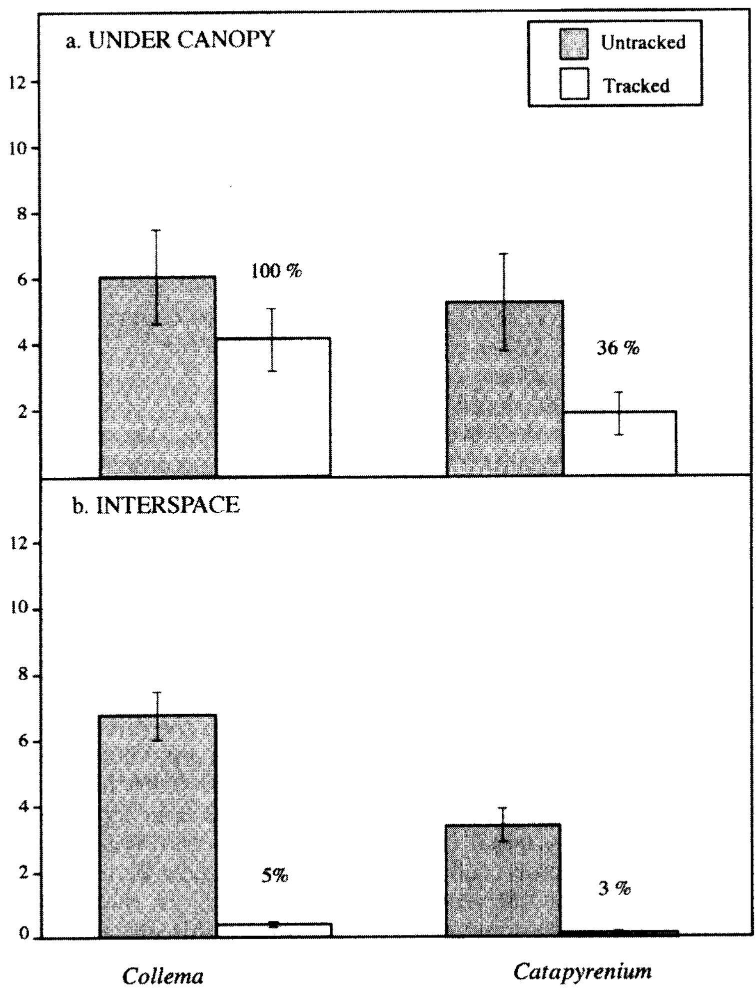

FIGURE 4 Percent cover of *Collema* and *Catapyrenium* in tracks and adjacent untracked areas, both under creosotebush canopies (a) and in plant interspaces (b). There was no statistical difference for *Collema* under canopies. *Collema* cover in interspaces and all *Catapyrenium* values were significantly different ($P < 0.04$) between tracked and untracked areas. Percent recovery is noted above bars.

plants, *C. tenax* covered 6.7% of the soil surface in untracked areas, but only 0.4% in tracked areas (Figure 4b). *C. squamulosum* cover averaged 3.4% outside the tracks, but only 0.1% in the tracks.

Biological soil crusts appear to follow a generalized successional sequence (Harper & Marble, 1988; Belnap & Eldridge, 2001). This is especially noticeable in soils with low inherent stability. Since mosses and lichens are easily buried by aeolian or alluvial sediments, they do not readily colonize unstable surfaces unless cyanobacteria, vascular plant roots, or fungal filaments first stabilize the soil. While some arid ecosystems have abundant microfungi and vascular plant roots in the top few centimeters of the soil (e.g., the Sonoran Desert), other areas, such as the Colorado Plateau and the Mojave Desert, contain few organisms other than cyanobacteria that can survive at the soil surface (Belnap & Gardner, 1993). Consequently, cyanobacterial colonization is a general precursor to moss and lichen establishment in these deserts.

We used both nitrogenase activity and chlorophyll *a* as indices of cyanobacterial colonization/recovery in our study. It is impossible to determine the actual condition of the cyanobacteria immediately following the original disturbance. However, if we assume that the tracking process reduced nitrogenase activity and live cyanobacterial biomass to near zero immediately following the tracking (as documented in other studies, as reviewed in Belnap & Eldridge, 2001), these indices indicate that there has been a recovery of 65% and 46%, respectively, in the cyanobacterial component of the biological soil crust. If we further assume that recovery has been and will continue to be linear (given only two data points, no other assumptions are justified), full recovery of the cyanobacterial component can be expected to occur between 85 and 120 years following disturbance. While visual recovery from human and livestock traffic may occur in as little as five to 20 years on the Colorado Plateau (Cole, 1990; Johansen & St. Clair, 1986), estimated times for full functional recovery of the cyanobacterial component of biological soil crusts in that ecoregion range from 30 to 65 years (Belnap, 1993). The slightly longer estimates for recovery at our study site are entirely consistent with the lower effective rainfall found there.

As expected, based on results from other studies (reviewed in Belnap & Eldridge, 2001), recovery of the lichen component of the biological soil crust is much slower than recovery of the cyanobacterial component. Lichen recovery rates are quite variable and depend on microhabitat conditions. Although the Mojave Desert is known for climatic extremes, these conditions are somewhat ameliorated beneath plant canopies relative to plant interspaces. Here the high temperatures are reduced, the soil is more protected from wind and water erosion, plant litter and roots contribute to higher soil organic content, and soils are often moist for longer periods of time. These conditions are more conducive to the reestablishment of lichens. Outside of the tracks, lichen cover under the plant canopy and in the interspaces was quite similar (11.3% and 10.1%, respectively). Inside the tracks, total lichen cover was 6% under plant canopies, representing a 53% recovery, and 0.5% in the open interspaces, representing a recovery of only 5%. Assuming that lichen cover was completely eliminated by the original tracking disturbance, and assuming that lichen cover follows a linear trajectory, full recovery of lichens under plant canopies can be expected in approximately 100 years, while full recovery in the interspaces may exceed 1000 years. The time estimated for full recovery at this site is up to an order of magnitude higher than for the same species at disturbed sites on the Colorado Plateau (i.e., 45 to 85 years; Belnap, 1993).

C. tenax appears to be the more resilient of the two lichen species present at our study site, as has been noted in other studies as well (Belnap, 1995, 1996; Belnap et al., 1994). After 55 years, cover of *C. tenax* had recovered 68% under the plant canopies and 6% in the interspaces. By contrast, recovery of *C. squamulosum* was approximately half that level (35% under plant canopies and 3% in the interspaces).

Recovery of the site can be considered complete only when the least resilient species, *C. squamulosum*, has fully recovered in the harshest microenvironment (interspaces). Applying the assumptions of a linear trajectory of recovery as previously discussed, we estimate that the time frame required for full recovery of *C. squamulosum* may approach two millennia. However, the estimate must be tempered by the possibility that recovery of at least some lichens may be episodic in nature, based primarily on periods of above-average precipitation (Johansen et al., 1984; Johansen & St. Clair, 1986). If the study area experiences a sustained period of above-average precipitation, it is possible that the time required for full recovery may be significantly shortened. By the same token, long-term changes in the climatic patterns in the region or disruption of the desert pavement may have altered the ecological potential of the site to the point that a return to the original state may never occur.

Conclusion

The results from this study are similar to many other studies done in the Mojave Desert: impacts to soil surfaces in the Mojave Desert are long-lasting. This demonstrated lack of resilience to disturbance is probably due primarily to the low rainfall and lack of freeze-thaw events that characterize this region. Because many critical ecosystem functions are impacted by off-road vehicles (whether tanks or wheeled vehicles), it is clearly important that these types of activities be restricted as much as possible, and that soil surface impacts be considered in land management decisions.

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