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SOIL COMPACTION FROM HUMAN TRAMPLING, BIKING, AND OFF-ROAD MOTOR VEHICLE ACTIVITY IN A BLACKBRUSH (*COLEOGYNE RAMOSISSIMA*) SHRUBLAND

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ABSTRACT.—Soil compaction from human trampling, biking, and off-road motor vehicle traffic was quantitatively investigated in a blackbrush (*Coleogyne ramosissima*) shrubland in Kyle Canyon of the Spring Mountains in southern Nevada. A significant difference was detected in soil compaction, bulk density, and percent pore space at a particular frequency of visits in each of 4 disturbance types. On average a single vehicle pass was equivalent to 10 human footprints. Ten and 100 footprints were equivalent to 1 motorcycle pass and 10 vehicle passes, respectively. Soil compaction is a product of increased bulk density and decreased pore space. The degree of soil compaction is a function of disturbance type and visit frequency when examining these 2 factors independently. However, interactive effects of disturbance type and visit frequency on soil bulk density, compaction, and percent pore space were not significantly different. The greatest effects occurred during the first few passes, with changes per pass decreasing as the number of passes increased in all 4 trails. Results of this study suggest that the effects of hiking and biking slowly increase over time relative to the effects of motor vehicle traffic in the *Coleogyne* shrubland of Kyle Canyon in southern Nevada.

Key words: trampling, hiking, biking, motorcycle, vehicle, soil compaction, disturbance, blackbrush, Coleogyne ramosissima, *Kyle Canyon, Spring Mountains, southern Nevada.*

Kyle Canyon, a part of the Toiyabe National Forest and located in the Spring Mountains, is a popular recreational area for nature-loving tourists and local residents in southern Nevada. Due to rapid population growth and use of off-road motor vehicles in recent years, considerable increase has occurred in anthropogenic (recreational) activities, and landscape disturbance has become increasingly noticeable. A complex network of roads and trails, including those created by human foot, bicycle, and motor vehicle traffic, is evident to casual observers and appears to have long-term, adverse effects on soil properties in a blackbrush *(Coleogyne ramosissima)* shrubland.

Coarse, sandy desert soils on bajadas and alluvial fans are significantly compacted by motorcycle traffic in creosote bush (*Larrea tridentata*) shrublands of southern California (Webb 1982, 1983, Webb et al. 1986). Motorcycle-induced compaction was studied using various numbers of passes (Davidson and Fox 1974, Wilshire and Nakata 1976, Webb 1982, 1983, Webb et al. 1986). Off-road motor vehicles can cause significant compaction with as few as 1 to 10 passes (Davidson and Fox 1974, Vollmer et al. 1976, Wilshire and Nakata 1976, Webb 1982, 1983, 2002, Webb et al. 1986). Weaver and Dale (1978) determined that soil bulk density increases with increasing use by horses, hikers, and motorcycles in Montana, but they did not relate the changes other than qualitatively to type of impact or number of passes.

Human trampling, biking, and off-road motor vehicle traffic adversely affect soil properties by compacting the soil (Wilshire and Nakata 1976). Severely compacted soils reduce porosity in southern Nevada (Marble 1985). Compaction through animal, human, or vehicle traffic can increase soil bulk density due to applied pressure or loading (Gill and Vandenberg 1967). Bulk density, which increases with compaction, is mainly a function of amount of void and density of soil minerals. Webb and Wilshire (1980) suggest that severely compacted soils may require at least a century for natural recovery in southern Nevada.

Soil compaction studies have been conducted in *Larrea tridentata–Atriplex* spp. (creosote bush–salt bush), *Larrea tridentata–Ambrosia dumosa* (creosote bush–white bursage), and *Coleogyne* shrublands in the Mojave Desert. Most studies have focused on the influence

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that severe compaction can have on soil physical attributes but have ignored slight soil compaction, such as that occurring from frequency of human visits. No comparative data are available to quantify the disturbance effect of an average human footprint relative to a rolling bike tire, a motorcycle tire, or the large wheel of a 4-wheeled vehicle. The objective of this study is to examine any significant differences that might exist in soil physical attributes at a particular frequency of visits in each of the 4 disturbance types (trampling, biking, motorcycle, and vehicle). In other words, do the effects of hiking and biking slowly increase over time relative to the effects of motor vehicle traffic?

METHODS

Study Site

Southern Nevada, within the Basin and Range geological province, is a region characterized by annual weather extremes and sparse vegetation cover (Brittingham and Walker 2000). Most annual precipitation occurs between October and April as frontal systems, with the remainder occurring in the summer as convectional thunderstorms (Smith et al. 1995). Summer rains occur as brief, intense, and localized events that are highly variable in both time and space. Prolonged mountain thunderstorms in the summer can cause flash flooding in the canyons and nearby washes. Winter rainfalls, on the contrary, are mild and widespread, and can last up to several days.

I conducted field studies in a *Coleogyne* shrubland during fall 2002 in Kyle Canyon (roughly 36°01′N, 115°09′W; elevation 1475 m) on the eastern slope of the Spring Mountains. Kyle Canyon was selected because soils on its alluvial fans and bajadas are representative of a large area in southern Nevada. Soils are calcareous, poorly developed (without distinct soil horizons), and composed primarily of weathered granite and limestone bedrock. Multiple caliche layers in the subsoil make this area edaphically arid, which in turn contributes to slow organic decomposition and soil formation. Soil textures near the surface are coarse and sandy. Numerous rocks litter the terrain, and dry wash channels dissect the rocky slopes and alluvial fans.

The study area is dominated by a closely spaced matrix of *Coleogyne* shrubs with a scattered distribution of other shrub species. Common associated woody species that occur in this vegetation zone include *Yucca brevifolia* (Joshua tree), *Ephedra nevadensis* (Nevada ephedra), *Menodora spinescens* (spiny menodora), *Thamnosma montana* (turpentine bush), and *Lycium andersonii* (Anderson lycium). The herbaceous species present are primarily members of the Asteraceae, Brassicaceae, Fabaceae, and Poaceae families.

Field Design and Sampling

To experimentally investigate recreation-induced compaction, my field assistants and I created 4 trails—hiking, biking, motorcycle, and vehicle—with 1, 10, 100, and 200 passes in Kyle Canyon (Table 1). Before this study these 4 linear trails, each 100 m in length and separated from the others by 50 m, showed no clear evidence of compaction or other types of soil disturbance. The hiking trail was trampled by a 78-kg person in hiking boots, with a pass being 1 walk down the lane at a normal gait. The mountain bike, motorcycle, and 4-wheeled vehicle were operated by a 78-kg rider who maintained a constant speed (32 kph) to avoid acceleration, braking, and turning effects. Soil measurements were taken at the pre-disturbance level in all 4 trails to ensure comparability. Soil measurements were also made after 1, 10, 100, and 200 passes (post-disturbance level). Within each type of disturbance, I collected 160 soil samples, with 40 from each trail. For each sample, I excavated soil in an area 10 cm in diameter and 10 cm deep. Intervals within each trail were randomly selected to avoid biased sampling. Despite carefully controlling the tire impact, some bicycle and motor vehicle passes did not overlap completely, leaving a rut approximately 2 to 3 times the tire width. Hence, soil measurements at any point on the trails were likely to be underestimates.

Soil samples were sieved through a 2-mm mesh to remove plant roots and rocks >2 mm in diameter. I performed all tests on <2 mm soils dried at 65°C for 72 hours, measuring bulk density, percent pore space, moisture, organic matter, and pH.

Fresh soil cores of known volume were carefully removed from the field and oven-dried at 65°C until they reached a constant mass. Soil bulk density was estimated by dividing mass by volume. I measured soil compaction in the field immediately after the impact

TABLE 1. Description of shoes, bicycle, and motor vehicle used under controlled traffic study in the *Coleogyne* shrubland of Kyle Canyon.

Disturbance type	Brand	Shoe/Tire width (cm)	Gross weight (kg)
Foot	Outback Footwear	9	0.9
Bicycle	Roadmaster Mountain Sport	5	17.3
Motorcycle	Yamaha YZ 250	8	88.2
Vehicle	Chevy Tahoe	22	3111.4

using a penetrometer, which was inserted into the soil after removing stony surface pavements. The penetrometer readings were taken at the point where the cone base reached the soil surface (point depth = 3.8 cm). I calculated average pore space using the equation:

$$\text{pore space (\%)} = 100 - (D_b/D_p * 100),$$

where D_b is bulk density of the soil and D_p is average particle density, usually about 2.65 g · cc^{-1} (Hausenbuiller 1972, Davidson and Fox 1974). Soil particle size distribution was determined by the hydrometer method as described by Bouycoucos (1951). Soil moisture content was measured gravimetrically by computing differences between fresh and oven-dried mass. Using a soil thermometer, I recorded soil temperature readings in the field at 15 cm below the soil surface. Soil organic matter was computed by mass loss on ignition at 550°C for 4 hours. Soil pH was determined by preparing a 1:1 paste of dry soil:distilled water and by measuring the mixture with an electrode pH meter.

Statistical Analyses

One-way analysis of variance (ANOVA; Analytical Software 1994), followed by Tukey's multiple comparison test, was performed to compare (1) differences in soil attributes (pH, moisture, temperature, texture, and organic matter) and (2) mean values among the 4 trails at the pre-disturbance level. Two-way ANOVA (Analytical Software 1994) was computed on soil compaction, bulk density, and percent pore space, with type of disturbance (hiking, biking, motorcycle, and vehicle) and frequency of visits (1, 10, 100, and 200 passes) as main effects. Mean values were presented with standard errors, and statistical significance was tested at $P \leq 0.05$.

RESULTS

Differences in soil pH, texture, moisture, temperature, and organic matter were not significant at the pre-disturbance level in all 4 trails ($P > 0.05$; Table 2). Nevertheless, soil compaction, bulk density, and percent pore space were significantly different between pre-disturbance and post-disturbance levels in all 4 trails. Soil compaction and bulk density increased, while percent pore space decreased significantly, with type of disturbance and with increasing frequency of visits when I examined these 2 factors alone ($P \leq 0.05$; Table 3). Soil compaction and bulk density were greatest in the vehicle trail and least in the hiking trail (Table 3).

Mountain bikes and motor vehicles created trails that were visible immediately after initial impact. The soil surface, disrupted by the impact, no longer had uniform gravel cover. A single mountain bike or motor vehicle pass left definite tire imprints with a slight indentation on the soil surface. Tire imprints became more evident after 10 passes and were up to 3 cm below the level of adjacent undisturbed soil after 200 passes.

I observed significant differences in soil compaction, bulk density, and percent pore space between 1 pass and 100 passes ($P \leq 0.05$). Yet, differences between 100 and 200 passes in all 4 disturbance types were not significant ($P > 0.05$; Table 3). Soil bulk density increased significantly from 1.30 to 1.51 g · cm^{-3} after 100 passes, but increased only slightly from 1.51 to 1.55 g · cm^{-3} after 200 passes (Table 2).

In each of the 4 disturbance types, I detected a significant difference in soil physical characteristics at a particular frequency of visits. On average a single vehicle pass was equivalent to 10 human footprints, and the ratio remained constant as the frequency increased to 10

TABLE 2. Soil properties (mean ± $s_{\bar{x}}$; n = 40 per treatment per characteristic) of the 4 trails at the pre-disturbance level in the *Coleogyne* shrubland of Kyle Canyon. Soil temperatures were measured at 10-cm depth. No significant differences were detected in all soil properties among the 4 trails (P > 0.05).

Soil property	Hiking	Biking	Motorcycle riding	Vehicle driving
Soil texture				
Sand	70.7 ± 3.1	70.9 ± 3.0	69.3 ± 2.8	69.5 ± 2.7
Silt	19.7 ± 1.9	18.3 ± 1.6	19.7 ± 2.0	19.9 ± 2.1
Clay	9.6 ± 0.7	11.8 ± 0.6	11.0 ± 0.5	10.6 ± 0.6
Moisture (%)	2.9 ± 0.4	3.0 ± 0.5	2.8 ± 0.5	3.0 ± 0.5
Temperature (°C)	23.8 ± 0.4	23.1 ± 0.5	23.2 ± 0.3	23.9 ± 0.3
Organic matter (%)	3.4 ± 0.3	3.5 ± 0.3	3.5 ± 0.4	3.4 ± 0.5
pH	7.5 ± 0.1	7.6 ± 0.1	7.6 ± 0.1	7.5 ± 0.5

TABLE 3. Changes in bulk density, compaction, and percent pore space (mean ± $s_{\bar{x}}$; n = 40 per treatment per characteristic) of the upper 10 cm of soil in response to various levels of trampling, mountain bike and motorcycle riding, and 4-wheeled vehicle driving in the *Coleogyne* shrubland of Kyle Canyon.

Disturbance type	Number of passes	Bulk density ($g \cdot cm^{-3}$)	Compaction ($kg \cdot cm^{-2}$)	Pore space (%)
Human foot	0	1.30 ± 0.07	6.0 ± 0.3	50.9 ± 2.9
	1	1.33 ± 0.06	6.1 ± 0.2	49.8 ± 2.9
	10	1.39 ± 0.06	6.4 ± 0.2	47.5 ± 2.8
	100	1.51 ± 0.05	7.0 ± 0.2	43.0 ± 2.7
	200	1.55 ± 0.05	7.3 ± 0.1	41.5 ± 1.9
Mountain bike	0	1.31 ± 0.07	6.0 ± 0.3	50.6 ± 3.2
	1	1.35 ± 0.08	6.2 ± 0.2	49.9 ± 2.9
	10	1.43 ± 0.06	6.6 ± 0.2	46.0 ± 2.7
	100	1.55 ± 0.06	7.2 ± 0.1	41.5 ± 2.2
	200	1.58 ± 0.06	7.3 ± 0.1	40.4 ± 2.3
Motorcycle	0	1.33 ± 0.07	6.1 ± 0.2	50.2 ± 3.3
	1	1.38 ± 0.07	6.4 ± 0.3	47.9 ± 2.9
	10	1.46 ± 0.06	6.8 ± 0.2	44.9 ± 2.7
	100	1.57 ± 0.05	7.4 ± 0.1	40.8 ± 2.7
	200	1.59 ± 0.06	7.4 ± 0.1	40.4 ± 2.7
Vehicle	0	1.30 ± 0.09	6.0 ± 0.3	50.9 ± 3.3
	1	1.39 ± 0.07	6.4 ± 0.2	47.5 ± 2.7
	10	1.51 ± 0.06	7.0 ± 0.2	43.0 ± 2.8
	100	1.62 ± 0.06	7.5 ± 0.1	38.9 ± 2.5
	200	1.63 ± 0.06	7.5 ± 0.1	38.5 ± 2.4

vehicle passes and 100 footprints. The same number of passes made by a mountain bike or motorcycle resulted in levels of bulk density and soil compaction intermediate to the other 2 (Table 3). Soils became significantly compacted after a single pass in the vehicle trail and after 10 passes in the other 3 trails.

The proportional extent of impact and the statistical variability of soil compaction, bulk density, and percent pore space decreased with increasing number of passes. Differences between biking and motorcycle trails, and between 100 and 200 passes in all 4 trails, were not significant ($P > 0.05$; Table 3). Moreover, significant interaction was not found between disturbance type and visit frequency for soil bulk density, compaction, and percent pore space ($P > 0.05$; Table 4).

DISCUSSION

I studied the interactive effects of disturbance type and visit frequency on soil physical attributes in a *Coleogyne* shrubland of southern Nevada to quantify soil compaction under controlled traffic conditions. Human recreational activities significantly increased soil compaction and soil bulk density, but decreased percent pore space. The greatest effects occurred during the first few passes, especially

TABLE 4. Results of 2-way ANOVA showing effects of disturbance type, visit frequency, and their interactions on soil bulk denstiy, compaction, and percent pore space. For disturbance type df = 3, for visit frequency df = 4, and for disturbance type * visit frequency combination df = 12.

Source of variation	Bulk density		Compaction		Pore space	
	F	*P*	*F*	*P*	*F*	*P*
Disturbance type	14.41	0.0000	3.93	0.0244	3.45	0.0373
Visit frequency	163.95	0.0000	117.30	0.0000	38.21	0.0000
Disturbance * Frequency	1.51	0.2036	1.61	0.1696	0.27	0.9885

in vehicle trails, with changes per pass decreasing as the number of passes increased in all 4 trails.

Soil texture is a major factor in determining the magnitude of bulk density increases under applied pressure or loading. Unlike playas and sand dunes with mixtures of equal-sized particles, many soils of the Mojave Desert are highly susceptible to soil compaction. Poorly sorted soils, particularly those with a loamy sand or sandy loam texture with abundant gravel in the profile, are most vulnerable to soil compaction, and these soils are most common in bajadas and alluvial fans of the Mojave Desert (Webb 1982).

Both the proportional extent of impact and the statistical variability of soil compaction, bulk density, and percent pore space decreased with increasing numbers of passes. Significant differences were detected between 1 pass and 100 passes, but differences between 100 passes and 200 passes were not significant in any of the 4 disturbance types. This study agrees with Webb's (1982) study, indicating that soil bulk density increases in the upper 6 cm and decreases in proportion to the inverse of number of passes. Thus, greatest bulk density increases and related property changes per pass will occur during the initial few passes (Webb 1982). Soil compaction is a product of increased bulk density and decreased pore space. The degree of soil compaction is a function of disturbance type and visit frequency when examining these 2 factors independently. However, interactive effects of disturbance type and visit frequency on soil bulk density, compaction, and percent pore space were not statistically significant. In this study additional passes caused no significant further compression because soils were already compacted. Effects of hiking and biking slowly increased over time relative to effects of motor vehicle traffic.

Results of this study illustrate the damage that recreational activities can do to dry desert soils in *Coleogyne* shrubland. Such activities cause soil disturbance through disruption and compaction of surface soil. Soil compaction, which adversely impacts various soil attributes, is one aspect of land degradation. Given the fragility of desert soils, random human trampling and off-road motor vehicle traffic can severely compact soils across large areas over time. Despite growing evidence that hiking, biking, and relentless motor vehicle use are very damaging to fragile desert soils, the public continues to use Kyle Canyon and other areas of the Mojave Desert for recreational activities. It is imperative to educate visitors about the ecological consequences of soil compaction. With this knowledge, they may more likely voluntarily minimize soil compaction by staying within established trails.

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