Reports

Physical Effects of Vehicular Disturbances on Arid Landscapes

Abstract. *Field experiments indicate that the use of off-road vehicles on arid land increases the amount and frequency of water runoff and erosion by decreasing soil porosity, infiltration capacity, effectiveness of surface stabilizers, and hydraulic resistance to overland flow. These effects are long-lived and may result even when the use of these vehicles is slight.*

Arid lands in the southwestern United States are being used increasingly for recreation, housing, and purposes of national defense (*1*). Thus it is desirable to document, analyze, and, ideally, predict the environmental impacts resulting from such uses. Among the most conspicuous of these impacts is the physical response of desert landscapes to off-road vehicles (ORV's) (*2*). Evaluation of this response can lead to better understanding of hydrological and geomorphological processes in arid regions and establish base-line information on substrate responses that affect overall desert ecology.

During the past decade a number of studies have documented the effects of ORV activity on physical and biological components of the desert environment (*3*). Very few studies, however, have addressed the processes involved and the possibility of prediction. In this report we summarize results of field experiments in which we investigated the effects of ORV's on (i) soil bulk density and infiltration capacity and (ii) runoff and water erosion processes in the western Mojave Desert, California. We also consider ways for predicting water erosion and expectations for landscape recovery.

Compaction of soil by vehicle tires may extend to a depth of several decimeters (*4, 5*). We found that soil bulk density increases logarithmically with the number of vehicle passes; that is, the largest increase per pass occurs during the first few passes. For a western Mojave Desert loamy sand subjected to 0, 1, 10, 100, and 200 motorcycle passes and having an average moisture content of 6.2 percent (by weight) at the time of compaction, the regression equation

$$\rho = 1.60 + 0.0337 \ln n \qquad (1)$$

relates dried bulk density ρ (tons per cubic meter) of cores, which sample the upper 60 mm of soil, to the number of passes n, with $r^2 = .79$. The form of this empirical equation also appears to be valid for different moisture contents and soil textures (*5*).

Compaction almost invariably reduces the infiltration capacity of soil and markedly increases its effective strength, as measured by its resistance to vertical cone penetration (*5–7*). Changes in bulk density however, do not fully reflect the extent to which soil hydrological properties are modified by vehicle use. The terminal infiltration rate f_t (millimeters per hour) of the compacted loamy sand, measured after 2 hours of infiltration from double-ring infiltrometers, is expressed by

$$f_t = 81 - 9.7 \ln n \qquad (2)$$

with $r^2 = .67$. Changes in moisture retention characteristics were analyzed in a laboratory pressure-plate apparatus. The samples analyzed were 40 minimally disturbed core samples, 57 mm in diameter by 30 mm in height, taken after various intensities of vehicle use (*5*). On the basis of these changes, effective pore-size distributions of soils subjected to 0, 1, 10, 100, and 200 motorcycle passes were calculated (*8*). It is evident that most of the observed increases in bulk density result from destruction of relatively large pores (effective diameter > 4.5 μm) (Table 1). Because soil infiltration capacity is predominantly controlled by the presence and interconnection of these large pores, vehicular use markedly reduces infiltration.

Under natural conditions, most soil-mantled western Mojave Desert surfaces have such high infiltration capacities that there is no runoff except during the most intense storms. Rainfall of 40 to 60 mm/hour for 20 minutes would be required to generate runoff on the initially dry, undisturbed surfaces we examined (*9*). Comparison with available rainfall data suggests that Horton overland flow and accompanying soil erosion may only recur at intervals of tens of years on many such surfaces (*10*). In contrast, ORV-impacted areas experience local ponding and runoff during rainfall of less than 10 mm/hour and, hence, are subjected to much more frequent erosion by overland flow.

In addition to promoting runoff, tire-soil interactions render the ground surface more susceptible to erosion. Granular desert soil materials generally are easily transported by water and wind, and the stabilizing influence of vegetation, surface crusts, and surface concentrations of coarse particles is often of paramount importance in inhibiting rapid erosion under natural conditions. This stabilizing influence is considerably reduced when the terrain is disrupted by ORV's (*11, 12*). The change is reflected in accelerated water erosion on ORV-used desert hillslopes, where the denudation rates are commonly one to two orders of magnitude greater than natural erosion rates (*13*).

We identified the principal factors affecting this accelerated water erosion by analyzing data from 50 rainfall simulation experiments on adjacent used and unused 1-m² plots in three ORV-used areas in the western Mojave (*7, 11*). Paired *t*-tests applied to paired-plot data show that ORV's increase both volume of surface water runoff and sediment yield at 99.9 percent confidence levels. Runoff was typically about 5 times greater and sediment yield 10 to 20 times greater on vehicle-used plots than on unused plots.

In addition to decreasing soil infil-

Table 1. Changes in soil bulk density and effective pore-size distribution due to compaction by motorcycle passage. The soil, a loamy sand from the western Mojave Desert, was sampled to a depth of 60 mm.

Number of passes	Mean bulk density* (g/cm³)	Pore volume (cm³/g) in effective radii range		
		$r >$ 4.5 μm	$1.5 < r <$ 4.5 μm	$r <$ 1.5 μm
0	1.52	0.21	0.012	0.051
1	1.60	0.19	0.015	0.050
10	1.68	0.17	0.013	0.046
100	1.77	0.15	0.012	0.046
200	1.78	0.14	0.011	0.043

*For 23 samples from the undisturbed area and 12 samples from each trail.

tration capacity and rendering more material available for entrainment, ORV's significantly modify runoff hydraulic properties. Boundary resistance to overland flow, as expressed by Darcy-Weisbach friction factors (*14*), is reduced an average of 13-fold after intensive ORV use (*11*). This reflects the smoothing of hillsides by vehicles traveling directly upslope. Microtopographic irregularities perpendicular to vehicle trails tend to be subdued, and ruts formed along trails accelerate erosion by channeling runoff and allowing it to propagate more rapidly downhill. Qualitative field observations indicate that intermittent ponding and flow diversions caused by microtopographic roughness—often created by plants and burrowing animals on natural desert hillslopes—are efficient dissipators of flow energy and commonly cause deposition of sediment at short (< 1-m) intervals. After ORV use, not only is more runoff power (*15*) usually available to transport sediment, but greater sediment yields usually result for equivalent amounts of runoff power (Fig. 1). This probably reflects an artificially induced change from water erosion limited by surface stabilization to erosion limited by the sediment transport capacity of runoff. Thus, ORV modifications of the desert surface fundamentally change its response to runoff.

We tentatively identified the areas most susceptible to ORV-induced increases in water erosion by performing multivariate statistical analyses of 22 experimental variables reflecting rainfall and slope characteristics, surface and subsurface soil textures and strength, and infiltration rates. The character of rainfall is by far the most important factor in predicting the increase in erosion. Multiple linear regression relating rainfall energy-intensity (*16*), slope inclination, and the proportion of the surface covered with fine particles (< 1-mm sieve diameter) on undisturbed plots to the increase in sediment yield after ORV use produces a multiple r^2 of .72. Alternatively, rainfall energy-intensity and undisturbed plot infiltration capacity can be used to predict increases in sediment yield (r^2 = .83). Overall, the analysis predicts that after ORV use, accelerated water erosion will be least severe in (i) areas subject to rainfall of short duration and low intensity, (ii) areas with high initial infiltration rates and low slope, and (iii) areas with abundant surface sand and gravel (7). However, many of these areas seem to be particularly susceptible to accelerated wind erosion after ORV use (*12*).

A key concern regarding desert terrain is its rate of recovery after these hydrologic and geomorphologic disturbances. Extrapolation of data reflecting 51 years of natural recovery from soil compaction at the abandoned Wahmonie townsite in southern Nevada suggests that roughly a century is required for bulk density, strength, and infiltration capacity to be restored. Invading vegetation usually appears in such compacted areas in a few years, but native perennial species are very slow to return (*17*). Our observations and those of others (*18*) suggest that surface crusts reform rather rapidly after disruption, often during the first subsequent period of wetting and drying. Reestablishment of well-developed surface stone covers in severely disturbed areas may require hundreds of years (*6*), while at other sites recovery may require tens of years (*19*). Due to this generally slow return to natural conditions, enhanced erosion may continue for a long time and, because of the exceedingly slow formation of desert soil, accelerated soil loss may be the most long-lasting and difficult to alleviate of all ORV impacts.

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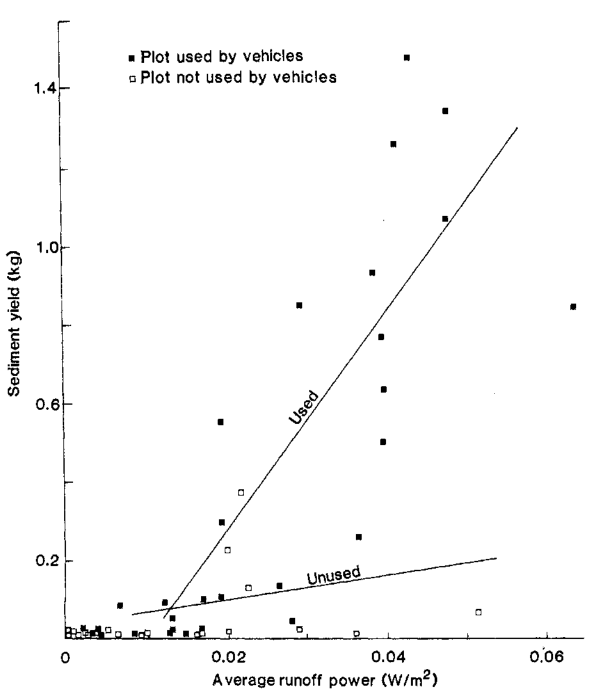

Fig. 1. Experimental data and computed regression lines for average runoff power versus sediment yield from 1-m² erosion plots used and not used by ORV's (*11*). These results were derived from 20-minute simulated rainstorms of about 66 mm/hour. Such rainstorms occur about once every 100 years in the western Mojave Desert (*10*). The greater sediment yield (for similar runoff power) from used plots suggests that entrainable grains are more readily available and that transport rates are more directly related to runoff power after use by ORV's.

References and Notes

1. The American Association for the Advancement of Science Committee on Arid Lands [*Science* **184**, 500 (1974)] addressed the impacts of vehicular recreation, and E. Marshall [*ibid.* **207**, 961 (1980)] described the environmental controversy surrounding construction of the MX missile system on desert lands in Nevada and Utah.
2. D. Sheridan [*Off-Road Vehicles on Public Land* (Council on Environmental Quality, Washington, D.C., 1979)] reported that 25 percent of Americans participate in ORV recreation.
3. R. H. Webb and H. G. Wilshire, [*U.S. Geol. Surv. Open-File Rep. 78-149* (1978)] provide an annotated bibliography of ORV studies.
4. C. T. Snyder, D. G. Frickel, R. F. Hadley, R. F. Miller, *U.S. Geol. Surv. Water Res. Invest. 76-99* (1976).
5. R. M. Webb, in preparation.
6. H. G. Wilshire and J. K. Nakata, *Calif. Geol.* **29**, 123 (1976).
7. B. S. Hinckley, in preparation.
8. Effective pore-size distributions were obtained by using the relation $r = 2\sigma/\psi$, where r is maximum effective radius of pores retaining water, σ is surface tension of the air-water interface, and ψ is matric potential. Matric potential is given as a function of volumetric moisture content by the experimentally determined moisture characteristic curve (*5*).
9. Rainfall simulation data (*7*, *11*) and drip infiltrometer data (*5*) at similar localities with predominantly sandy soils yielded similar results.
10. We used *U.S. Weather Bur. Tech. Pap. 28* (1958) to estimate the relations between the intensity, duration, and frequency of rainfall in the study areas. Horton overland flow is generated when rainfall intensity exceeds soil infiltration capacity.
11. R. M. Iverson [*Earth Surf. Process.* **5**, 369 (1980)] studied processes of accelerated pluvial erosion on desert hillslopes modified by vehicular traffic.
12. D. A. Gillette, J. Adams, A. Endo, D. Smith, and R. Kihl (*J. Geophys. Res.*, in press) experimentally studied accelerated wind erosion on desert surfaces used by ORV's.
13. Erosion rates for small drainage basins in semiarid Wyoming, as measured by R. F. Hadley and S. A. Schumm [*U.S. Geol. Surv. Water Supply Pap. 1531-B* (1961)], varied from 0.02 to 0.6 mm/year. Erosion measured in New Mexico by L. B. Leopold, W. W. Emmett, and R. M. Myrick [*U.S. Geol. Surv. Prof. Pap. 352-G* (1966)] averaged 5.3 mm/year. Compare these values to the 150 mm/year measured by Snyder *et al.* (*4*) in Dove Springs Canyon, California, an area subjected to ORV use, or the 220 mm/year measured by R. Stull, S. Shipley, E. Hovanitz, S. Thompson, and K. Hovanitz [*Geology* 7, 19 (1979)] in Ballinger Canyon, California, another such area.
14. The friction factor is defined as $f = 8gq(\sin\theta)/v^3$, where g is gravitational acceleration, q is runoff

discharge per unit width, θ is the inclination of water surface, and v is mean runoff velocity.
15. Spatially and temporally averaged runoff power per unit area is $P = \tau_0 v = \rho g q(\sin \theta)$, where τ_0 is mean bed shear stress and ρ is fluid density. R. A. Bagnold [*Water Resour. Res.* **13**, 303 (1977)] discussed the general relation between flow power and sediment transport. M. Kilinc and E. V. Richardson [*Colo. State Univ. (Fort Collins) Hydrol. Pap.* *63* (1973)] found that the rate of sediment transport by artificially generated shallow flows was closely related to flow power. See also (*11*).
16. Energy-intensity for these experiments is equal to the average intensity of the rainfall during 20 minutes multiplied by the total kinetic energy released.
17. R. H. Webb and H. G. Wilshire (*J. Arid Envir.*, in press) determined soil property and vegetation recovery rates through measurements of areas undisturbed for known times since their initial severe disturbance. The Wahmonie site offers this unique opportunity because it is located on the Nevada Military Test Site, which is closed to the public.
18. R. E. Eckert, M. K. Wood, W. H. Blackburn, F. F. Peterson [*J. Range Manage.* **32**, 394 (1979)] studied the effects of crust development on infiltration and the production of suspended sediment on ORV-modified desert soils. P. Farres [*Earth Surf. Process.* **3**, 243 (1978)] experimentally demonstrated that a considerable surface crust may form during a single rainfall.
19. D. Sharon, *Z. Geomorphol.* **6**, 129 (1962).
20. This research was supported by the U.S. Army Research Office. We thank H. Wilshire, A. Heyneman, D. Booth, and B. Aubry for critically reading the manuscript.

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Photoperiodic Control and Effects of Melatonin on Nonshivering Thermogenesis and Brown Adipose Tissue

Abstract. *Exposure to a short photoperiod improved the thermogenic capacity, and cold resistance of Djungarian hamsters and increased the respiratory power of their brown adipose tissue. Exposure to a long photoperiod caused a decrease in thermogenic measurements. This thermotropic action of the short photoperiod was detectable only during late summer and fall. A similar thermotropic response could be elicited by implanting hamsters with melatonin, indicating that the pineal may be involved in photoperiodic control of thermoregulatory effectors.*

At thermoneutrality, most small mammals have only a small capacity for nonshivering thermogenesis (NST); full capacity is developed after a few weeks of cold adaptation (*1*). This thermogenic improvement is always accompanied by an increase in mass or by structural changes improving the metabolic capacity of brown adipose tissue (BAT), which is the most important site of NST (*2*). The uniformity and intensity of thermogenic improvements during cold adaptation in the laboratory suggest that seasonal changes of NST in field populations of small mammals living in temperate latitudes are simply a consequence of seasonal changes in ambient temperature (T_a). However, there is evidence that nonthermal stimuli, such as the photoperiod, may also affect the development of NST and BAT (*3*). Furthermore, seasonal changes of NST were observed in Djungarian hamsters living in a seasonally changing photoperiod at constant thermoneutral T_a (*4*). To test whether this seasonality was the result of photoperiodic control, we exposed Djungarian hamsters to long or short photoperiods at different times of the year and measured the changes in their thermogenic capacity as well as in the oxidative capacity of BAT.

Djungarian hamsters, *Phodopus s. sungorus*, were bred and raised in the laboratory under naturally changing photoperiodic conditions, at a constant T_a of 23°C. At different times of the year (Fig. 1), hamsters were transferred from the natural photoperiod to either a long (16 hours of light per day) or short (8 hours of light) photoperiod at the same T_a of 23°C. After 2 months, the hamsters were subjected to a cold resistance test (*5*), and their capacity for NST was estimated from the thermogenic response to noradrenaline (NA) (0.8 mg per kilogram of body weight) in the nonanesthetized animals. After analysis of thermogenic measurements, BAT was removed for preparation of mitochondria (*6*). The specific amount of mitochondria was determined from the activity of four mitochondrial marker enzymes measured in the tissue homogenates and in the isolated mitochondrial fraction (*7*). In addition, the DNA content of BAT was determined in order to evaluate changes in the mitochondrial portion per cell of BAT.

Djungarian hamsters responded to the short photoperiod by an increase in thermogenic capacity in comparison with hamsters kept at the long photoperiod (Table 1). Maximum cold-induced oxygen consumption ($\dot{V}O_2$) and NST were both elevated by about 2.5 ml of oxygen per gram per hour (29 percent and 36 percent, respectively), which enabled these hamsters to maintain normothermia down to a T_a of −41°C during the cold resistance test. The effect of the short photoperiod was even more exaggerated when respiratory capacities of BAT were compared. Cytochrome oxidase activity was increased by 116 percent, and mitochondrial protein was increased by 76 percent in the short photoperiod. These biochemical changes indicate an improvement of thermogenic capability for BAT, as expected for an enhanced NST capacity. Cytochrome oxidase and mitochondrial protein were evaluated per unit of fresh weight of BAT as well as per unit weight of DNA in BAT. The two modes of expression gave similar changes due to photoperiodic stimulation, indicating that intracellular respiratory capability of single BAT cells was affected by the photoperiod.

Similar photoperiodic treatments were

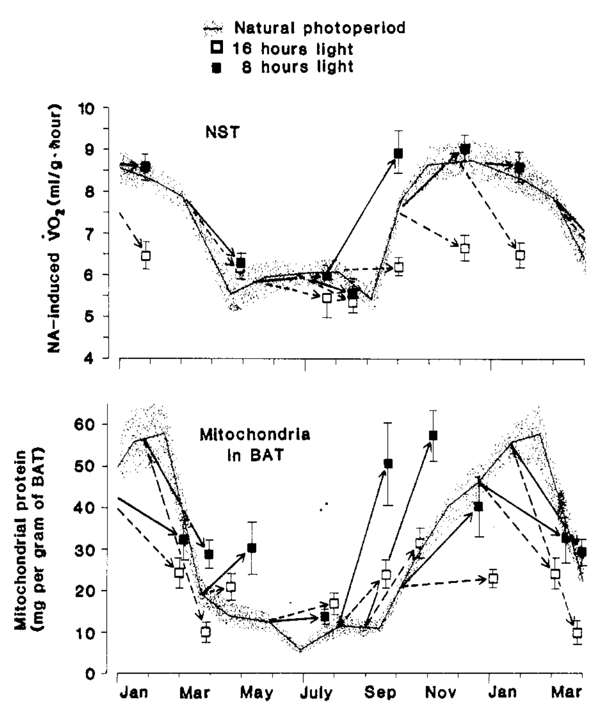

Fig. 1. Seasonal variation of photoperiodic effects on NST and on BAT mitochondria. The solid line surrounded by a dotted area shows the seasonal development of both parameters when hamsters were kept in a seasonally changing photoperiod but at constant T_a of 23°C. The arrows indicate the changes induced by exposure to short (■) or long (□) photoperiods at that particular time of the year. Values are means ± standard error (S.E.).

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