Final Report

Sustainable Disturbance Levels for Military Training on Gypsic Soils (Phase III)

PROJECT LOCATION: Holloman Air Force Base (HAFB)

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Organization

This report is organized into six sections. The ***Introduction*** provides a general background and discussion of the problem. Protocols used are outlined under ***Methods,*** and the data are summarized in tabular form and discussed under ***Results and Discussion***. The ***Synthesis*** section integrates the indicators in order to assess the resistance and resilience (recovery potential) for each of three soil types and three disturbance classes. A preliminary conceptual model is the basis for management and monitoring decisions addressed in the ***Recommendations*** sections. A **Web-based Decision Tool/Model** was developed based on the results of this study.

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1. Introduction:

Large areas of military land throughout the western United States have been degraded by military and nonmilitary uses, including livestock grazing, ground defense training and vehicle maneuvers. These activities disturb the soil surface and have direct and indirect effects on vegetation. The net impacts of these activities vary depending on the resistance and resilience of the ecosystem.

1.1. Soils. Surface disturbances by humans, livestock and vehicles have multiple effects on soils (Webb and Wilshire, 1983; Thurow, 1991). Few studies, however, have addressed the effects of disturbance on gypsiferous soils covered by microbiotic crusts. These soils cover most of Holloman AFB. Previous studies in arid regions have illustrated the critical importance of soil biological crusts for surface stabilization and erosion control (Belnap, 1995; Belnap and Gillette, 1998), and the importance of crust biological nitrogen fixation for maintaining soil fertility in some arid systems (Belnap, 1994). The effects of soil biological crusts and their disturbance vary in different parts of the world (Webb and Wilshire, 1983; Eldridge and Greene, 1994). A study similar to the one initiated in Phase I of this study was implemented on nongypsiferous soils at a site in the Chihuahuan Desert near Holloman AFB. Observations and preliminary results of this study support the general conclusion that interactions between soils and types of disturbance dramatically affect impacts on ecosystem function in areas dominated by microbiotic crusts. Ancillary studies using a rainfall simulator and a wind tunnel have shown that climate and, especially, the temporal distribution of rainfall plus the frequency and intensity of high-wind events must be considered together with soil and disturbance type. Results of both studies are now being analyzed and prepared for publication (Herrick et al., unpub. data).

1.2. Vegetation. Direct effects of disturbance on vegetation are widely recognized. Trampling and vehicle traffic tend to have a negative effect on woody vegetation, while herbaceous vegetation can be positively or negatively affected. Indirect effects include changes in soil water and nutrient availability (Webb and Wilshire, 1983; Thurow, 1991).

The objectives of this study were to: (1) identify gypsic soil(s) most suitable for military training exercises; (2) evaluate the impact of different disturbance types associated with military training activities on the resistance and resilience of a suite of vegetation, microbiotic crust, hydrology and water erosion, and wind erosion indicators; and (3) develop a preliminary conceptual model and set of recommendations for where and when military training is most suitable in these semi-arid landscapes.

The information gained from this study is already being applied to assessment (Pellant et al., 2005), monitoring (Herrick and Whitford, 1995; Herrick et al., 2005), and remediation of degraded land (Herrick et al., 1997; Herrick et al., 2006; Rango et al., In Press).

2. Methods:

2.1. Study sites. Three study sites were chosen to represent the dominant soil types at Holloman AFB. A full replication of treatments was performed at these three sites. All sites were flat (<2% slope). All three sites may have been extensively grazed by livestock prior to 1942 when DOD acquired the land on which Holloman AFB is now located. The three sites were:

2.1.1. Dune margin. This site had nearly 100% gypsum soil and was located near the eastern border of the White Sands Missile Range, less than 200 m east (downwind) of active dunes. Highly dispersed low-statured shrubs dominate the site. Little, if any, anthropogenic disturbance has occurred here for at least 35 years.

2.1.2. Transition. This site was located in an area with gypsum intergrading with silty, silica-based material. It is covered by a patchy (1-20 m diameter) mosaic of dense perennial grasses with interspersed shrubs. The site has had very limited anthropogenic disturbance.

2.1.3. Outcrop. This site was located on partially indurated gypsum, exposed at and near the surface. The site is dominated by dispersed sub-shrubs, perennial grasses and forbs. There is some evidence of military training in the area, including several communications wires and foxholes. These would have been generated in the past 30 years; the mission of the base was changed from missile research to supporting tactical fighter aircraft in the early 1970's. Plots were located to avoid clear signs of historic disturbance.

2.2. Experimental design. A randomized, complete block design, with six blocks and four treatments, was applied at each of the three sites. The 24 individual plots at each site measured 8x30 m.

2.3. Treatments. The treatments listed below were first applied in 1997. In 2000, the treatments were re-applied to half of each treatment plot (4x30 m).

2.3.1. Control. These plots were left untreated for the duration of the study.

2.3.2. Horse. For this treatment, horses were guided by their riders back and forth across each plot until it appeared that every point had been disturbed (either having been stepped on or had soil directly kicked onto it) at least once. The number of times the horses passed across each plot was standardized across blocks and sites.

2.3.3. Infantry. For this treatment, booted soldiers crossed across each treated plot a fixed number of times in the same manner as described in the horse treatment above.

2.3.4. Track. For this treatment, a WWII-vintage jeep was driven back and forth across the plots at a speed of 5 to 10 kph. Each point on each treated plot was run across twice by two wheels for a total of four wheel passes. Tire inflation pressure was kept standardized at approximately 15 psi.

2.4. Chronology.

Oct-Nov, 1997:	Baseline measurements completed for selected variables. Treatments applied to each 8x30 m plot. Post-treatment measurements completed.
Oct-Nov, 1998:	One-year, post-treatment measurements completed.
Oct-Nov, 2000:	Three-year, post-treatment measurements completed. Treatments re-applied to half of each treatment plot (4x30 m). Post-re-treatment measurements completed.
Oct-Nov, 2001:	Four-year, post-treatment measurements completed. One-year, post-re-treatment measurements completed.
Oct-Nov, 2003:	Six-year, post-treatment measurements completed. Three-year, post-re-treatment measurements completed.

Several additional erosion bridge and wind erosion measurements were also completed (see Results section below) during other data collection periods. Laboratory measurements and erosion bridge photograph analyses were completed during non-field months.

2.5. Measurements. At each 8x30 m plot, a single, 30 m long transect was set up along one side of the plot. With the exception of the dust collector (BSNE boxes) all measurements were taken along these transects. For each measurement year, transects were moved 50 cm towards the center of each plot to ensure that previously-disturbed areas were not remeasured or resampled. This approach increased the amount of variability in vegetation measurements from year to year, but minimized the impact of previous measurement disturbance. All of the following measurements were taken pre-treatment (1997), immediately post treatment (early November 1997), at the same time of year in 1998, 2000, 2001, and 2003, unless otherwise stated.

2.5.1. Vegetation indicators. Plant cover was determined using the continuous line-intercept method. Percentage total canopy, shrub, and grass cover was calculated from canopy length measurements along each 30 m transect. (While the Jornada has since replaced this method with the more rapid, accurate, and repeatable line-point method, the continuous line-intercept method was used for the duration of this study in order to maintain a consistent dataset.)

2.5.2. Microbiotic crust indicators.

2.5.2.1. Lichen cover. Lichen cover was recorded every 25 cm along each 30 m transect using the line-point intercept method. Percentage lichen cover per plot was calculated from the resulting data. No immediate post-treatment measurements were made for lichen cover since it was impossible to do so accurately until after the dust had been redistributed by rainfall, exposing still-intact crust fragments.

2.5.2.2. Chlorophyll content. This indicator of cyanobacterial biomass was estimated using absorbance techniques. Ten dry samples were collected per plot. Chlorophyll was extracted from samples with dimethylsulfoxide (DMSO) in the dark for 40 minutes at 65°C. Samples were then centrifuged. Absorption spectra were measured at 666 nm in a Hewlett-Packard diode array spectrophotometer after calibration with a DMSO blank.

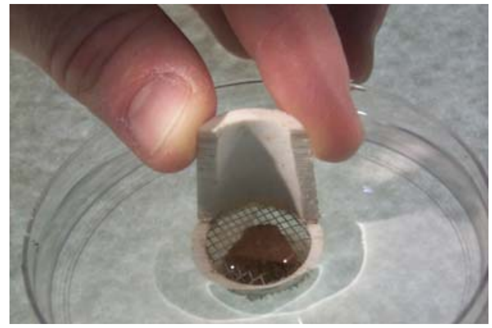
2.5.2.3. Nitrogen fixation potential based on nitrogenase activity. Fifteen dry samples per plot were collected. Samples were placed in clear, gas-tight tubes; the entire crustal surface was wetted equally with distilled water and then injected with enough acetylene to create a 10% acetylene atmosphere. After injection, samples were incubated for 4 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 an 8 foot, 8% NaCl on alumina column, using helium as the carrier gas (30 ml/min). Results are reported as gas chromatographic units and are not convertible to kg/ha of N without calibration by N^{15}.

2.5.3. Hydrology and water erosion indicators.

2.5.3.1. Water infiltration. Water infiltration rates were measured using a 12.5 cm ring infiltrometer (Bouwer, 1986) at five locations along the 30 m transect (at 3, 9, 15, 21, and 27 m) in each plot. The soil surface was pre-wetted to a minimum depth of 4 cm and an aluminum irrigation pipe ring inserted to a depth of 3 cm. The ring was filled to a depth of 3 cm and an inverted, one-liter soda bottle with an air tube was used to maintain water at a constant depth within the ring. At least 2.5 cm of water was allowed to infiltrate into the soil before measurements were begun, ensuring infiltration rates were at or near steady state. Once the water level in the inverted bottle had dropped a minimum of 5 cm, times and water depth were recorded and the rate of water movement calculated in mm/h. Due to time constraints, infiltration was not measured pre-disturbance in 1997.

Figure 1. Single ring infiltrometer.

2.5.3.2. Field soil stability. At 2 m intervals along each 30 m transect, soil surface stability was measured using a field stability test (Herrick et al., 2001). A small aluminum sampling scoop was used to gently lift 6-8 mm diameter, 3-4 mm thick soil fragments from the soil surface at each sampling point. Each sample was ranked to generate qualitative stability index values (from 1 to 6: lowest to highest stability) (Herrick et al., 2001).



(1) Collect 6-8 mm-diameter sample from surface and 20-25mm depth (1 sample/sieve)
(2) Immerse in dI water.
(3) Record slaking in 1st 5 min.
(4) Sieve 5x.
(5) Rate sample on a scale from 1 to 6.

Stability class	Criteria for assignment to stability class (for Standard Characterization)
0	Soil too unstable (falls through sieve).
1	50 % of structural integrity lost within 5 seconds of insertion in water.
2	50 % of structural integrity lost 5 - 30 seconds.
3	50 % of structural integrity lost 30 - 300 seconds after insertion OR <10% of soil remains on sieve after 5 dipping cycles.
4	10 - 25% of soil remains after 5 dipping cycles.
5	25 - 75% of soil remains after 5 dipping cycles.
6	75 - 100% of soil remains after 5 dipping cycles.

Figure 2. Field soil stability kit.

2.5.3.3. Pocket penetrometer. A SoilTest pocket penetrometer (Bradford, 1986) was used to measure soil surface resistance to penetration. The flat-tipped end of the penetrometer was 6.5 mm in diameter. Surface resistance was measured to a depth of 6.5 mm. For post-disturbance measurements, a foot extension that was 25 mm wide was used in order to increase sensitivity to treatment differences. Numbers were converted to correct for the differences in foot diameters. Pocket penetrometer measurements were taken in 1998, 2000, 2001 and 2003 only.

2.5.3.4. Surface roughness. Using an erosion bridge method, soil surface roughness was calculated as the standard deviation of the heights of 24 pins placed in a 50 cm line at 2 cm spacing along the surface. Estimates were made at five permanent locations per plot immediately following treatment. These measurements were repeated in December 1997, May 1998, May 1999, October 2000, December 2000, June 2001, October 2001, and March 2004.

Figure 3. Erosion bridge.

2.5.4. Wind erosion indicators.

2.5.4.1. Wind boxes. Relative differences in soil detachment and transport by wind were estimated by anchoring a Big Spring Number Eight (BSNE) dust trap (Fryrear, 1986) on the soil surface at one end of each study plot, parallel to the long side facing either west (dune margin and transition sites) or south (outcrop site). Wind erosion was calculated from resulting samples as kg of sediment per m^2 per month for each plot. Measurements were taken five times: post-treatment in 1997, March 1998, May 1998, May 1999, and October 2000.

Figure 4. BSNE wind box.

2.5.4.2. Torvane. Crust strength was measured using a standard Torvane apparatus. Measurements were taken five times every 2 m along the 30 m transect of each plot. For most measurements, a 2.5 cm diameter disk was used. For the post-disturbance measurements, a 4.75 cm diameter disk was used to increase sensitivity to treatment differences. A factory-supplied conversion factor was used to correct for differences in disk diameter.

2.6. Calculations.

2.6.1. Single disturbance.
2.6.1.1. Resistance. Resistance to each treatment was calculated as a percentage of the control value. Some properties change immediately in response to disturbance, while disturbance effects on others are delayed. Consequently, we calculated resistance as the smaller of the post-disturbance values (1997 through 2003).

2.6.1.2. Relative resilience (6 yr). This is the proportion of the function recovered 6 years after treatment as a percentage of function lost following treatment. We adjusted for natural variability using values from control plots at each site. Where this value is negative, the treatment continued to decline relative to the control.

2.6.1.3. Absolute resilience or percent of control (2003). This is simply the 2003 treatment value as a percentage of the 2003 control (the 2004 data was used for the Erosion Bridge). It reflects how far below potential the plot is 6 years post-disturbance.

2.6.2. Double disturbance.

2.6.2.1. Resistance (2X). This is the treatment value as a percentage of the control value. The smaller of the post-disturbance values was used to calculate resistance.

2.6.2.2. Resistance (+1). This is the ratio of the smallest double-disturbance plot value to the same year single-disturbance, post-disturbance value for the same indicator. This is the resistance of plots to additional disturbance. Plots that have not recovered may show higher resistance than some that had recovered.

2.6.2.3. Relative resilience (6 yr). This is the proportion of the function recovered 6 years after treatment as a percentage of function lost following treatment. We adjusted for natural variability using values from control plots at each site.

2.6.2.4. Absolute resilience or percent of control (2003). This is the 2003 treatment value as a percentage of the 2003 control (the 2004 data was used for the Erosion Bridge).

2.7. Statistical analysis.

2.7.1. Treatment effects. An Analysis of Variance (ANOVA) was used to test for treatment effects during each year and univariate comparisons were made with the Control for each site. For those variables that did not meet the assumptions for ANOVA in any given year, treatment effects were tested using a Kolmogorov-Smirnov non-parametric test. In these cases, pairwise comparisons between treatments and controls were performed using Friedman's test. In all cases, the plot was always used as the experimental unit (n = 6 plots per site). Where more than one measurement per plot was made, the mean value of all measurements was used for analyses.

3. Results and Discussion:

3.1. Overview. The results for each indicator are presented on a single page in a set of tables and figures (see Table 1 example). There is one table for each of the three sites. Each table includes treatment means and standard errors for each measurement date. Resistance and resilience values (Table 2) for each site are included, as are plots of treatment:control ratios by site and treatment through time. Resistance is generally defined as percent of pre-disturbance. Because some effects are delayed we use the minimum value for up to 6 years following disturbance. In order to account for natural annual variability we use control plots as the reference. Resilience is commonly defined as either percent recovery of what was lost over a particular period of time, or as percent of control at a particular point in time. It can also be defined as the rate of recovery (e.g., percent recovery/yr). This definition was not used here. This set of definitions is commonly referred to as "Engineering Resilience". Note that much of the recent ecological literature combines the concepts of resistance and resilience into a single definition of resilience, as the amount of stress a system can absorb before crossing a threshold. We have not used this definition because it is virtually impossible to calculate and extremely expensive to determine experimentally.

Table 1. Example of complete results for single-ring infiltration. Values are means based on n = 6 plots. Five measurements were made in each plot.

WATER INFILTRATION (MM/HR)

DUNE MARGIN	**Control** Avg	*SE*	**Horse** Avg	*SE*	**Infantry** Avg	*SE*	**Track** Avg	*SE*	*p*	*Power*
Single Disturbance										
1997 (Pre-disturbed)										
1997 (Post-disturbed)	373	33	294	38	**275**	30	**172**	13	0.00	0.975
1998	430	22	**360**	16	**347**	27	**202**	9	0.00	1.000
2000	345	14	**270**	31	293	21	**196**	19	0.00	0.961
2001	455	80	343	34	342	22	**268**	22	0.07	0.578
2003	357	23	322	48	309	34	**245**	19	0.07	0.565
Resistance	--	--	76		74		46			
Resilience (6 yr)	--	--	69		51		44			
% of control (2003)	--	--	90		87		69			
Double Disturbance										
2000 (Post-)	390	32	**242**	21	**267**	15	**181**	20	0.00	1.000
2001 (1 yr post)	455	80	**294**	26	**251**	13	**270**	32	0.04	0.678
2003 (3 yr post)	357	23	**256**	20	**285**	4.9	**228**	24	<0.01	0.987
Resistance (2X)	--	--	62		55		46			
Resistance (+1)	--	--	90		73		93			
Resilience (6 yr)	--	--	32		65		38			
% of control (2003)	--	--	72		80		64			
TRANSITION	**Control** Avg	*SE*	**Horse** Avg	*SE*	**Infantry** Avg	*SE*	**Track** Avg	*SE*	*p*	*Power*
Single Disturbance										
1997 (Pre-disturbed)										
1997 (Post-disturbed)	101	15	135	11	154	36	52	2	0.01	0.875
1998	223	27	207	24	209	29	141[a]	42	0.26	0.310
2000	158	29	117	21	148	17	165	68	0.84	0.092
2001	192	33	195	40	201	47	160	38	0.88	0.083
2003	146	32	143	15	174	20	135	22	0.67	0.132
Resistance	--	--	74		93		51			
Resilience (6 yr)	--	--	93		(361)		76			
% of control (2003)	--	--	98		119		92			
Double Disturbance										
2000 (Post-)	162	25	122	12	179	27	**82**	14	0.02	0.795
2001 (1 yr post)	192	33	149	12	189	23	156	13	0.38	0.239
2003 (3 yr post)	146	32	99	11	184	28	123	15	0.02	0.749
Resistance (2X)	--	--	67		99		50			
Resistance (+1)	--	--	69		121		49			
Resilience (6 yr)	--	--	0		(1536)		71			
% of control (2003)	--	--	67		126		84			
OUTCROP	**Control** Avg	*SE*	**Horse** Avg	*SE*	**Infantry** Avg	*SE*	**Track** Avg	*SE*	*p*	*Power*
Single Disturbance										
1997 (Pre-disturbed)										
1997 (Post-disturbed)	369	40	**253**	25	**269**	46	**197**	12	0.02	0.765
1998	464	43	386	17	397	30	**368**	45	0.17	0.394
2000	389	20	321	21	330	42	**289**	39	0.06	0.614
2001	367	35	**291**	19	362	43	342	15	0.13	0.459
2003	347	57	**253**	14	295	22	260	19	0.16	0.410
Resistance	--	--	69		73		53			
Resilience (6 yr)	--	--	19		48		49			
% of control (2003)	--	--	73		85		75			
Double Disturbance										
2000 (Post-)	367	20	**258**	24	**255**	19	**259**	42	0.02	0.809
2001 (1 yr post)	367	35	**258**	16	302	12	**256**	27	0.03	0.734
2003 (3 yr post)	347	57	275	11	269	41	**231**	16	0.14	0.433
Resistance (2X)	--	--	70		69		67			
Resistance (+1)	--	--	80		77		89			
Resilience (6 yr)	--	--	34		30		0			
% of control (2003)	--	--	79		77		67			

[a] The average and SE are based on n=5 blocks instead of n=6 due to missing data

Values significantly different from Control ($p<0.05$), based on univariate comparisons or the Friedman's test, are in bold type.

Treatment effects were analyzed using analysis of variance or the Kolmogorov-Smirnov test.

Power is the probability of detecting a difference (i.e., 1- Type II error).

Table 2. Formulas used to calculate resistance and resilience.

Single Disturbance
Resistance **Description:** Resistance in response to each treatment disturbance. **Formula:** min(1997-2003 trtmt / control)
Resilience (6 yr) **Description:** Proportion of the function recovered 6 years after treatment as a percentage of function lost following treatment. **Formula:** 100 * {1 - (2003 control – 2003 trtmt) / (post-dist. control – post-dist. trtmt)}
% of control (2003) **Description:** This indicates how far below potential the plot is 6 years post-disturbance. **Formula:** 100 * (2003 trtmt / 2003 control)
Double Disturbance
Resistance (2X) **Description:** Resistance of the plots to two disturbances. **Formula:** min(2000-2004 trtmt / control)
Resistance (+1) **Description:** Resistance of the plots to additional disturbance. **Formula:** min(2000-2004 double dist. trtmt / same yr single dist. trtmt)
Resilience (6 yr) **Description:** Proportion of the function recovered 6 years after treatment as a percentage of function lost following treatment. **Formula:** 100 * {1 - (2003 control – 2003 trtmt) / (post-dist. control – post-dist. trtmt)}
% of control (2003) **Description:** This indicates how far below potential the plot is 6 years post-disturbance. **Formula:** 100 * (2003 trtmt / 2003 control)

3.2. Specific indicators.

3.2.1. Vegetation indicators. All three treatments significantly reduced vegetative cover relative to the control. The reduction was due primarily to a loss of shrub cover which declined more than grass cover in response to all treatments. It took 4 years for canopy cover to recover at the dune margin site, four times longer than it took at the transition site. The rapid recovery at the transition site was due to grass regrowth: 1998 grass cover in the infantry and track plots actually exceeded cover in the control plots by up to 60%, though the differences were not significant ($p>0.15$). The transition site differs from the other two sites in that the grass community is dominated by *Sporobolus airoides* Torrey, while *Sporobolus nealleyi* Vasey is the dominant grass on most plots at the other two sites. Shrub recovery was slow at all sites, particularly in the track plots which were significantly below the control at all three sites 6 years post-treatment. Grass cover at the dune margin site and shrub cover at the outcrop site were highly variable among plots and treatments in 2003. Overall canopy cover declined at the dune margin and outcrop sites from 2001 to 2003, possibly in response to drought conditions.

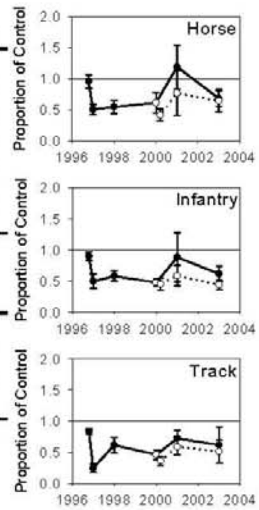
3.2.1.1. Resistance and resilience: site comparison. Vegetation at the dune margin site had both low resistance and low resilience compared to the other two sites. Resistance was high at both the transition and outcrop sites. These site differences reflect differences in species composition. The transition and outcrop sites support much higher grass cover, which is both more resistant and resilient than shrub cover. Also, shrub cover at the dune margin site is dominated by fourwing saltbush (*Atriplex canescens* (Pursh) Nutt.) which is very brittle and, therefore, susceptible to trampling. It is also possible that there is increased competition from the rapidly recovering grasses, though additional work would be needed to test this hypothesis.

3.2.1.2. Resistance and resilience: treatment comparison. While there wasn't a highly significant difference between the different treatments, the track treatment had the most negative and persistent impacts on vegetation at all sites. Shrub cover was particularly affected by the track treatment, with significant reductions persisting for 6 years at the dune margin and transition sites. Horse and infantry disturbance had a significant impact on vegetation for 3 years at the dune margin and transition sites.

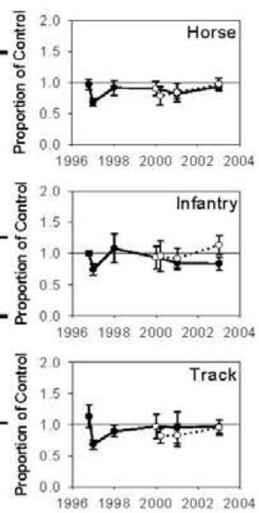
3.2.1.3. Double disturbance. The pattern for the second disturbance was similar to that of the first applied 3 years earlier. The dune margin site was most severely affected and the track treatment had the most negative effects.

TOTAL VEGETATIVE COVER (%)

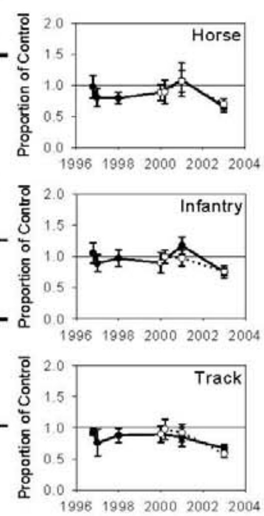
DUNE MARGIN	Control Avg	SE	Horse Avg	SE	Infantry Avg	SE	Track Avg	SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	27.3	2.0	25.8	2.3	24.6	2.3	**22.8**	1.7	0.12	0.462
1997 (Post-disturbed)	22.8	3.0	**10.7**	1.4	**10.0**	1.7	**5.0**	1.2	0.00	0.998
1998	19.7	1.2	**10.4**	1.4	**11.3**	1.6	**12.3**	2.9	0.02	0.803
2000	16.3	2.3	**9.1**	2.1	**7.5**	1.0	**7.3**	1.3	0.01	0.914
2001	11.8	1.6	11.8	1.8	7.9	1.8	9.0	2.5	0.44	0.209
2003	14.0	2.2	9.6	2.0	**8.3**	2.4	**5.8**	1.1	0.04	0.677
Resistance	--	--	47		44		22			
Resilience (6 yr)	--	--	64		56		54			
% of control (2003)	--	--	68		59		41			
Double Disturbance										
2000 (Post-)	14.7	1.4	**6.3**	1.6	**6.2**	1.2	**5.0**	0.7	0.00	0.999
2001 (1 yr post)	11.8	1.6	**6.6**	1.6	**5.7**	1.1	**6.2**	0.8	0.03	0.695
2003 (3 yr post)	14.0	2.2	**7.6**	1.6	**6.7**	1.4	**5.4**	0.4	<0.01	0.961
Resistance (2X)	--	--	43		42		34			
Resistance (+1)	--	--	70		72		68			
Resilience (6 yr)	--	--	24		14		11			
% of control (2003)	--	--	55		48		38			



TRANSITION	Control Avg	SE	Horse Avg	SE	Infantry Avg	SE	Track Avg	SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	39.0	2.5	37.9	4.1	38.9	1.9	42.3	3.9	0.77	0.108
1997 (Post-disturbed)	39.0	2.5	**26.2**	1.9	**28.7**	3.6	**25.8**	1.8	0.01	0.912
1998	31.6	3.0	28.0	3.1	31.9	5.2	27.3	2.2	0.60	0.153
2000	35.2	2.8	30.9	3.2	30.9	3.8	31.7	4.6	0.85	0.089
2001	31.8	2.6	25.9	3.2	26.7	2.9	27.5	4.2	0.64	0.143
2003	25.2	2.5	23.0	1.6	20.2	2.2	23.5	1.8	0.37	0.241
Resistance	--	--	67		74		66			
Resilience (6 yr)	--	--	83		51		87			
% of control (2003)	--	--	91		80		93			
Double Disturbance										
2000 (Post-)	37.1	3.3	27.1	2.4	32.2	4.8	28.6	2.2	0.22	0.349
2001 (1 yr post)	31.8	2.6	25.3	3.2	27.1	2.5	24.2	2.5	0.23	0.340
2003 (3 yr post)	25.2	2.5	23.9	1.9	27.2	2.3	23.2	2.6	0.64	0.141
Resistance (2X)	--	--	73		85		77			
Resistance (+1)	--	--	104		102		99			
Resilience (6 yr)	--	--	86		142		76			
% of control (2003)	--	--	95		108		92			

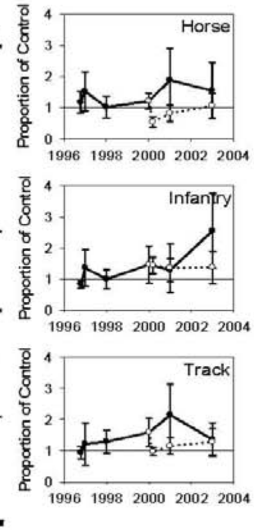


OUTCROP	Control Avg	SE	Horse Avg	SE	Infantry Avg	SE	Track Avg	SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	36.6	3.7	33.7	3.7	37.4	4.2	33.3	2.4	0.71	0.124
1997 (Post-disturbed)	33.9	3.1	26.0	3.7	28.9	3.0	24.2	5.6	0.48	0.195
1998	20.8	2.1	16.1	1.6	19.3	1.8	17.4	1.5	0.20	0.370
2000	24.1	1.4	21.4	3.3	21.4	3.6	21.0	2.3	0.78	0.106
2001	21.4	1.5	21.9	3.9	24.3	1.5	17.7	2.7	0.45	0.205
2003	21.8	1.3	**14.2**	1.7	**16.0**	1.7	**14.8**	1.8	0.01	0.904
Resistance	--	--	65		73		68			
Resilience (6 yr)	--	--	0		0		0			
% of control (2003)	--	--	65		73		68			
Double Disturbance										
2000 (Post-)	22.0	2.1	18.0	2.7	21.7	2.6	19.8	1.9	0.64	0.141
2001 (1 yr post)	21.4	1.5	21.7	2.2	20.1	2.0	18.8	1.9	0.71	0.123
2003 (3 yr post)	21.8	1.3	**14.8**	1.3	**16.2**	0.9	**12.6**	1.2	<0.01	0.981
Resistance (2X)	--	--	68		75		58			
Resistance (+1)	--	--	104		102		85			
Resilience (6 yr)	--	--	0		0		0			
% of control (2003)	--	--	68		75		58			

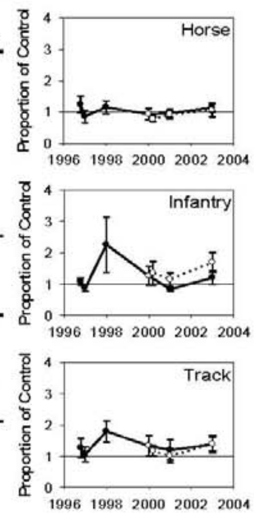


GRASS COVER (%)

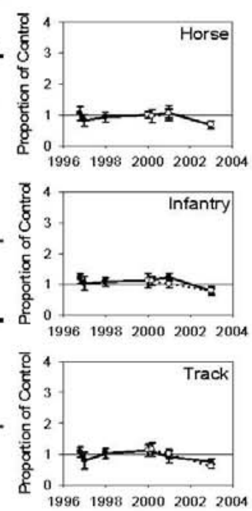
DUNE MARGIN	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	13.5	1.3	13.8	2.8	10.7	1.4	11.8	1.6	0.58	0.159
1997 (Post-disturbed)	9.4	3.1	6.3	1.4	5.7	1.5	4.1	1.4	0.41	0.226
1998	7.4	2.3	6.0	1.4	7.2	1.5	9.7	2.0	0.59	0.155
2000	3.3	0.5	4.0	1.1	4.0	1.2	4.4	0.9	0.88	0.082
2001	4.8	1.0	4.9	1.3	5.4	1.5	6.9	2.6	0.82	0.095
2003	3.4	0.6	3.3	1.0	6.4	2.6	3.3	1.0	0.45	0.205
Resistance	--	--	67		61		44			
Resilience (6 yr)	--	--	98		181		99			
% of control (2003)	--	--	98		188		99			
Double Disturbance										
2000 (Post-)	3.3	0.5	2.1	0.7	5.5	1.2	3.8	0.7	0.03	0.693
2001 (1 yr post)	4.8	1.0	3.3	1.2	3.5	0.8	4.7	0.8	0.60	0.152
2003 (3 yr post)	3.4	0.6	2.6	0.9	4.0	1.3	3.2	0.4	0.76	0.110
Resistance (2X)	--	--	64		72		94			
Resistance (+1)	--	--	53		64		96			
Resilience (6 yr)	--	--	35		142		(0)			
% of control (2003)	--	--	78		117		94			



TRANSITION	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	26.5	3.6	29.4	3.9	27.2	2.6	28.9	3.7	0.94	0.069
1997 (Post-disturbed)	26.5	3.6	20.3	2.7	22.4	2.9	24.5	2.3	0.49	0.191
1998	17.8	3.6	18.8	2.8	29.4	5.6	26.7	2.3	0.15	0.421
2000	26.3	3.4	24.0	4.5	28.5	3.4	30.7	4.5	0.72	0.119
2001	25.4	2.3	23.7	2.8	21.3	2.3	27.1	4.2	0.65	0.138
2003	18.6	3.1	19.7	2.0	19.3	1.9	22.8	1.2	0.52	0.180
Resistance	--	--	77		84		92			
Resilience (6 yr)	--	--	119		119		(310)			
% of control (2003)	--	--	106		104		123			
Double Disturbance										
2000 (Post-)	26.3	3.4	20.0	2.8	31.1	4.8	28.5	2.3	0.17	0.395
2001 (1 yr post)	25.4	2.3	22.1	2.6	26.8	2.5	23.6	2.4	0.57	0.161
2003 (3 yr post)	18.6	3.1	19.7	2.0	19.3	1.9	22.8	1.2	0.21	0.352
Resistance (2X)	--	--	76		104		93			
Resistance (+1)	--	--	100		100		100			
Resilience (6 yr)	--	--	118		(0)		(339)			
% of control (2003)	--	--	106		104		123			

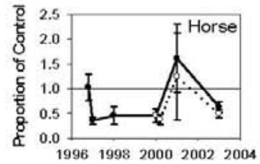


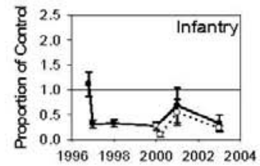
OUTCROP	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	30.4	4.6	27.7	3.1	33.7	3.6	29.2	2.2	0.58	0.159
1997 (Post-disturbed)	29.7	3.8	21.6	3.3	27.1	2.7	21.7	6.1	0.56	0.166
1998	17.1	2.1	14.6	1.3	17.4	1.4	16.3	1.7	0.62	0.148
2000	19.1	2	18.5	1.7	20.7	3.8	20.3	2.5	0.89	0.080
2001	19.2	1.8	19.4	3.7	22.7	1.8	16.5	2.9	0.49	0.189
2003	19.7	2	**12.5**	1.9	**14.3**	1.6	14.5	1.7	0.05	0.631
Resistance	--	--	63		73		73			
Resilience (6 yr)	--	--	0		0		35			
% of control (2003)	--	--	63		73		74			
Double Disturbance										
2000 (Post-)	19.1	2.0	16.3	2.7	20.3	2.3	19.1	2.0	0.69	0.128
2001 (1 yr post)	19.2	1.8	19.1	1.7	18.9	2.3	18.3	2.0	0.99	0.056
2003 (3 yr post)	19.7	2.0	**12.4**	1.4	**15.0**	1.2	**11.5**	1.5	0.01	0.868
Resistance (2X)	--	--	63		76		58			
Resistance (+1)	--	--	100		105		79			
Resilience (6 yr)	--	--	0		0		0			
% of control (2003)	--	--	63		76		58			

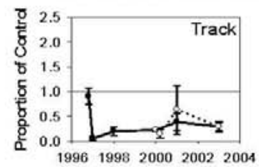


SHRUB COVER (%)

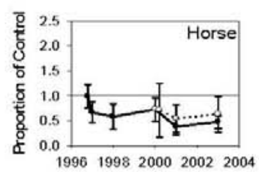
DUNE MARGIN	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	13.8	2.3	11.9	1.5	13.8	2.2	11.0	0.8	*0.55*	*0.169*
1997 (Post-disturbed)	13.4	1.4	**4.3**	0.7	**4.2**	1.3	**0.9**	0.5	*0.00*	*1.000*
1998	12.4	1.8	**4.4**	1.3	**4.0**	1.1	**2.7**	1.4	*0.00*	*0.994*
2000	13.1	2.5	**5.1**	1.2	**3.5**	1.3	**2.9**	0.6	*0.00*	*0.998*
2001	6.9	1.4	6.9	2.0	**2.5**	0.8	**2.1**	1.1	*0.04*	*0.669*
2003	10.6	1.9	**6.2**	1.5	**1.9**	0.6	**2.5**	0.6	*<0.01*	*0.990*
Resistance	--	--	32		18		6			
Resilience (6 yr)	--	--	52		0		35			
% of control (2003)	--	--	59		18		23			
Double Disturbance										
2000 (Post-)	10.6	1.2	**4.2**	1.2	**0.7**	0.3	**1.2**	0.4	*0.00*	*1.000*
2001 (1 yr post)	6.9	1.4	**3.4**	1.0	**2.2**	0.4	**1.5**	0.6	*0.01*	*0.852*
2003 (3 yr post)	10.6	1.9	**5.0**	1.2	**2.5**	0.5	**2.2**	0.2	*<0.01*	*1.000*
Resistance (2X)	--	--	40		7		11			
Resistance (+1)	--	--	49		21		41			
Resilience (6 yr)	--	--	12		18		10			
% of control (2003)	--	--	47		24		21			

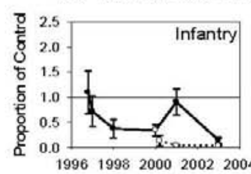


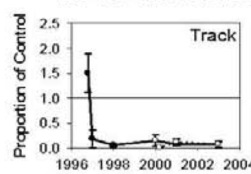




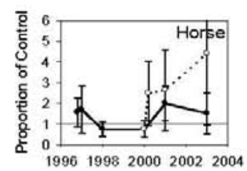
TRANSITION	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	12.5	3.5	8.5	1.7	11.8	3.4	13.4	2.5	*0.62*	*0.148*
1997 (Post-disturbed)	12.5	3.5	5.9	1.7	6.3	2.0	**1.3**	1.2	*0.03*	*0.715*
1998	13.9	3.0	9.2	5.7	**2.5**	0.8	**0.6**	0.3	*0.03*	*0.699*
2000	8.9	1.9	6.9	3.3	**2.3**	0.7	**1.0**	0.8	*0.02*	*0.778*
2001	6.4	1.4	**2.3**	0.9	5.4	1.8	**0.5**	0.3	*0.01*	*0.918*
2003	6.7	1.1	**3.3**	1.1	**0.8**	0.4	**0.7**	0.7	*<0.01*	*1.000*
Resistance	--	--	35		13		4			
Resilience (6 yr)	--	--	19		0		55			
% of control (2003)	--	--	49		13		10			
Double Disturbance										
2000 (Post-)	11.2	1.2	4.2	1.2	**0.7**	0.3	**1.2**	0.4	*0.03*	*0.708*
2001 (1 yr post)	6.4	1.4	**3.2**	1.2	**0.3**	0.2	**0.6**	0.4	*0.00*	*0.989*
2003 (3 yr post)	6.7	1.1	5.0	3.4	**0.2**	0.2	**0.6**	0.5	*0.05*	*0.640*
Resistance (2X)	--	--	38		3		9			
Resistance (+1)	--	--	140		23		89			
Resilience (6 yr)	--	--	76		0		0			
% of control (2003)	--	--	75		3		9			

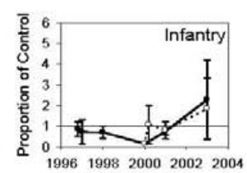


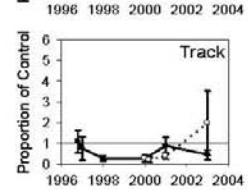




OUTCROP	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	6.3	1.4	6.0	1.7	3.7	1.0	4.1	1.3	*0.47*	*0.197*
1997 (Post-disturbed)	4.2	1.3	4.3	1.7	1.7	0.9	2.5	0.9	*0.27*	*0.306*
1998	3.7	1.2	**1.4**	0.5	**1.9**	0.5	**1.0**	0.5	*0.04*	*0.677*
2000	5.0	1.3	3.0	1.7	**0.7**	0.3	**0.7**	0.3	*0.05*	*0.648*
2001	2.3	0.8	2.5	0.4	1.7	0.5	1.2	0.5	*0.32*	*0.270*
2003	2.5	1.1	1.7	0.6	1.7	0.4	**0.2**	0.1	*0.14*	*0.433*
Resistance	--	--	39		15		9			
Resilience (6 yr)	--	--	65		81		0			
% of control (2003)	--	--	69		68		9			
Double Disturbance										
2000 (Post-)	2.8	1.4	1.7	0.4	1.4	0.6	0.8	0.4	*0.37*	*0.246*
2001 (1 yr post)	2.3	0.8	2.7	1.3	1.3	0.5	0.5	0.2	*0.25*	*0.318*
2003 (3 yr post)	2.5	1.1	2.4	0.6	1.2	0.7	1.1	0.4	*0.33*	*0.268*
Resistance (2X)	--	--	63		50		24			
Resistance (+1)	--	--	59		73		46			
Resilience (6 yr)	--	--	86		0		17			
% of control (2003)	--	--	94		50		43			







3.2.2. Microbiotic crust indicators. The viability of the microbiotic crust community is reflected in three indicators: lichen cover, chlorophyll content, and nitrogen fixation potential. Chlorophyll content is an indicator of the total biomass of photosynthetically active organisms at the soil surface, including both free-living and lichen-associated algae and cyanobacteria. Some of the lichen species fix nitrogen. The potential to fix nitrogen is correlated with nitrogenase activity measured in the laboratory. Results are reported as gas chromatographic units and are not convertible to kg/ha of N without calibration by N^{15}, which was not done. No post-disturbance lichen results are reported because it was impossible to do so accurately until after the dust had been redistributed by rainfall, exposing still-intact crust fragments.

Lichen cover 1 year after disturbance was reduced by at least 40% in all treatments at both the dune margin and outcrop sites. Lichen cover was extremely variable at the transition site, as reflected in the fact that the average cover in the six control plots was much higher than in the treatment plots even before treatments were applied. Although resilience was generally low throughout, the dune margin and outcrop sites showed very strong recovery trends, particularly when compared with similar studies in other parts of the western United States (Belnap and Eldridge, 2001). A general decline in lichen cover was observed from 2001 to 2003, possibly in response to the drought during these years.

The general pattern of chlorophyll content response was similar across sites and treatments, with a fairly dramatic reduction following disturbance followed by near-complete recovery during the next 6 years. This indicator reflects the more rapid recovery of free-living cyanobacteria. Within-site variability was also extremely high for chlorophyll.

The effect on nitrogen fixation followed a similar pattern to that of lichen cover, except that the reduction was even more dramatic with nitrogen fixation potential dropping to almost zero 1-year post-disturbance, and had a slower recovery rate in many cases. There are two possible explanations for this dramatic decline: (1) the nitrogen-fixing lichens were more severely affected by disturbance than other lichens, and (2) some of the lichen cover recorded, particularly in 1998, was dead or at least not capable of supporting nitrogen fixation. Regardless of the explanation, the implication is that retention or recovery of lichen cover is not necessarily correlated with its functional status; cover of individual species may be more closely related to nitrogen fixation (e.g., *Collema*).

3.2.2.1. Resistance and resilience: site comparison. Resistance of lichen cover to all treatments was low at all three sites. Given that pre-disturbance lichen cover was very low at the transition site, the lack of recovery here is to be expected given that conditions were clearly not suitable for microbiotic crust development. Resistance was low across sites for nitrogen fixation potential and there was little recovery at the dune margin and transition sites. Chlorophyll content was both more resistant and more resilient than lichen and nitrogen fixation, reflecting the more rapid recovery of cyanobacteria on disturbed surfaces.

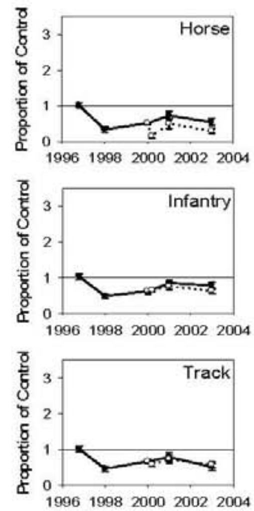
3.2.2.2. Resistance and resilience: treatment comparison. Little difference was observed between treatments, overall. Resistance to horse and track was generally lower than to infantry disturbances for all three indicators, however. Recovery was quite variable with no clear pattern emerging across sites and indicators.

3.2.2.3. Double disturbance. The second disturbance had a negative effect on most indicators at most sites. The one exception was infantry, which appeared to have caused little or no additional degradation in most cases.

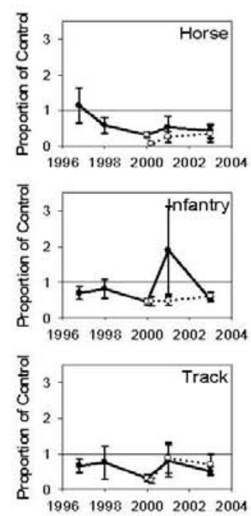
Figure 5. Typical lichen crust.

LICHEN COVER (%)

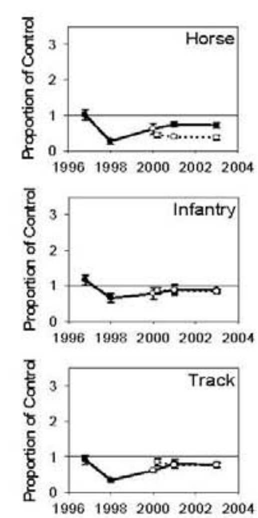
DUNE MARGIN	Control		Horse		Infantry		Track			
	Avg	*SE*	Avg	*SE*	Avg	*SE*	Avg	*SE*	*p*	*Power*
Single Disturbance										
1997 (Pre-disturbed)	47.8	1.9	48.3	1.8	49.2	3.7	48.2	2.8	*0.98*	*0.057*
1997 (Post-disturbed)										
1998	26.0	1.2	**8.7**	1.4	**12.5**	1.4	**11.7**	1.6	*0.00*	*1.000*
2000	44.9	2.1	**23.1**	2.1	**27.8**	2.9	**29.7**	1.1	*0.00*	*1.000*
2001	54.2	3.9	**40.3**	8.3	46.1	6.0	43.8	8.7	*0.10*	*0.500*
2003	48.2	0.8	**26.5**	4.5	38.2	3.4	**24.4**	4.7	*<0.01*	*0.939*
Resistance	--	--	33		48		45			
Resilience (6 yr)	--	--	-25		26		-66			
% of control (2003)	--	--	55		79		51			
Double Disturbance										
2000 (Post-)	44.4	2.5	**7.1**	2.8	**28.8**	2.0	**26.0**	3.7	*0.00*	*1.000*
2001 (1 yr post)	54.2	3.9	**28.8**	9.1	**42.6**	7.8	**40.6**	8.4	*0.00*	*0.975*
2003 (3 yr post)	48.2	0.8	**14.2**	3.3	**30.1**	2.5	**27.5**	3.9	*<0.01*	*1.000*
Resistance (2X)	--	--	16		63		57			
Resistance (+1)	--	--	31		104		87			
Resilience (6 yr)	--	--	9		0		0			
% of control (2003)	--	--	29		63		57			



TRANSITION	Control		Horse		Infantry		Track			
	Avg	*SE*	Avg	*SE*	Avg	*SE*	Avg	*SE*	*p*	*Power*
Single Disturbance										
1997 (Pre-disturbed)	22.3	6.7	12.5	1.2	14.7	3.5	**9.7**	2.3	*0.14*	*0.438*
1997 (Post-disturbed)										
1998	4.5	1.5	1.5	0.3	3.7	1.9	1.8	0.5	*0.23*	*0.336*
2000	12.5	2.3	**4.2**	1.4	**6.0**	1.8	**4.0**	1.0	*0.00*	*0.992*
2001	8.9	1.8	**2.5**	0.7	6.9	1.4	**3.3**	0.9	*0.01*	*0.876*
2003	8.5	2.2	**2.8**	0.8	**4.4**	1.2	**3.2**	0.5	*0.02*	*0.764*
Resistance	--	--	28		48		32			
Resilience (6 yr)	--	--	11		38		38			
% of control (2003)	--	--	33		52		38			
Double Disturbance										
2000 (Post-)	8.2	1.9	**0.7**	0.3	**2.8**	0.7	**2.5**	0.7	*0.00*	*0.999*
2001 (1 yr post)	8.9	1.8	**1.1**	0.3	**4.9**	1.1	**4.4**	0.7	*0.00*	*0.997*
2003 (3 yr post)	8.5	2.2	**1.8**	1.0	**4.3**	0.5	4.3	1.2	*0.03*	*0.711*
Resistance (2X)	--	--	8		34		31			
Resistance (+1)	--	--	17		47		62			
Resilience (6 yr)	--	--	11		23		27			
% of control (2003)	--	--	21		51		51			

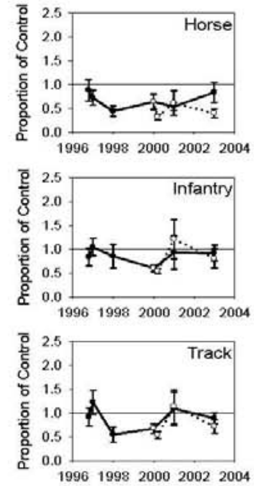


OUTCROP	Control		Horse		Infantry		Track			
	Avg	*SE*	Avg	*SE*	Avg	*SE*	Avg	*SE*	*p*	*Power*
Single Disturbance										
1997 (Pre-disturbed)	40.4	4.2	39.2	5.0	44.7	3.4	35.5	4.6	*0.17*	*0.398*
1997 (Post-disturbed)										
1998	20.5	4.5	**5.8**	2.1	**12.2**	3.3	**6.8**	1.9	*0.00*	*0.990*
2000	50.7	5.7	**26.7**	2.3	**35.4**	1.7	**30.0**	3.4	*0.00*	*0.975*
2001	40.7	3.0	**29.0**	1.2	35.0	4.0	33.2	5.7	*0.15*	*0.426*
2003	44.0	3.7	**31.1**	3.0	38.6	3.3	**34.0**	3.9	*<0.01*	*0.944*
Resistance	--	--	28		59		33			
Resilience (6 yr)	--	--	12		35		27			
% of control (2003)	--	--	71		88		77			
Double Disturbance										
2000 (Post-)	44.9	1.4	**19.4**	3.2	38.6	4.1	37.6	4.5	*0.00*	*1.000*
2001 (1 yr post)	40.7	3.0	**15.6**	1.7	35.4	2.4	**30.7**	3.8	*0.00*	*1.000*
2003 (3 yr post)	44.0	3.7	**16.0**	2.2	37.4	4.6	33.9	4.5	*<0.01*	*1.000*
Resistance (2X)	--	--	36		85		75			
Resistance (+1)	--	--	54		101		92			
Resilience (6 yr)	--	--	0		0		-1			
% of control (2003)	--	--	36		85		77			

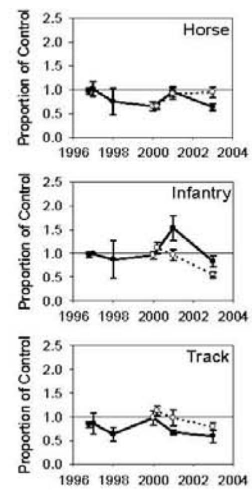


CHLOROPHYLL (MG CHL A/M2 SOIL)

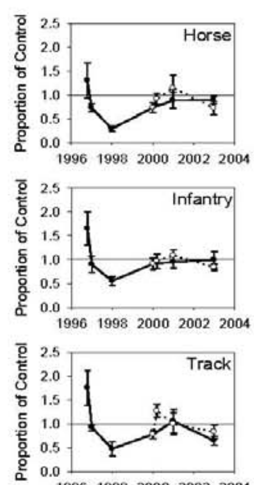
DUNE MARGIN	Control		Horse		Infantry		Track			
	Avg	*SE*	Avg	*SE*	Avg	*SE*	Avg	*SE*	*p*	*Power*
Single Disturbance										
1997 (Pre-disturbed)	12.9	3.2	13.6	2.3	12.5	2.1	13.4	1.9	*0.99*	*0.055*
1997 (Post-disturbed)	18.7	4.1	**11.2**	1.6	16.2	2.7	20.1	4.7	*0.06*	*0.596*
1998	32.3	10.0	**11.6**	3.6	23.6	7.1	**14.2**	3.4	*0.03*	*0.722*
2000	31.7	1.6	**19.6**	4.3	**18.4**	1.5	**20.8**	2.5	*<0.01*	*0.925*
2001	20.7	4.8	**12.4**	3.2	18.0	3.9	20.4	4.5	*0.11*	*0.484*
2003	48.6	5.5	37.4	8.6	40.2	5.3	40.4	2.4	*0.54*	*0.173*
Resistance	--	--	36		58		44			
Resilience (6 yr)	--	--	45		36		54			
% of control (2003)	--	--	77		83		83			
Double Disturbance										
2000 (Post-)	38.6	2.8	**11.7**	1.7	**20.1**	1.4	**20.4**	2.3	*<0.01*	*1.000*
2001 (1 yr post)	20.7	4.8	**11.8**	2.7	23.7	5.2	18.9	3.8	*0.04*	*0.655*
2003 (3 yr post)	48.6	5.5	**18.0**	2.4	34.5	6.9	31.9	5.3	*0.02*	*0.789*
Resistance (2X)	--	--	30		52		53			
Resistance (+1)	--	--	59		109		93			
Resilience (6 yr)	--	--	-14		24		8			
% of control (2003)	--	--	37		71		66			



TRANSITION	Control		Horse		Infantry		Track			
	Avg	*SE*	Avg	*SE*	Avg	*SE*	Avg	*SE*	*p*	*Power*
Single Disturbance										
1997 (Pre-disturbed)	9.8	1.2	9.6	1.4	9.5	1.2	**8.1**	0.8	*0.09*	*0.516*
1997 (Post-disturbed)	8.0	0.5	8.2	1.5	7.9	0.5	6.6	1.8	*0.70*	*0.125*
1998	13.8	3.0	7.4	2.1	8.7	1.9	8.6	2.4	*0.24*	*0.327*
2000	25.0	3.8	**15.2**	1.6	23.2	2.8	23.3	3.9	*0.04*	*0.674*
2001	8.6	0.5	8.0	0.6	**12.9**	2.3	5.8	0.5	*0.01*	*0.852*
2003	27.5	2.7	**17.8**	3.1	21.8	2.7	**16.8**	4.4	*0.03*	*0.706*
Resistance	--	--	53		63		61			
Resilience (6 yr)	--	--	-49		-9		0			
% of control (2003)	--	--	65		80		61			
Double Disturbance										
2000 (Post-)	22.1	2.3	**14.5**	2.1	24.2	3.1	23.9	1.4	*<0.01*	*0.968*
2001 (1 yr post)	8.6	0.5	7.8	0.8	8.1	0.8	8.2	1.3	*0.94*	*0.068*
2003 (3 yr post)	27.5	2.7	25.2	2.7	**14.3**	0.8	22.3	3.9	*<0.01*	*0.929*
Resistance (2X)	--	--	66		52		81			
Resistance (+1)	--	--	97		63		142			
Resilience (6 yr)	--	--	71		0		0			
% of control (2003)	--	--	92		52		81			

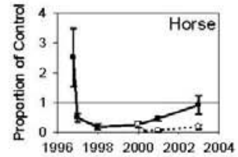


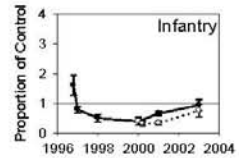
OUTCROP	Control		Horse		Infantry		Track			
	Avg	*SE*	Avg	*SE*	Avg	*SE*	Avg	*SE*	*p*	*Power*
Single Disturbance										
1997 (Pre-disturbed)	17.1	3.9	24.6	5.6	**26.9**	5.9	24.8	5.4	*0.14*	*0.441*
1997 (Post-disturbed)	21.4	2.1	**15.7**	2.1	18.6	2.8	19.5	1.7	*0.17*	*0.392*
1998	51.6	18.0	**12.4**	2.7	**26.2**	9.4	**15.3**	1.2	*0.02*	*0.789*
2000	26.8	4.5	**18.7**	2.3	22.7	2.5	**18.9**	1.0	*0.05*	*0.641*
2001	23.1	3.5	19.1	2.8	20.6	2.4	22.4	3.6	*0.72*	*0.121*
2003	36.0	3.7	31.5	3.0	32.9	2.3	**21.6**	1.3	*0.01*	*0.912*
Resistance	--	--	24		51		30			
Resilience (6 yr)	--	--	88		88		60			
% of control (2003)	--	--	87		91		60			
Double Disturbance										
2000 (Post-)	24.3	2.9	22.3	2.3	22.4	1.9	29.5	2.6	*0.11*	*0.473*
2001 (1 yr post)	23.1	3.5	24.1	5.9	23.3	2.5	20.8	3.3	*0.94*	*0.069*
2003 (3 yr post)	36.0	3.7	**24.0**	1.5	29.3	2.1	**27.5**	2.1	*0.04*	*0.670*
Resistance (2X)	--	--	67		81		76			
Resistance (+1)	--	--	119		99		93			
Resilience (6 yr)	--	--	0		0		0			
% of control (2003)	--	--	67		81		76			

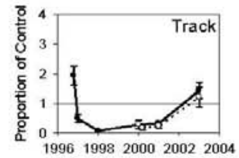


NITROGEN FIXATION (UMOL ETHYLENE/M2/HR)

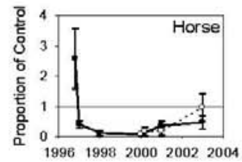
DUNE MARGIN	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	2.6	0.9	5.4	2.0	3.1	0.4	4.4	1.1	0.23	0.334
1997 (Post-disturbed)	2.8	0.5	**1.4**	0.5	2.1	0.4	**1.1**	0.1	0.02	0.759
1998	1.3	0.2	**0.2**	0.1	**0.6**	0.1	**0.1**	0.0	<0.01	0.999
2000	3.9	0.2	**0.9**	0.4	1.5	0.5	1.1	0.5	0.06	0.587
2001	16.4	1.2	**7.3**	1.0	**10.4**	0.6	**5.4**	1.3	<0.01	1.000
2003	7.4	0.9	6.1	2.1	6.5	1.3	10.5	2.9	0.14	0.439
Resistance	--	--	14		38		5			
Resilience (6 yr)	--	--	-13		65		354			
% of control (2003)	--	--	83		89		143			
Double Disturbance										
2000 (Post-)	7.8	1.3	**0.2**	0.1	**2.6**	0.7	**1.3**	0.6	<0.01	1.000
2001 (1 yr post)	16.4	1.2	**0.9**	0.4	**5.2**	1.0	**3.6**	0.9	<0.01	1.000
2003 (3 yr post)	7.4	0.9	**1.3**	0.6	5.5	1.5	8.0	2.0	0.01	0.882
Resistance (2X)	--	--	3		32		17			
Resistance (+1)	--	--	26		171		117			
Resilience (6 yr)	--	--	19		83		110			
% of control (2003)	--	--	17		75		109			

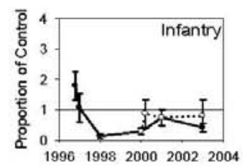


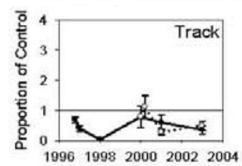




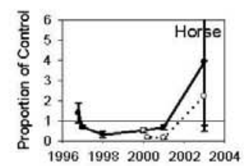
TRANSITION	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	5.5	1.8	7.6	1.1	7.2	1.5	4.2	1.7	0.20	0.360
1997 (Post-disturbed)	3.8	1.2	**1.5**	0.6	2.3	0.7	**1.4**	0.4	0.06	0.591
1998	1.0	0.3	**0.1**	0.0	**0.1**	0.0	**0.0**	0.0	<0.01	0.953
2000	2.4	1.0	**0.2**	0.0	**0.8**	0.3	**1.1**	0.5	0.06	0.587
2001	1.7	0.5	**0.3**	0.1	**0.7**	0.3	**0.6**	0.3	0.04	0.655
2003	1.6	0.6	**0.4**	0.1	**0.6**	0.3	**0.3**	0.1	0.05	0.641
Resistance	--	--	6		8		2			
Resilience (6 yr)	--	--	47		-16		-39			
% of control (2003)	--	--	24		35		17			
Double Disturbance										
2000 (Post-)	2.1	0.5	**0.2**	0.1	1.4	0.5	1.8	0.4	0.01	0.893
2001 (1 yr post)	1.7	0.5	**0.2**	0.1	0.8	0.4	**0.3**	0.1	0.01	0.814
2003 (3 yr post)	1.6	0.6	1.9	1.5	0.4	0.2	0.4	0.1	0.41	0.225
Resistance (2X)	--	--	10		27		17			
Resistance (+1)	--	--	50		77		48			
Resilience (6 yr)	--	--	122		0		17			
% of control (2003)	--	--	121		27		25			

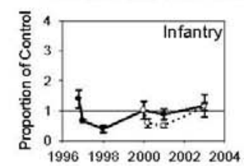


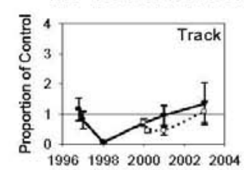




OUTCROP	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	3.2	1.1	2.6	0.4	3.1	0.8	2.5	0.6	0.74	0.115
1997 (Post-disturbed)	5.0	0.9	3.4	0.6	3.3	0.6	3.3	1.0	0.30	0.284
1998	2.4	0.3	**0.7**	0.4	**0.9**	0.2	**0.1**	0.0	<0.01	1.000
2000	3.4	0.2	**1.8**	0.4	3.3	0.8	2.4	0.5	0.11	0.483
2001	11.3	1.1	7.8	1.6	9.1	1.1	9.6	2.8	0.62	0.147
2003	15.3	5.8	23.0	11.4	19.7	10.4	11.9	4.5	0.68	0.131
Resistance	--	--	31		36		6			
Resilience (6 yr)	--	--	570.3		388		-54			
% of control (2003)	--	--	150		129		77			
Double Disturbance										
2000 (Post-)	18.9	1.4	**3.1**[a]	0.3	**10.5**[a]	2.3	**8.4**	1.4	<0.01	0.999
2001 (1 yr post)	11.3	1.1	**1.9**	0.9	**5.7**	0.9	**4.7**	1.4	<0.01	1.000
2003 (3 yr post)	15.3	5.8	14.7	6.4	18.4	7.4	16.3	8.6	0.95	0.066
Resistance (2X)	--	--	16		50		41			
Resistance (+1)	--	--	24		62		49			
Resilience (6 yr)	--	--	96		155		115			
% of control (2003)	--	--	96		120		107			







[a] The average and SE are based on n=5 blocks instead of n=6 due to missing data

3.2.3. Hydrology and water erosion indicators. The effects of the three disturbance types on site susceptibility to water runoff and erosion were quantified by four measurements: infiltration, soil stability, penetrometer and erosion bridge. Single ring infiltration measurements of water infiltration capacity reflect relative changes in the infiltration rate of water when the soil is saturated. Despite the fact this measurement can overestimate infiltration rates during rainstorms by a factor of 10 or more, it is a very useful indicator of changes in near-surface soil structure (e.g., destruction of soil macropores) that are closely related to infiltration under natural conditions. Field soil stability and pocket penetrometer resistance are also indicators of near-surface soil structure. Increases in pocket penetrometer values are correlated with compaction in the top 1 cm or less, reflecting a loss of potentially water-conducting pores. Reductions in soil stability values reflect a loss or weakening of bonds (usually organic matter) between soil particles. As these bonds are lost, the soil becomes more susceptible to both water erosion and physical crusting during rainfall events. Physical crusts are very dense and tend to have a platy structure that conducts water laterally instead of vertically. The fourth indicator, soil surface roughness, is calculated from erosion bridge data (see photos associated with the data). The erosion bridge is not sufficiently sensitive to detect soil loss rates as low as those occurring at these three sites during such a short study. It does, however, accurately reflect changes in surface roughness. Water moves more slowly across a rougher surface, so it has more time to infiltrate and less energy available for erosion. Rougher surfaces also slow near-surface wind speeds, reducing wind erosion (see next section).

In general, the treatments reduced water infiltration and slightly reduced soil stability. There was one notable exception to this pattern. The horse and infantry treatments appear to have increased infiltration capacity at the transition site immediately post-disturbance, although the differences were not statistically significant. By 1998, however, infiltration in both treatments had returned to control levels or dropped below them. There is much less lichen cover at the transition site than at the other two sites. Instead, it appears to have a surface crust stabilized by cyanobacteria. Destruction of this type of crust by infantry and horses could temporarily increase infiltration. After the first severe storm, the physical crust re-forms. While the density of living cyanobacteria may take several years to return to control levels (see “Chlorophyll”), polysaccharides and other organic matter previously generated by the cyanobacteria, or even the dead cyanobacteria themselves could easily stabilize the new crust (see “Field Soil Stability”). Litter generated by the relatively high total plant cover could also contribute to the relatively rapid restabilization. The track treatment tended to compact rather than disturb the crust.

The infiltrometer and penetrometer data together support the hypothesis that, even in those few cases when the initial effect of the treatments may possibly facilitate water entry and seedling emergence, the formation of a physical crust rapidly negates any potential benefits. There was no evidence of any benefits of disturbance for the track treatment.

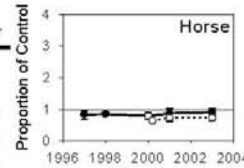
3.2.3.1. Resistance and resilience: site comparison. For infiltration rates, resistance to disturbance was relatively unaffected and resilience was low at the dune margin and outcrop sites. The transition site was relatively unaffected and may have even increased in response to horse and infantry treatments. Soil stability showed lower resistance to disturbance at the outcrop site. There was recovery in soil stability over 6 years at all sites, although a decline occurred between 2001 and 2003, matching that observed in vegetation cover. Soil compaction as measured by the pocket penetrometer was significantly higher than the control at the dune margin and outcrop sites by the time the first measurements were made in 2000.

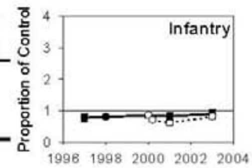
3.2.3.2. Resistance and resilience: treatment comparison. There was no consistent difference in resistance and resilience of infiltration rates and surface soil stability between treatments. Both the penetrometer and erosion bridge measurements differed in their response to different treatments, however. The track treatment had a much more persistent effect on the penetrometer readings, particularly at the dune margin site. The horse treatment had the biggest impact upon erosion bridge measurements. The track treatment reduced surface roughness, whereas the horse treatment increased it, with the infantry treatment having little effect. Belnap and co-workers have reported similar effects for the Colorado Plateau where freeze-thaw processes interact with microbiotic crusts to create greater microrelief. There was a steady decline in surface roughness for the horse treatment plots through time, but erosion bridge levels did not reach control levels after 6 years at the dune margin or outcrop site. At the dune margin site, infantry and track surface roughness remained below control levels and continued to decline from 2001 to 2003. These treatments were not significantly different from the controls at the transition site. None of the track treatments reached control levels for penetrometer readings.

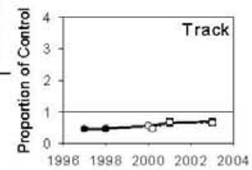
3.2.3.3. Double disturbance. The double-disturbance data suggest that at the dune margin site, at least, penetrometer resistance may be initially reduced by horses due to the destruction of the biological crust; but, within a year, the reformation of the physical crust had already pushed the resistance past control levels. The pattern for infiltration was nearly identical to the first disturbance with a further reduction occurring across all sites and treatments, except for the transition site, infantry and track treatments, where there were non-significant increases relative to the single-disturbed plots. Field soil stability was again minimally affected. The horse treatment significantly reduced stability at all three sites. Sampling problems at the outcrop site probably contributed to variability in the data.

WATER INFILTRATION (MM/HR)

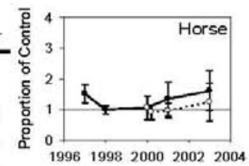
DUNE MARGIN	Control Avg	SE	Horse Avg	SE	Infantry Avg	SE	Track Avg	SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)										
1997 (Post-disturbed)	373	33	294	38	**275**	30	**172**	13	0.00	0.975
1998	430	22	**360**	16	**347**	27	**202**	9	0.00	1.000
2000	345	14	**270**	31	293	21	**196**	19	0.00	0.961
2001	455	80	343	34	342	22	**268**	22	0.07	0.578
2003	357	23	322	48	309	34	**245**	19	0.07	0.565
Resistance	--	--	76		74		46			
Resilience (6 yr)	--	--	69		51		44			
% of control (2003)	--	--	90		87		69			
Double Disturbance										
2000 (Post-)	390	32	**242**	21	**267**	15	**181**	20	0.00	1.000
2001 (1 yr post)	455	80	**294**	26	**251**	13	**270**	32	0.04	0.678
2003 (3 yr post)	357	23	**256**	20	**285**	4.9	**228**	24	<0.01	0.987
Resistance (2X)	--	--	62		55		46			
Resistance (+1)	--	--	90		73		93			
Resilience (6 yr)	--	--	32		65		38			
% of control (2003)	--	--	72		80		64			

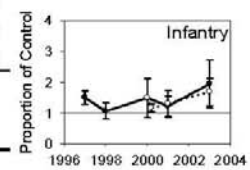


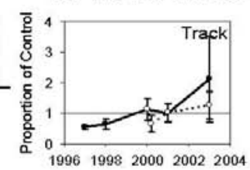




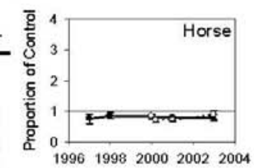
TRANSITION	Control Avg	SE	Horse Avg	SE	Infantry Avg	SE	Track Avg	SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)										
1997 (Post-disturbed)	101	15	135	11	154	36	52	2	0.01	0.875
1998	223	27	207	24	209	29	141[a]	42	0.26	0.310
2000	158	29	117	21	148	17	165	68	0.84	0.092
2001	192	33	195	40	201	47	160	38	0.88	0.083
2003	146	32	143	15	174	20	135	22	0.67	0.132
Resistance	--	--	74		93		51			
Resilience (6 yr)	--	--	93		(361)		76			
% of control (2003)	--	--	98		119		92			
Double Disturbance										
2000 (Post-)	162	25	122	12	179	27	**82**	14	0.02	0.795
2001 (1 yr post)	192	33	149	12	189	23	156	13	0.38	0.239
2003 (3 yr post)	146	32	99	11	184	28	123	15	0.02	0.749
Resistance (2X)	--	--	67		99		50			
Resistance (+1)	--	--	69		121		49			
Resilience (6 yr)	--	--	0		(1536)		71			
% of control (2003)	--	--	67		126		84			

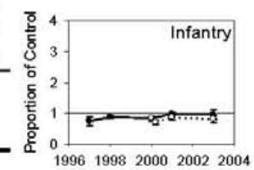


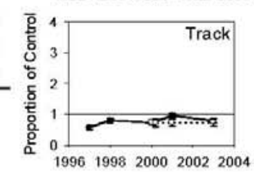




OUTCROP	Control Avg	SE	Horse Avg	SE	Infantry Avg	SE	Track Avg	SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)										
1997 (Post-disturbed)	369	40	**253**	25	**269**	46	**197**	12	0.02	0.765
1998	464	43	386	17	397	30	**368**	45	0.17	0.394
2000	389	20	321	21	330	42	**289**	39	0.06	0.614
2001	367	35	**291**	19	362	43	342	15	0.13	0.459
2003	347	57	**253**	14	295	22	260	19	0.16	0.410
Resistance	--	--	69		73		53			
Resilience (6 yr)	--	--	19		48		49			
% of control (2003)	--	--	73		85		75			
Double Disturbance										
2000 (Post-)	367	20	**258**	24	**255**	19	**259**	42	0.02	0.809
2001 (1 yr post)	367	35	**258**	16	302	12	**256**	27	0.03	0.734
2003 (3 yr post)	347	57	275	11	269	41	**231**	16	0.14	0.433
Resistance (2X)	--	--	70		69		67			
Resistance (+1)	--	--	80		77		89			
Resilience (6 yr)	--	--	34		30		0			
% of control (2003)	--	--	79		77		67			



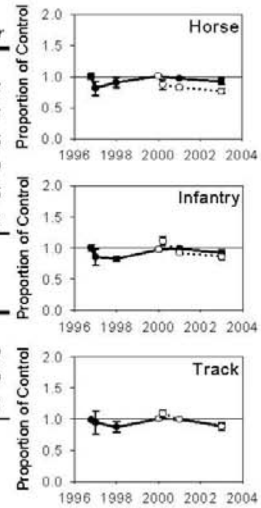




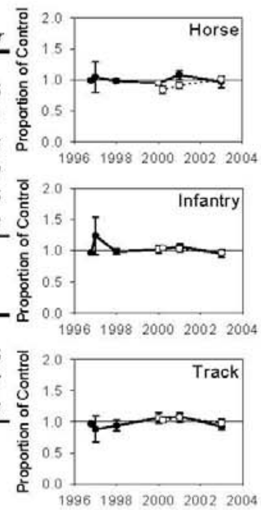
[a] The average and SE are based on n=5 blocks instead of n=6 due to missing data

FIELD SOIL STABILITY

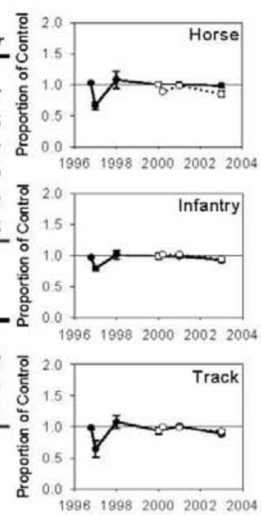
DUNE MARGIN	Control		Horse		Infantry		Track			
	Avg	*SE*	Avg	*SE*	Avg	*SE*	Avg	*SE*	*p*	*Power*
Single Disturbance										
1997 (Pre-disturbed)	5.4	0.2	5.5	0.1	5.4	0.1	5.4	0.2	*0.98*	*0.058*
1997 (Post-disturbed)	4.3	0.4	3.3	0.3	3.5	0.4	3.7	0.3	*0.18*	*0.386*
1998	4.9	0.3	4.4	0.2	**4.0**	0.2	**4.2**	0.3	*0.05*	*0.615*
2000	5.7	0.1	5.7	0.1	5.5	0.1	5.7	0.1	*0.44*	*0.210*
2001	5.9	0.0	5.8	0.0	5.9	0.1	5.9	0.0	*0.32*	*0.975*
2003	5.4	0.1	4.9	0.2	4.9	0.1	**4.8**	0.2	*0.13*	*0.454*
Resistance	--	--	77		81		85			
Resilience (6 yr)	--	--	56		45		22			
% of control (2003)	--	--	92		92		89			
Double Disturbance										
2000 (Post-)	5.2	0.2	4.5	0.3	5.7	0.1	5.6	0.2	*0.01*	*0.819*
2001 (1 yr post)	5.9	0.0	**4.9**	0.2	**5.5**	0.1	5.9	0.1	*0.00*	*1.000*
2003 (3 yr post)	5.4	0.1	**4.1**	0.2	**4.6**	0.2	**4.7**	0.2	*0.01*	*0.894*
Resistance (2X)	--	--	77		86		87			
Resistance (+1)	--	--	84		94		98			
Resilience (6 yr)	--	--	0		0		0			
% of control (2003)	--	--	77		86		87			



TRANSITION	Control		Horse		Infantry		Track			
	Avg	*SE*	Avg	*SE*	Avg	*SE*	Avg	*SE*	*p*	*Power*
Single Disturbance										
1997 (Pre-disturbed)	4.7	0.1	4.6	0.1	4.5	0.2	4.5	0.1	*0.56*	*0.165*
1997 (Post-disturbed)	3.0	0.5	2.7	0.3	3.1	0.5	2.3	0.4	*0.61*	*0.151*
1998	4.4	0.2	4.3	0.1	4.3	0.1	4.0	0.3	*0.56*	*0.166*
2000	4.6	0.2	4.4	0.2	4.7	0.3	4.8	0.3	*0.44*	*0.209*
2001	4.7	0.2	5.0	0.1	5.0	0.1	5.1	0.2	*0.48*	*0.195*
2003	4.2	0.2	4.0	0.2	3.9	0.1	3.8	0.1	*0.51*	*0.183*
Resistance	--	--	90		94		79			
Resilience (6 yr)	--	--	(37)		(0)		38			
% of control (2003)	--	--	96		94		91.0			
Double Disturbance										
2000 (Post-)	5.0	0.1	**4.2**	0.3	5.3	0.1	5.1	0.2	*<0.01*	*0.935*
2001 (1 yr post)	4.7	0.2	4.3	0.1	4.8	0.1	5.0	0.2	*0.05*	*0.627*
2003 (3 yr post)	4.2	0.2	4.2	0.2	4.0	0.1	4.0	0.1	*0.77*	*0.108*
Resistance (2X)	--	--	84		96		96			
Resistance (+1)	--	--	105		103		106			
Resilience (6 yr)	--	--	103		(0)		(0)			
% of control (2003)	--	--	101		96		96			

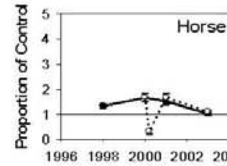


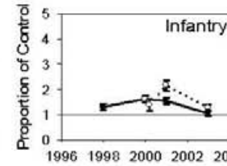
OUTCROP	Control		Horse		Infantry		Track			
	Avg	*SE*	Avg	*SE*	Avg	*SE*	Avg	*SE*	*p*	*Power*
Single Disturbance										
1997 (Pre-disturbed)	5.5	0.2	5.6	0.1	5.3	0.1	5.3	0.2	*0.07*	*0.577*
1997 (Post-disturbed)	5.2	0.1	**3.4**	0.3	**4.1**	0.2	**3.3**	0.7	*0.01*	*0.905*
1998	4.5	0.4	4.7	0.3	4.5	0.3	4.7	0.1	*0.92*	*0.073*
2000	5.1	0.2	5.1	0.1	5.1	0.3	4.8	0.3	*0.40*	*0.230*
2001	5.9	0.0	5.9	0.1	5.8	0.1	5.9	0.1	*0.73*	*0.118*
2003	5.6	0.1	5.5	0.1	5.2	0.2	**4.9**	0.2	*0.06*	*0.595*
Resistance	--	--	66		80		64			
Resilience (6 yr)	--	--	95		64		65			
% of control (2003)	--	--	99		93		88			
Double Disturbance										
2000 (Post-)	5.6	0.1	**5.0**	0.1	5.7	0.1	5.6	0.1	*<0.01*	*0.992*
2001 (1 yr post)	5.9	0.0	5.8	0.1	6.0	0.0	5.8	0.1	*0.03*	*0.741*
2003 (3 yr post)	5.6	0.1	**4.7**	0.2	5.2	0.1	5.1	0.2	*0.05*	*0.624*
Resistance (2X)	--	--	85		94		92			
Resistance (+1)	--	--	86		101		105			
Resilience (6 yr)	--	--	0		(0)		(0)			
% of control (2003)	--	--	85		94		92			

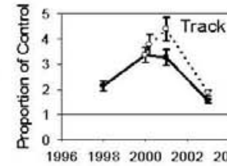


POCKET PENETROMETER (KG/CM2)

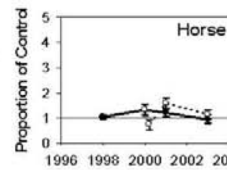
DUNE MARGIN	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)										
1997 (Post-disturbed)										
1998	1.6	0.2	**2.0**	0.1	**1.9**	0.1	**3.2**	0.1	<0.01	1.000
2000	0.6	0.0	**0.9**	0.1	**0.9**	0.1	**1.8**	0.1	<0.01	1.000
2001	0.5	0.0	**0.8**	0.1	**0.8**	0.1	**1.7**	0.1	<0.01	1.000
2003	0.9	0.1	0.9	0.1	0.9	0.1	**1.3**	0.1	<0.01	1.000
Resistance	--	--	102		103		152			
Resilience (4 yr)	--	--	(0)		(0)		(0)			
% of control (2003)	--	--	102		103		152			
Double Disturbance										
2000 (Post-)	0.9	0.1	**0.2**	0.0	**1.2**	0.1	**3.2**	0.1	<0.01	1.000
2001 (1 yr post)	0.5	0.0	**0.9**	0.1	**1.1**	0.1	**2.3**	0.2	<0.01	1.000
2003 (3 yr post)	0.9	0.1	1.0	0.0	1.1	0.1	**1.6**	0.1	<0.01	1.000
Resistance (2X)	--	--	28		125		185			
Resistance (+1)	--	--	27		121		121			
Resilience (6 yr)	--	--	113		(0)		(0)			
% of control (2003)	--	--	109		125		185			

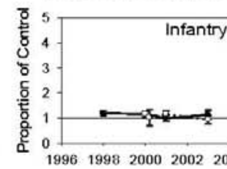


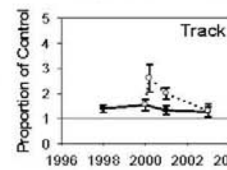




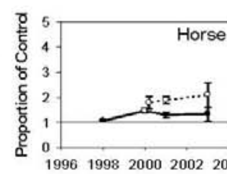
TRANSITION	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)										
1997 (Post-disturbed)										
1998	1.3	0.1	1.4	0.2	1.6	0.2	**1.8**	0.1	0.04	0.652
2000	0.9	0.2	1.1	0.1	1.0	0.1	**1.3**	0.1	0.09	0.521
2001	0.9	0.1	0.9	0.0	0.8	0.1	1.1	0.1	0.22	0.344
2003	1.0	0.1	0.9	0.1	1.1	0.1	1.2	0.2	0.47	0.200
Resistance	--	--	88		94		117			
Resilience (4 yr)	--	--	0		(157)		(0)			
% of control (2003)	--	--	88		103		117			
Double Disturbance										
2000 (Post-)	1.8[a]	0.9	0.8	0.0	1.1	0.1	2.9	0.5	0.01	0.913
2001 (1 yr post)	0.9	0.1	**1.2**	0.0	0.9	0.0	**1.6**	0.1	<0.01	1.000
2003 (3 yr post)	1.0	0.1	1.1	0.1	0.9	0.1	1.2	0.1	0.20	0.363
Resistance (2X)	--	--	43		62		116			
Resistance (+1)	--	--	73		82		100			
Resilience (6 yr)	--	--	105		77		(0)			
% of control (2003)	--	--	105		85		116			

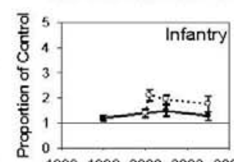


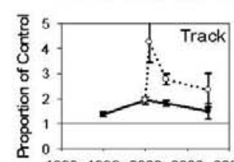




OUTCROP	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)										
1997 (Post-disturbed)										
1998	2.2	0.1	2.4	0.1	**2.6**	0.1	**3.1**	0.2	<0.01	0.991
2000	1.1	1.0	**1.5**	0.2	**1.4**	0.2	**2.0**	0.2	<0.01	0.999
2001	1.1	0.1	1.4	0.0	**1.6**	0.3	**2.0**	0.2	<0.01	0.923
2003	1.2	0.2	1.4	0.2	1.4	0.3	**1.6**	0.3	0.22	0.346
Resistance	--	--	106		116		134			
Resilience (4 yr)	--	--	(-53)		(30)		(0)			
% of control (2003)	--	--	117		122		134			
Double Disturbance										
2000 (Post-)	1.0	0.2	**1.7**	0.1	**2.0**	0.2	**3.8**	0.1	<0.01	1.000
2001 (1 yr post)	1.1	0.1	**2.0**	0.1	**2.1**	0.2	**3.0**	0.2	<0.01	1.000
2003 (3 yr post)	1.4	0.2	**2.1**	0.2	**1.8**	0.2	**2.3**	0.4	<0.01	0.961
Resistance (2X)	--	--	153		132		170			
Resistance (+1)	--	--	110		126		147			
Resilience (6 yr)	--	--	(0)		(0)		(0)			
% of control (2003)	--	--	153		132		170			



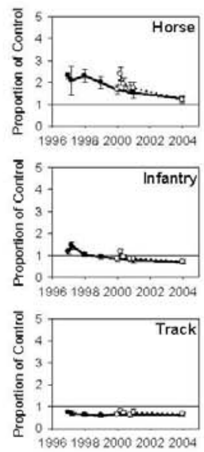




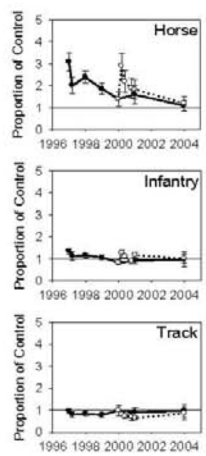
[a] The average and SE are based on n=4 blocks instead of n=6 due to missing data

EROSION BRIDGE (AVERAGE SD)

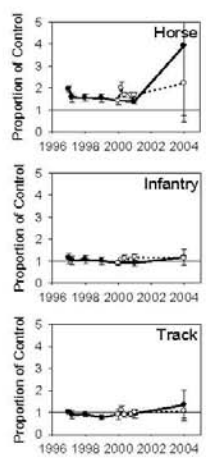
DUNE MARGIN	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Post-disturbed)	6.1	0.4	**13.5**	1.2	6.9	0.4	4.4	0.3	<0.01	1.000
December 1997	5.5[a]	0.6	10.8[a]	2.3	8.2[a]	1.7	3.7[a]	0.0	0.10	0.474
May 1998	5.0	0.4	**11.2**	0.8	5.1	0.3	**3.1**	0.2	<0.01	1.000
May 1999	5.6	0.3	**10.8**	0.9	5.2	0.4	**3.3**	0.2	<0.01	1.000
October 2000	5.1	0.4	**8.2**	0.5	4.1	0.3	**3.2**	0.2	<0.01	1.000
October 2001	5.9	0.6	**8.3**	0.5	**4.3**	0.2	**3.7**	0.2	<0.01	1.000
March 2004	5.8	0.4	**7.2**	0.2	**4.0**	0.2	**3.5**	0.3	<0.01	1.000
Resistance	--	--	124		70		59			
Resilience (6 yr)	--	--	(0)		0		1			
% of control (2004)	--	--	124		70		61			
Double Disturbance										
October 2000	5.1	0.4	**11.7**	1.1	5.8	0.4	4.0	0.3	<0.01	1.000
December 2000	5.1	0.4	**9.3**	1.0	4.6	0.3	3.4	0.4	<0.01	1.000
June 2001	5.6	0.5	**9.3**	0.9	4.6	0.3	**3.4**	0.3	<0.01	1.000
October 2001	5.9	0.6	**9.6**	0.8	4.7	0.4	3.9	0.4	<0.01	0.999
March 2004	5.8	0.4	6.9	0.6	**4.1**	0.3	**3.6**	0.2	<0.01	0.997
Resistance (2X)	--	--	120		70		60			
Resistance (+1)	--	--	97		101		93			
Resilience (6 yr)	--	--	(0)		0		3			
% of control (2004)	--	--	120		70		63			



TRANSITION	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Post-disturbed)	4.1	0.5	**12.1**	1.3	5.2	0.2	3.7	0.3	<0.01	1.000
December 1997	4.9	0.6	**9.3**	1.2	5.0	0.3	3.6	0.3	<0.01	0.999
May 1998	4.2	0.6	**9.5**	0.9	4.5	0.2	3.3	0.3	<0.01	1.000
May 1999	3.8	0.3	**6.7**	0.7	3.8	0.1	2.8	0.3	<0.01	1.000
October 2000	3.9	0.5	5.0	0.9	3.1	0.3	3.6	0.7	0.09	0.513
October 2001	4.6	0.9	6.0	1.0	3.8	0.4	3.8	0.8	0.16	0.411
March 2004	4.4	0.7	4.3	0.5	3.5	0.7	3.7	0.7	0.62	0.146
Resistance	--	--	97		79		72			
Resilience (6 yr)	--	--	(0)		-10		47			
% of control (2004)	--	--	97		80		84			
Double Disturbance										
October 2000	3.9	0.5	**9.9**	0.9	4.8	0.6	3.1	0.4	<0.01	1.000
December 2000	3.9	0.5	**7.4**	1.0	4.3	0.6	2.7	0.3	<0.01	0.969
June 2001	5.5	1.6	7.5	0.9	4.2	0.6	3.1[b]	0.3	0.05	0.633
October 2001	4.6	0.9	**6.9**	0.9	4.8	0.4	2.7	0.3	0.01	0.886
March 2004	4.4	0.7	4.5	0.6	3.9	0.3	3.2	0.6	0.29	0.288
Resistance (2X)	--	--	102		77		56			
Resistance (+1)	--	--	105		112		74			
Resilience (6 yr)	--	--	(0)		62		48			
% of control (2004)	--	--	102		89		72			



OUTCROP	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Post-disturbed)	5.4	0.1	**10.5**	0.7	6.1	1.2	5.5	0.5	0.001	0.987
December 1997	5.5	0.5	**8.2**	0.8	5.6	1.0	4.6	0.6	0.04	0.666
May 1998	5.1	0.1	**7.9**	0.7	5.5	1.0	4.6	0.4	0.02	0.747
May 1999	4.7	0.3	**7.1**	0.6	4.7	0.8	3.5	0.4	0.01	0.886
October 2000	4.8	0.4	**6.6**	0.7	4.3	0.6	4.0	0.6	0.03	0.708
October 2001	4.8	0.5	6.5	0.8	4.2	0.5	4.2	0.5	0.05	0.620
March 2004	4.8	0.3	**5.9**	0.5	**4.9**	0.4	**5.2**	1.1	0.65	0.140
Resistance	--	--	124		87		75			
Resilience (6 yr)	--	--	(0)		115		136			
% of control (2004)	--	--	124		102		109			
Double Disturbance										
October 2000	4.8	0.4	**9.5**[c]	1.0	5.1[c]	0.2	5.2[c]	0.8	<0.01	0.959
December 2000	4.8	0.4	**7.9**	0.6	5.1	0.6	4.1	0.5	<0.01	0.996
June 2001	5.2	0.4	**8.6**	0.8	5.2	0.6	4.6	0.5	<0.01	0.993
October 2001	4.8	0.5	**7.9**	0.7	5.3	0.6	4.7	0.5	<0.01	0.980
March 2004	4.8	0.3	6.4	1.0	5.2	0.4	4.4	0.5	0.15	0.415
Resistance (2X)	--	--	134		101		86			
Resistance (+1)	--	--	108		120		103			
Resilience (6 yr)	--	--	(0)		(-863)		42			
% of control (2004)	--	--	134		109		92			



[a] The average and SE are based on n=3 blocks instead of n=6 due to missing data

[b] The average and SE are based on n=5 blocks instead of n=6 due to missing data

[c] The average and SE are based on n=4 blocks instead of n=6 due to missing data

3.2.4. Wind erosion indicators. BSNE eolian sediment collection boxes ("wind boxes") placed parallel to the long side facing either west (dune margin and transition sites) or south (outcrop site) provided a direct indicator of sediment movement. The method was limited by the low level of replication and especially by plot size (8x30 m). The torvane test generated a less direct but more sensitive indicator of the shear strength of the soil surface, which is positively related to its resistance to wind erosion.

At both the dune margin and outcrop sites, all three treatments had increased sediment trapped by a factor of two or more following disturbance. Mean values in horse and track treated plots also exceeded control values at the transition site, but results were more variable and non-significant.

The torvane test showed a short-term reduction by all treatments at all sites followed by a rapid recovery. There was some indication that subsequent crust re-formation was actually increasing treatment values to exceed control values, especially in the track treatment at the dune margin and outcrop sites. While this is good for wind erosion resistance, it has potentially negative implications for seedling emergence and water infiltration.

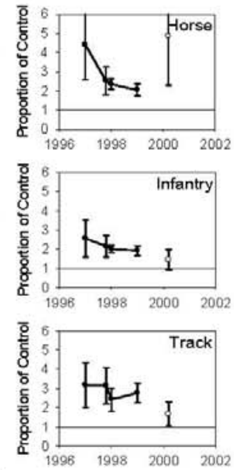
3.2.4.1. Resistance and resilience: site comparison. Treatment impacts were clearly more severe at the dune margin site. Resistance was high and resilience was low at this site. Treatment effects were non-significant for wind boxes at the transition site where resistance was high. The combination of higher vegetative cover and finer textures at the transition site probably limited detachment and transport of soil particles. For the torvane, resistance was low at all three sites, but there was high resilience throughout. Recovery to control levels occurred at all sites for torvane.

3.2.4.2. Resistance and resilience: treatment comparison. Resistance to horse and track treatments was greater for wind box measurements at the dune margin and outcrop sites. The horse treatment also had the greatest effect at the dune margin site, and was statistically significant. The horse treatment tended to pulverize the surface, significantly increasing the wind erodibility of the soil surface. The track treatment also broke the surface but not to the same degree. Torvane demonstrated little in the way of treatment differences.

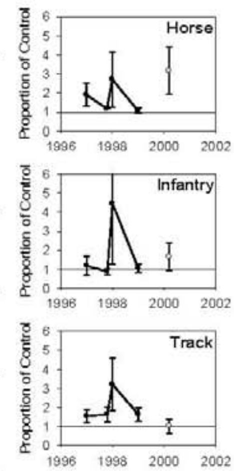
3.2.4.3. Double disturbance. The second disturbance had similar effects to the first with the horse treatment at the dune margin site and the infantry treatment at the outcrop site having the most noticeable effects. Again, the small sample size and even smaller plots (now 4x30 m) significantly limited our ability to interpret these data.

WIND BOX (KG OF SEDIMENT/M2/MONTH)[a,b]

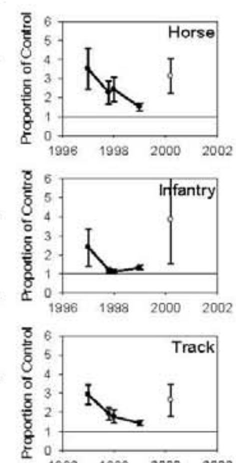
DUNE MARGIN	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
November 1997	1.1	0.4	**3.4**	0.2	**2.0**	0.2	**2.5**	0.5	<0.01	0.980
March 1998	0.3[c]	0.1	**0.7**	0.0	**0.6**	0.0	**0.8**	0.0	<0.01	1.000
May 1998	0.6	0.1	**1.3**	0.1	**1.1**	0.2	**1.2**	0.1	0.01	0.890
May 1999	1.7	0.3	**3.4**	0.3	**3.2**	0.3	**4.4**	0.4	<0.01	0.999
Resistance	--	--	194		183		224			
Resilience (4 yr)	--	--	(0)		(0)		(-294)			
% of control (1999)	--	--	194		183		256			
Double Disturbance										
October 2000	0.1	0.0	**0.4**	0.1	0.1	0.0	0.2	0.0	0.01	0.916
Resistance (2X)	--	--	--		--		--			
Resistance (+1)	--	--	--		--		--			
Resilience (6 yr)	--	--	--		--		--			
% of control (2003)	--	--	--		--		--			



TRANSITION	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
November 1997	1.2	0.1	2.3	0.7	1.4	0.6	1.9	0.3	0.38	0.194
March 1998	0.5	0.0	0.6	0.0	0.4	0.1	0.8	0.1	0.11	0.434
May 1998	0.5	0.2	0.8	0.1	1.1	0.4	1.0	0.1	0.31	0.229
May 1999	1.7	0.1	1.8	0.1	1.8	0.4	2.7	0.4	0.20	0.309
Resistance	--	--	106		89		151			
Resilience (4 yr)	--	--	(0)		288		(-58)			
% of control (1999)	--	--	106		106		158			
Double Disturbance										
October 2000	0.1	0.0	**0.1**	0.0	0.1	0.0	0.1	0.0	0.12	0.451
Resistance (2X)	--	--	--		--		--			
Resistance (+1)	--	--	--		--		--			
Resilience (6 yr)	--	--	--		--		--			
% of control (2003)	--	--	--		--		--			



OUTCROP	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
November 1997	0.7	0.1	2.4	0.6	1.6	0.5	2.2	0.6	0.28	0.248
March 1998	0.3	0.0	0.6	0.2	0.3	0.1	0.5	0.1	0.22	0.295
May 1998	0.3	0.0	**0.7**	0.2	0.3	0.0	0.5	0.1	0.08	0.514
May 1999	1.2	0.1	**1.9**	0.1	1.7	0.1	**1.8**	0.2	0.07	0.547
Resistance	--	--	149		112		143			
Resilience (4 yr)	--	--	(0)		(-1027)		(0)			
% of control (1999)	--	--	149		133		143			
Double Disturbance										
October 2000	0.1[d]	0.0	0.3	0.0	**0.5**	0.2	0.2	0.0	0.13	0.443
Resistance (2X)	--	--	--		--		--			
Resistance (+1)	--	--	--		--		--			
Resilience (6 yr)	--	--	--		--		--			
% of control (2003)	--	--	--		--		--			



[a] All Single Disturbance averages and SEs are based on n=3 blocks instead of n=6, unless otherwise indicated

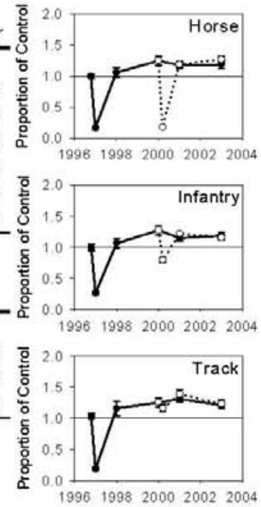
[b] All Double Disturbance averages and SEs are based on n=5 blocks instead of n=6, unless otherwise indicated

[c] The average and SE are based on n=2 blocks instead of n=3 due to a missing block

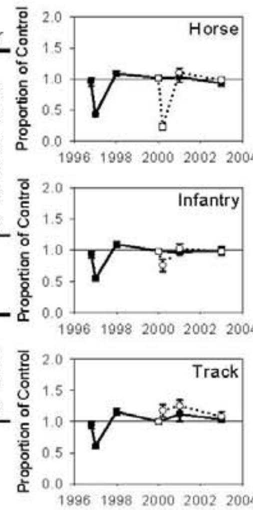
[d] The average and SE are based on n=4 blocks instead of n=5 due to a missing block

TORVANE (KG/CM2)

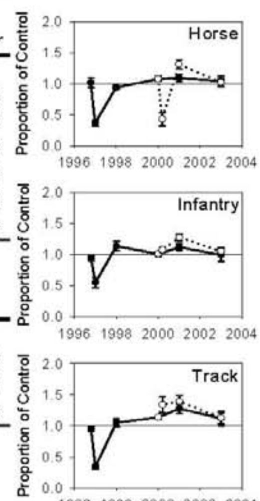
DUNE MARGIN	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	1.5	0.1	1.5	0.1	1.5	0.1	1.6	0.1	*0.73*	*0.118*
1997 (Post-disturbed)	1.3	0.1	**0.2**	0.0	**0.3**	0.1	**0.2**	0.0	*0.00*	*1.000*
1998	0.8	0.0	0.8	0.1	0.8	0.1	0.9	0.1	*0.35*	*0.252*
2000	1.6	0.1	**2.0**	0.1	**2.1**	0.1	**2.0**	0.1	*0.00*	*0.994*
2001	1.8	0.1	**2.1**	0.1	**2.1**	0.1	**2.4**	0.1	*0.00*	*1.000*
2003	1.2	0.0	**1.4**	0.1	**1.4**	0.1	**1.5**	0.1	*0.01*	*0.878*
Resistance	--	--	17		27		19			
Resilience (6 yr)	--	--	121		124		124			
% of control (2003)	--	--	119		119		121			
Double Disturbance										
2000 (Post-)	1.6	0.0	**0.3**	0.0	**1.3**	0.1	**1.9**	0.1	*0.00*	*1.000*
2001 (1 yr post)	1.8	0.1	**2.1**	0.1	**2.2**	0.1	**2.5**	0.1	*0.00*	*1.000*
2003 (3 yr post)	1.2	0.0	1.5	0.0	**1.4**	0.1	**1.5**	0.1	*<0.01*	*0.958*
Resistance (2X)	--	--	18		80		116			
Resistance (+1)	--	--	15		63		102			
Resilience (6 yr)	--	--	125		157		(-6)			
% of control (2003)	--	--	127		116		123			



TRANSITION	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	1.8	0.1	1.7	0.1	1.7	0.1	1.7	0.0	*0.51*	*0.182*
1997 (Post-disturbed)	1.2	0.1	**0.5**	0.0	**0.7**	0.1	**0.7**	0.0	*0.00*	*1.000*
1998	1.5	0.1	1.7	0.1	1.7	0.1	**1.8**	0.1	*0.10*	*0.505*
2000	1.8	0.1	1.8	0.1	1.7	0.1	1.7	0.1	*0.83*	*0.094*
2001	2.3	0.2	2.4	0.2	2.2	0.2	2.5	0.2	*0.53*	*0.176*
2003	1.2	0.1	1.2	0.1	1.2	0.1	1.3	0.1	*0.42*	*0.218*
Resistance	--	--	43		55		60			
Resilience (6 yr)	--	--	87		96		110			
% of control (2003)	--	--	93		98		103.9			
Double Disturbance										
2000 (Post-)	1.8	0.1	**0.4**	0.1	**1.4**	0.2	2.1	0.2	*0.00*	*1.000*
2001 (1 yr post)	2.3	0.2	2.5	0.2	2.3	0.2	**2.8**	0.2	*0.02*	*0.755*
2003 (3 yr post)	1.2	0.1	1.2	0.0	1.2	0.1	1.3	0.1	*0.50*	*0.188*
Resistance (2X)	--	--	24		77		107			
Resistance (+1)	--	--	24		98		103			
Resilience (6 yr)	--	--	98		90		(0)			
% of control (2003)	--	--	98		97		107			

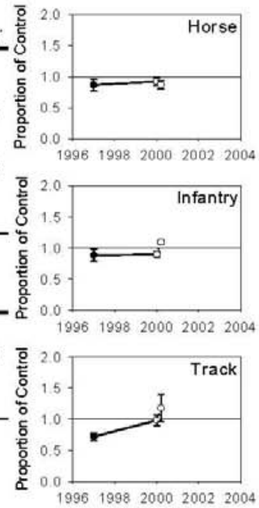


OUTCROP	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)	2.2	0.2	2.2	0.1	2.1	0.1	2.1	0.1	*0.47*	*0.200*
1997 (Post-disturbed)	1.3	0.0	**0.5**	0.1	**0.7**	0.1	**0.5**	0.1	*0.00*	*1.000*
1998	1.0	0.0	0.9	0.1	1.1	0.1	1.0	0.1	*0.13*	*0.452*
2000	2.0	0.1	2.1	0.1	2.0	0.1	**2.2**	0.1	*0.02*	*0.810*
2001	2.7	0.3	2.9	0.2	3.0	0.3	**3.4**	0.3	*0.02*	*0.750*
2003	1.3	0.1	1.3	0.1	1.3	0.1	1.4	0.2	*0.41*	*0.224*
Resistance	--	--	37		56		34			
Resilience (6 yr)	--	--	107		99		117			
% of control (2003)	--	--	105		99		112			
Double Disturbance										
2000 (Post-)	1.9	0.1	**0.8**	0.2	2.0	0.1	**2.5**	0.2	*0.00*	*1.000*
2001 (1 yr post)	2.7	0.3	**3.6**	0.3	**3.5**	0.3	**3.7**	0.3	*0.01*	*0.901*
2003 (3 yr post)	1.3	0.1	1.3	0.1	1.3	0.1	1.4	0.1	*0.27*	*0.305*
Resistance (2X)	--	--	44		105		112			
Resistance (+1)	--	--	39		106		100			
Resilience (6 yr)	--	--	103		(0)		(0)			
% of control (2003)	--	--	103		105		112			

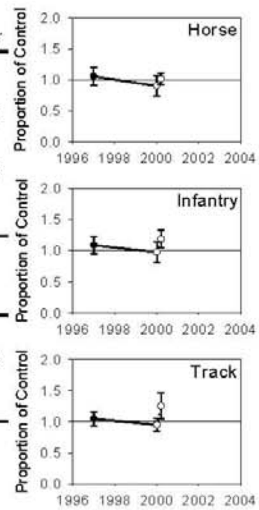


SAND-FREE AGGREGATE STABILITY

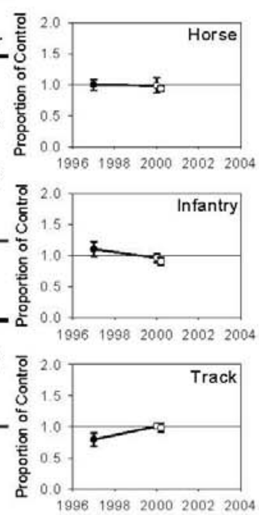
DUNE MARGIN	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)										
1997 (Post-disturbed)	18.1	2.7	14.6	0.6	14.9	1.1	**12.6**	0.7	*0.04*	*0.671*
1998										
2000	22.3	0.7	20.7	1.6	20.1	1.2	21.9	1.7	*0.62*	*0.146*
2001										
2003										
Resistance	--	--	81		83		70			
Resilience (6 yr)	--	--	--		--		--			
% of control (2000)	--	--	93		90		98			
Double Disturbance										
2000 (Post-)	17.9	0.9	15.4	0.6	19.6	1.0	20.0[a]	2.5	*0.11*	*0.478*
2001 (1 yr post)										
2003 (3 yr post)										
Resistance (2X)	--	--	--		--		--			
Resistance (+1)	--	--	--		--		--			
Resilience (6 yr)	--	--	--		--		--			
% of control (2003)			--		--		--			



TRANSITION	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)										
1997 (Post-disturbed)	13.0	1.6	12.9	0.7	13.4	1.6	13.0	0.8	*0.97*	*0.062*
1998										
2000	20.0	2.0	17.2	2.8	18.4	2.4	18.2	1.5	*0.82*	*0.096*
2001										
2003										
Resistance	--	--	86		92		91			
Resilience (6 yr)	--	--	--		--		--			
% of control (2000)	--	--	86		92		91			
Double Disturbance										
2000 (Post-)	14.7	0.8	14.8	1.2	17.0	1.4	17.8	2.4	*0.30*	*0.283*
2001 (1 yr post)										
2003 (3 yr post)										
Resistance (2X)	--	--	--		--		--			
Resistance (+1)	--	--	--		--		--			
Resilience (6 yr)	--	--	--		--		--			
% of control (2003)			--		--		--			



OUTCROP	Control Avg	Control SE	Horse Avg	Horse SE	Infantry Avg	Infantry SE	Track Avg	Track SE	p	Power
Single Disturbance										
1997 (Pre-disturbed)										
1997 (Post-disturbed)	18.7	3.8	16.9	2.8	17.2	1.6	**13.3**	1.3	*0.06*	*0.589*
1998										
2000	22.1	1.3	21.7	1.4	20.9	0.8	22.5	1.3	*0.86*	*0.086*
2001										
2003										
Resistance	--	--	91		92		71			
Resilience (6 yr)	--	--	--		--		--			
% of control (2000)	--	--	98		95		102			
Double Disturbance										
2000 (Post-)	17.8[a]	1.3	16.4	0.6	16.1	0.7	17.0	0.7	*0.25*	*0.314*
2001 (1 yr post)										
2003 (3 yr post)										
Resistance (2X)	--	--	--		--		--			
Resistance (+1)	--	--	--		--		--			
Resilience (6 yr)	--	--	--		--		--			
% of control (2003)	--	--	--		--		--			



[a] The average and SE are based on n=5 blocks instead of n=6 due to missing data

4. Synthesis. The sustainability or health of rangeland ecosystems can be described in terms of three attributes: soil and site stability, hydrologic function and biotic integrity (Pellant et al., 2000). These three attributes are key to maintaining the capacity of ecosystems to support DOD land management objectives.

4.1. Soil and site stability.

4.1.1. Water erosion. Both the dune margin and outcrop sites have naturally high resistance to water erosion. Slopes are low at both sites and infiltration capacity is high at the dune site due to coarse soil textures. Field soil stability values are inherently high due to high microbiotic crust cover. The lichens and cyanobacteria suffered minimal reductions following disturbance and recovered relatively quickly. Transition was the only site with significant evidence of overland flow. The control plots at this site also had the lowest and most variable (highest coefficient of variation) infiltration rates and the lowest soil stability, suggesting it is inherently more susceptible to water erosion. Fortunately, however, it was also relatively resistant and resilient to all three types of single disturbances.

4.1.2. Wind erosion. The dune margin site is inherently susceptible to wind erosion, and wind erosion was significantly increased at this site by all three treatments during all measurement periods and, at the outcrop site, by all treatments during at least one measurement period. Loss of vegetative canopy cover ensured that sediment movement remained high even after torvane and pocket penetrometer measurements showed restabilization of the soil surface. The transition site appears to be more resistant to wind erosion due to higher vegetative cover and finer soil texture.

4.2. Hydrologic function. The greatest threat to hydrologic function at all three sites is clearly vehicle traffic. Just two passes of a small jeep with extremely low tire inflation (15 psi) on dry soil reduced equilibrium infiltration rates by 40-50%. Recovery was relatively rapid at the outcrop and transition sites, particularly when compared with the dune margin site where infiltration rates were still 40% below control levels 4 years after the first disturbance. Under more typical training conditions with more passes, higher tire inflation pressures and occasionally moist soils, the effects would be expected to be even greater and more persistent. These data, together with the penetrometer resistance values, suggest vehicle traffic has a long-term, significant effect on soil structure at the dune margin site.

4.3. Biotic integrity. The significant and persistent reduction in shrub cover at all three sites, particularly in response to the track treatment, has significant implications for biotic integrity. It is correlated with reduction in foliage height diversity (not measured) which, in turn, is correlated with a number of wildlife species. The relatively slow recovery of nitrogenase activity (“Nitrogen Fixation”) suggests a loss of the integrity of the microbiotic crust community despite relatively rapid recovery of crust cover.

4.4. Site comparisons. The dune margin site was clearly the most sensitive to disturbance and the slowest to recover. Several factors combine to make this site particularly sensitive to all types of disturbance. One is the low vegetative cover and dominance by low-stature saltbush which appears to be particularly susceptible to breakage and recovers slowly. The second is that gypsic soils have very low strength and are highly susceptible to compaction. Both the transition and outcrop sites have characteristics making them more resistant to degradation. The near-surface petrogypsic horizon at the outcrop site appears to provide greater resistance to both compactive and trampling-type disturbances, while the relatively high cover of resistant plant species and possibly higher water-holding capacity give the transition site a comparative advantage. However, the extremely slow rate of lichen and nitrogenase recovery at this site suggests that disturbance may have some effects on plant production not apparent in this relatively short-term (6 years) dataset. One factor which may have affected resistance and possibly recovery results is the disturbance history at each site. We believe the dune margin site was in a relatively pristine state when we initiated the experiments, while it was clear that the outcrop site had been previously used for training activities. It is possible, therefore, one of the reasons the outcrop site appeared to be so resistant to degradation is that it had already been degraded. Based on our analysis and an examination of variability within the site, however, we do not believe this factor is sufficiently important to change our conclusions.

4.5. Treatment comparisons. Off-road vehicle traffic is clearly the greatest threat to all three sites. Intensive horse trampling and even trampling by humans can also negatively affect soil stability, hydrologic function, and biotic integrity. However, the magnitude and persistence of the impacts on most indicators is generally much less. This conclusion is reinforced by the fact that the horse and infantry treatments imposed were relatively intense compared to what would normally occur during training exercises (infantry), wildlife and livestock management, or recreational activities (horse). The vehicle treatment imposed (jeep) was relatively mild with tires set at a low inflation pressure and a slow driving speed with no turns.

5. Recommendations. The following recommendations assume that the primary objective is to sustain the capacity of the land to support military training activities and other land use values. This is achieved by planning training so that recovery time is minimized. Recovery time is minimized by selecting site/training combinations that cause relatively little degradation (high resistance) or which result in rapid recovery (high resilience). The key variable to consider in each case is the number of years required for recovery.

Military planners can do this by controlling *what* types of activities occur, *where*, they occur, and *when* they occur. One of the primary conclusions of this study is that the effect of each of these variables (what, where, and when) depends on the others.

The outcrop site clearly represents the most suitable soil for both single and repeated disturbance. However, vehicle disturbances are the most destructive and generally require the longest recovery at all three sites. The dune site is the most sensitive to all three types of disturbance. Consequently, we recommend focusing training activities on soils similar to those found at the outcrop site and avoiding the dune margin. Based on the results, we also strongly recommend limiting traffic to existing roadways: our data show that just two passes with a light vehicle and low tire pressure can cause damage requiring 5 years or more for recovery.

6. Web-based Decision Tool/Model. A simple decision tool based on the results of this study is included on the attached CD and is posted at http://usda-ars.nmsu.edu/JER/Monit_Assess/monitoring.php.

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