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F. R. Kay · H. M. Sobhy · W. G. Whitford

Soil microarthropods as indicators of exposure to environmental stress in Chihuahuan Desert rangelands

Abstract We studied soil microarthropod communities along livestock grazing disturbance gradients, inside and outside grazing exclosures, and on areas subjected to restoration efforts (herbicide and bulldozing) in order to test the suitability of mites as indicators of rangeland soil quality. We found that mite numbers generally increased with decreased grazing disturbance. Soil microarthropods appeared to respond to a complex of factors including soil compaction, depth to an impervious soil layer, below-ground vegetative biomass, and residual effects of herbicide. All of our study plots, except those that had been herbicide treated, were dominated by microbivorous mites of the family Nanorchestidae. The numerical responses of mites, especially nanorchestids, appeared to provide a sensitive indicator of ecosystem health in a Chihuahuan Desert grassland.

Key words Desertification · Desert grassland · Grazing · Herbicides · Indicators

Introduction

Soil microarthropods play important roles in decomposition and nutrient cycling in the northern Chihuahuan Desert (Santos and Whitford 1981; Santos et al. 1981; Parker et al 1984; Fisher et al. 1990; Whitford and Parker 1990). Most of those earlier studies were conducted in shrub dominated ecosystems. In a study of a Chihua-

huan Desert watershed, Cepeda-Pizarro and Whitford (1989) found a pattern of a greater number of species and a higher abundance of soil mites on the lower slopes of the watershed in areas of mixed grass and shrubs. All previous studies of soil microarthropods in the northern Chihuahuan Desert were conducted on sites from which livestock grazing had been excluded for more than 20 years.

In the northern Chihuahuan Desert there are extensive desert grasslands in the intermountain basins. There have been no studies of soil microarthropods in the basin grasslands. We designed a study to provide information on the microarthropod fauna of the desert basin grasslands and to examine the effects of livestock grazing and grassland restoration efforts on the microarthropod fauna. We compared the soil microarthropod communities along grazing disturbance gradients, outside and inside livestock grazing exclosures, and on plots that had been bulldozed or treated with herbicide in attempts to increase grass production and eliminate shrubs.

We hypothesized that soil microarthropods would be sensitive indicators of exposure to the environmental stress of livestock grazing and indicators of the quality of rangeland soils. Microarthropods were chosen as the indicator fauna because of their importance in ecosystem processes and because they are the only component of the soil fauna that remains active in dry soils (Whitford 1989).

There have been large changes in the vegetation of the northern Chihuahuan Desert since the development of commercial livestock ranching in the 1870s (Buffington and Herbel 1965; Hennessy et al. 1983; Gibbens and Beck 1988). As a result of a combination of factors such as drought and overgrazing, the formerly shrub-free grasslands now exist as shrub-grass mosaics, coppice dunes, or shrubland with little grass understory. The remnant patches of grassland have varying densities of shrubs and there are very few patches of shrub-free grassland that are 1 km² or larger in extent. Within the remnant patches of grassland, the con-

F. R. Kay · H. M. Sobhy[1] · W. G. Whitford (✉)
Jornada Experimental Range, PO Box 30003, MSC 3JER,
New Mexico State University, Las Cruces, NM 88003-8003, USA

W. G. Whitford
US Environmental Protection Agency, National Exposure
Laboratory, Environmental Sciences Division, PO Box 93478,
Las Vegas, NV 89196, USA

Present address:
[1] Institute of Ecology, Ecology Annex, University of Georgia,
Athens, GA 30602-2360, USA

centration of livestock at water points has created steep gradients from barren soil with sparse shrubs to high cover grasslands. Since the intensity of disturbance by domestic livestock decreases exponentially with distance from the water point, we sampled microarthropod communities at fixed distances from water points in pastures with remnant grassland. In order to evaluate effects of grazing per se on desert grassland soil microarthropods, we studied mite communities on plots inside a grazing exclosure and in an adjacent grazed area.

The degradation of the production potential of the desert rangelands stimulated research on methods of restoring productivity. Some of the methods tested in the northern Chihuahuan Desert grasslands included bulldozing to level mesquite (*Prosopis glandulosa*) coppice dunes and applying herbicides to kill shrubs. While these restoration efforts did not restore the areas to the original grasslands, they did result in increased grass cover, elimination of dunes, and reduced shrub cover. In order to evaluate the impact of restoration efforts on soil fauna, we compared soil microarthropod communities in areas subjected to restoration efforts and adjacent untreated areas.

Methods

Our studies were conducted on the USDA, ARS Jornada Experimental Range and New Mexico State University's Chihuahuan Desert Rangeland Research Center. The two adjacent facilities are located approximately 40 km north, northeast of Las Cruces, Doña Ana County, New Mexico. These research stations comprise more than 500 000 km^2 of desert rangeland in the Jornada Basin which includes two mountain ranges. The elevation of the basin is approximately 1230 m above sea level. Long-term average rainfall for the Jornada Basin is 225 mm with 55% of that falling between July and September. Summer maximum temperatures regularly reach 40 °C and winter minima are frequently below 0 °C. The study sites with their soil and vegetation characteristics are presented in Table 1.

We randomly selected points within 1 ha plots and collected soil cores at the edge of the canopy of the nearest grass or herbaceous perennial. Four, six, nine, or ten cores were collected from each plot. Soil cores were 6 cm in diameter and 10 cm deep. The cores were transferred to zip-lock plastic bags, placed in an insulated cooler, and transported to the laboratory.

The soil cores were placed in modified Tullgren funnels and extracted into water over 48 h as described by Santos et al. (1978). Microarthropods were counted and identified to family using reference collections for the Jornada Experimental Range and keys in Krantz (1978).

Count data are often not normally distributed and ours were no exception. We used Kruskal-Wallis Analysis of Variance of

Table 1 Characteristics of range sites where soil microarthropods were sampled. Vegetation characteristics are percent cover of perennial grasses and shrubs. Average size of unvegetated patches is reported as average bare diameter in centimeters. [Data from Whitford et al. (in press) & Peters et al. (1997)]. The bulldozed and herbicide-treated areas and the untreated controls had a history of variable seasonal grazing

Site – Distance	Disturbance/grazing history	Grass (%)	Shrub (%)	Bare (cm)	Soil
Grazing intensity (Well) gradients					
Camp Well – 0–50 m	Winter-Spring	0.47	5.7	396.2	Sandy-loam, indurated
Camp Well – 250–350 m	Winter-Spring	3.4	8.6	126.0	caliche at 40–100 cm
Camp Well – 450–550 m	Winter-Spring	4.5	5.5	126.9	
Camp Well – 1000–1100 m	Winter-Spring	20.8	4.3	68.5	
Mayfield Well – 0–50 m	Continuous	1.2	6.8	296.4	Sandy-loam, indurated
Mayfield Well – 250–350 m	Continuous	4.1	17.2	96.9	caliche at 40–100 cm
Mayfield Well – 450–550 m	Continuous	5.7	10.9	90.2	
Mayfield Well – 1000–1100 m	Continuous	23.7	6.7	62.6	
West Well – 0–50 m	Winter-Spring	0.88	15.9	197.6	Sandy loam, indurated
West Well – 250–350 m	Winter-Spring	3.3	21.7	139.2	caliche at 40–100 cm
West Well – 450–550 m	Winter-Spring	8.9	13.7	133.1	
West Well – 1000–1100 m	Winter-Spring	27.6	5.1	50.9	
Exclosed/grazed site					
Exclosure west	Exclosed 1946	47.9	0.66	54.1	Sandy-loam
Exclosure west control (grazed)	Continuous	6.7	17.5	125.1	Sandy-loam
Bulldozed site					
Bulldozed mesquite dunes	Bulldozed 1975/1976	4.2	5.8	99.9	Sandy-loam, indurated
Bulldozed mesquite control	Untreated	1.8	24.8	311.9	caliche
Herbicide treated sites					
Mesquite, Hdqtrs, Jornada (hand-sprayed)	Treated 1979	10.2	12.9	ND	Sandy-loam, indurated caliche at 20–70 cm
East mesquite site (control)	Untreated	2.3	33.3	ND	
Rabbit rain gauge (aerial-sprayed)	Treated 1968, 1978, 1980	5.4	16.2	ND	
Rabbit rain gauge (control)	Untreated	Essentially the same as East mesquite site			

Ranks (K-W ANOVA) and Rank Sum Tests as appropriate for data analysis (Zar 1974). As an exploratory tool, we also carried out standard one-, two-, and three-way ANOVA on the data, but, for consistency, we report the results of the K-W ANOVA for most analyses. To evaluate differences between ranks or means within ANOVA, we used the Student-Newman-Kuel (SNK) method for multiple comparisons (Zar 1974). Because our data tended to exhibit very high coefficients of variation, we used $P \leq 0.1$ as our criterion for biologically significant statistical difference. Sigma Stat was our statistical analysis package.

Results

Community composition

Twenty-seven taxa of mites and insects were found in the soil samples from our plots. Several of the taxa were found in single samples and/or at single sites and others were often represented by few individuals. To make maximum use of the data and to reflect the trophic status of the groups, we lumped the taxa into feeding guilds for purposes of our analyses. The assignment of taxa to a feeding guild was based on the literature. Microbivores included taxa that fed on bacteria, fungi, and/or algae. Oribatids were placed in a separate feeding guild because they were reported to feed on plant litter as well as fungi. The granivore guild was included for the Penthaleidae based on information in Krantz (1978). Table 2 is a listing of all of the taxa, the guild to which they were assigned, and total numbers in each sample.

Across and within sites, microbivores tended to be dominant. Within sites microbivores ranged from 22.0% of mites counted on the hand-sprayed herbicide plot to 78.4% on the grazed plot. Overall, microbivores represented 48.6% of all mites sampled. Of the microbivores, Nanorchestidae were most abundant, representing 64.1% of microbivores and 31.1% of all mites. Tarsonemidae made up 21.7% of microbivores and 10.5% of all mites sampled. Tydeidae represented 14.2% of microbivores and 6.9% of all mites.

Ten taxa of omnivores comprised 22.5% of all mites. Stigmaeidae represented 31.4% of the omnivores and 7.1% of all mites sampled. Anystidae represented 22.8% of the omnivores and 5.1% of all mites sampled, Nematalycidae accounted for 21% of omnivores and 4.7% of all mites, and 11.8% of the omnivores were Eupodidae. None of the remaining six taxa of omnivores exceeded 1% of the total mites.

Predatory mites in our samples were represented by six families. Predators represented 11.7% of all mites sampled. The Cunaxidae, Bdellidae, and Smaridiidae

Table 2 Summary of numbers of individuals of taxa and feeding guilds found in various samples at 11 study sites in a Chihuahuan Desert grassland in southern New Mexico

Guild	Taxon	Camp Well	May-field Well	West Well	Exclo-sure	Grazed	Bull-dozed	Bull-dozed control	Hand-sprayed herbicide	Hand-sprayed control	Aerial-sprayed herbicide	Aerial-sprayed control	Total
Collembola	Sminthuridae			3									3
	Entomobryidae		20	14	3	5	5	8	6	8	6	13	101
Fungivore	Pyemotidae	5	45	31	3	10	3	12	14	18	25	15	181
Granivore	Penthaleidae	6	85	51					8	36	6	18	210
Herbivore	Allochaetophoridae										2	1	3
	Tenuipalpidae		5									7	12
	Tetranychidae		6										6
Microbivore	Nanorchestidae	179	241	210	26	64	58	74	5	71	43	97	1068
	Tarsonemidae	28	109	103	12	12	14	9	12	14	28	21	362
	Tydeidae	39	74	42	10	15	4	15	10	10	5	13	237
Omnivore	Anystidae		60	50	2	2	10	5	5	8	11	23	176
	Caeculidae	3	6							7	3		19
	Cheyletidae		7										7
	Eupodidae	1	59	18			13						91
	Linotetranidae		12										12
	Nematalycidae	10	38	48			11	12	8	2	15	18	162
	Scutacaridae		4							8			12
	Stigmaeidae	21	74	39	3	1	13	11	22	13	4	41	242
	Teneriffidae		5						5		10	1	21
	Trombidiidae		7				12	10					29
Oribatid	Oribatidae		24	15		2	3	5	6	4	6	11	76
Predator	Bdellidae	5	52							12	5	3	77
	Cunaxidae	33	60	46	3	1	6	7	20	13	17	16	222
	Paratydeidae		9										9
	Raphignathidae		3								10	1	14
	Smaridiidae		19				8	10				8	45
	Mesostigmata	2	13	13	4			2		1	5	8	35

accounted for 55.2%, 19.2%, and 11.2% of the predators, respectively.

Grazing disturbance (well) gradients

Five guilds (fungivores, granivores, predators, omnivores, and microbivores) contributed most of the data at Mayfield (MW) and West Wells (WW) and all of the data at Camp Well (CW). Only three of the feeding guilds (omnivores, predators, and microbivores) were sufficiently abundant at all three of the well gradients to contribute to our analysis.

MW and WW were each sampled on two dates (25 August and 12 November and 22 September and 22 November, respectively) in 1994 and CW was sampled once (21 June) in 1995. At both MW and WW, there were significant differences in median numbers in the three guilds between sampling dates (K-W ANOVA, MW, $H = 32.3$, $df = 1$, $P < 0.001$; WW, $H = 13.6$, $df = 1$, $P < 0.001$). The median number of microarthropods found in the August sample from MW and the September sample from WW was greater than in either of the November samples. The November data showed little

differentiation between guilds with uniformly low numbers of organisms present.

Camp Well

The median values for guild and distance-from-the-well at CW for September 1994 were significantly different ($H = 46.1$, $df = 11$, $P < 0.001$). In general, numbers of soil microarthropods increased with distance from the well and microbivores exceeded both predators and omnivores (Fig. 1). Multiple comparisons of the ranked data indicated that microbivores were more abundant than either predators or omnivores at all distances from the well (SNK, $P < 0.1$). Median numbers of omnivores were higher than for predators at CW-0, but did not differ at CW-1, -2, or -3 (Fig. 1).

Microbivores differed significantly along the gradient of distance from the well. Microbivores occurred in significantly higher median numbers at CW-3 than at either CW-0, -1, or -2; higher at CW-2 than either CW-0 or -1; and higher at CW-0 than CW-1 (SNK, $P < 0.1$; Fig. 1). The predators at CW-3 occurred in higher median numbers than those at CW-0, and CW-1, but not

Fig. 1 Relationships of three feeding guilds of soil microarthropods to distance from three wells where livestock watering occurred in a Chihuahuan Desert grassland on the Jornada del Muerto of southern New Mexico. Intensity of grazing impacts decreased as distance from well increased. Legend indicates distances of samples from wells. Data presented as total counts of each guild
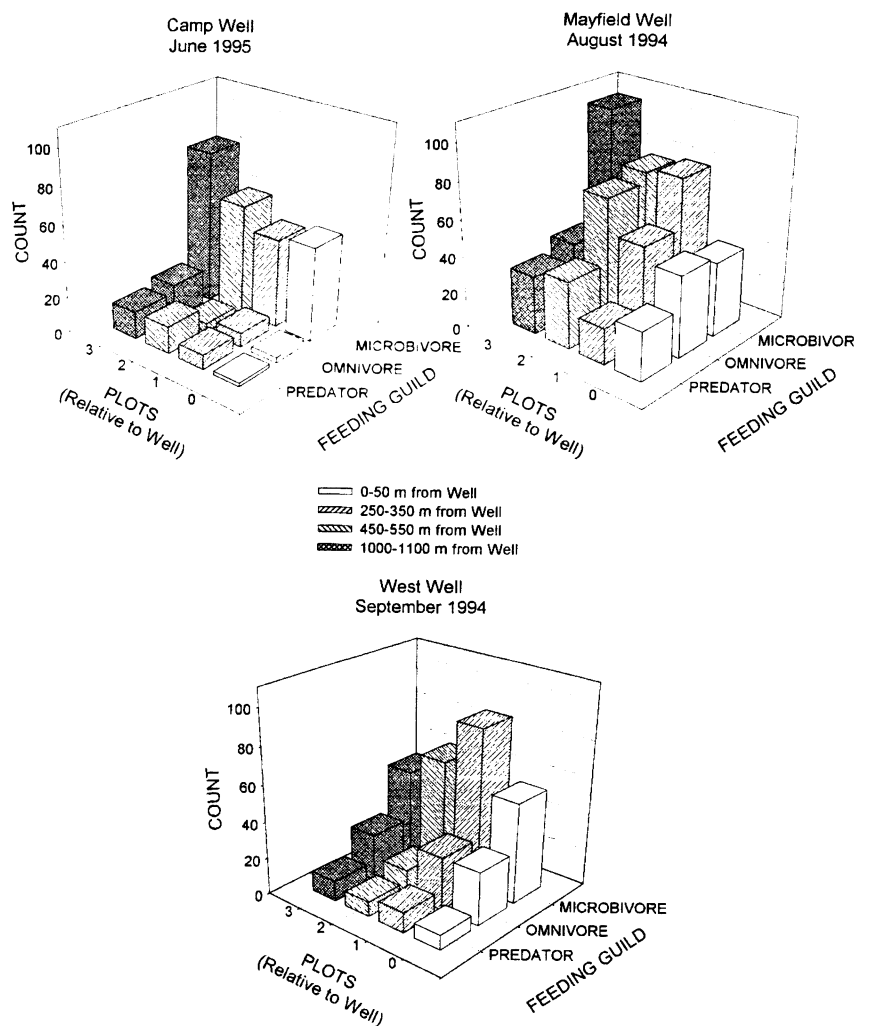
CW-2. Predator numbers were also higher at CW-2 than either CW-0 or -1 (SNK, $P<0.1$; Fig. 1). Omnivores were found in higher median numbers at CW-3 than at CW-1 or -2, but not CW-0 (SNK, $P<0.1$; Fig. 1). Omnivores did not differ between CW-0, -1, or -2.

Mayfield Well

The differences in median numbers between feeding guild and position along the well gradient at MW for August 1994 was highly significant ($H=33.3$, $df=11$, $P<0.001$). Numbers tended to increase with distance from the well and microbivores were numerically dominant (Fig. 1). Microbivores at MW-3 had higher median numbers than either omnivores or predators (SNK, $P<0.1$), and omnivores and predators did not differ (Fig. 1). At MW-2, microbivores did not have higher median values than omnivores, but both omnivores and microbivores differed significantly from predators (SNK, $P<0.1$). Microbivores had significantly higher values than either omnivores or predators at MW-1 and omnivores were higher than predators (SNK, $P<0.1$; Fig. 1). At MW-0, microbivores and omnivores did not differ, and microbivores, but not omnivores, differed from predators (SNK, $P<0.1$), although omnivores approached significance (Fig. 1).

Microbivores had significantly higher median numbers at MW-3 than at any other sampling point (SNK, $P<0.1$; Fig. 1). Microbivores at MW-1 and -2 did not differ from one another, but both ranked significantly higher than at MW-0 (SNK, $P<0.1$; Fig. 1). Omnivores at MW-2 had significantly higher median values than at MW-0, -1, or -2 and those at MW-1 were higher than at either MW-0 or -3 (SNK, $P<0.1$). Omnivores at MW-3 and MW-0 did not differ (Fig. 1). Predators sampled at MW-2 and -3 had higher median numbers than those from MW-0 and -1 (SNK, $P<0.1$), but not each other (Fig. 1). Predators ranked significantly higher at MW-0 than at MW-1 (SNK, $P<0.1$; Fig. 1).

West Well

Microbivores had significantly higher values than either omnivores or predators at WW at all sampling points (SNK, $P<0.1$; Fig. 1). Omnivores had higher median numbers than predators at all distances from the well (SNK, $P<0.1$; Fig. 1). Along the gradient, microbivores were most abundant at WW-1 compared to WW-0, -2, or -3 (SNK, $P<0.1$; Fig. 1). There were no significant differences between microbivores at WW-0, -2, or -3 (Fig. 1). Omnivores were highest at WW-1 compared to WW-0, -2, or -3 (SNK, $P<0.1$). Omnivores were higher at WW-3 than at WW-0 or -2 and ranked higher at WW-0 than at WW-2 (SNK, $P<0.1$; Fig. 1). Predators had higher median numbers at WW-3 and -1 than at WW-0 and predatory mites at WW-2 were higher than at WW-0 (SNK, $P<0.1$; Fig. 1).

Grazing exclosure

Five guilds were identified in the grazing and exclosure plots: collembola, fungivores, microbivores, omnivores, oribatids and predators (Fig. 2A). Microbivores represented the bulk of the mites sampled. There was a significant difference in median numbers among guilds between the grazing and the exclosed plot and between guilds within the plots ($H=36.1$, $df=11$, $P<0.001$). Microbivore abundance ranked significantly higher in the exclosed versus the grazed plot and higher than any other guild sampled (SNK, $P<0.1$) in either the exclosure or grazed plot. Fungivores were the next most abundant (Fig. 2A), but did not rank significantly higher than any other guild and were not significantly different inside and outside the exclosure.

Bulldozed site

There was a significant difference in the medians of the data compared between bulldozed and control plots and among the six feeding guilds represented ($H=65.2$, $df=11$, $P<0.001$). Microbivores and omnivores, but none of the other guilds, differed between bulldozed and control plots (SNK, $P<0.1$; Fig. 2B).

Microbivores on the bulldozed site had higher median numbers than fungivores, oribatids, collembola or predators, but ranked lower than omnivores despite having a higher total count (SNK, $P<0.1$). Omnivores on the bulldozed plots occurred in higher median numbers than fungivores, oribatids, collembola, or predators (SNK, $P<0.1$; Fig. 2B). Predators on the bulldozed plot were significantly different from fungivores, oribatids, and collembola. Microbivores had higher values on the control plot than oribatids, fungivores, collembola and predators (SNK, $P<0.1$). Omnivores on the control plot were significantly different from oribatids, fungivores, collembola and predators (SNK, $P<0.1$). Predators had higher median counts than oribatids, fungivores, or collembola in the control plot.

Herbicide-treated sites

We sampled two herbicide-treated sites that had different treatment modalities and histories. The hand-sprayed (HS) site was treated once in 1979 with an unknown herbicide. Treatment consisted of hand spraying individual shrubs with a resultant very high shrub mortality. The aerial-sprayed (AS) site was treated in 1968, 1978, and 1980. An unknown herbicide was applied in 1968. In 1978, the plot was sprayed with Tebuthiuron and in 1980, with 2, 4, 5-T. Rates of application are unknown to us.

HS site

The HS site was sampled twice, in August and again in October 1994 (Fig. 2C). Rank Sum Tests indicated a

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Fig. 2 Responses to four anthropogenic stressors of feeding guilds of soil microarthropods at experimental sites in a Chihuahuan Desert grassland on the Jornada Experimental Range in southern New Mexico. Data presented as total counts for each guild
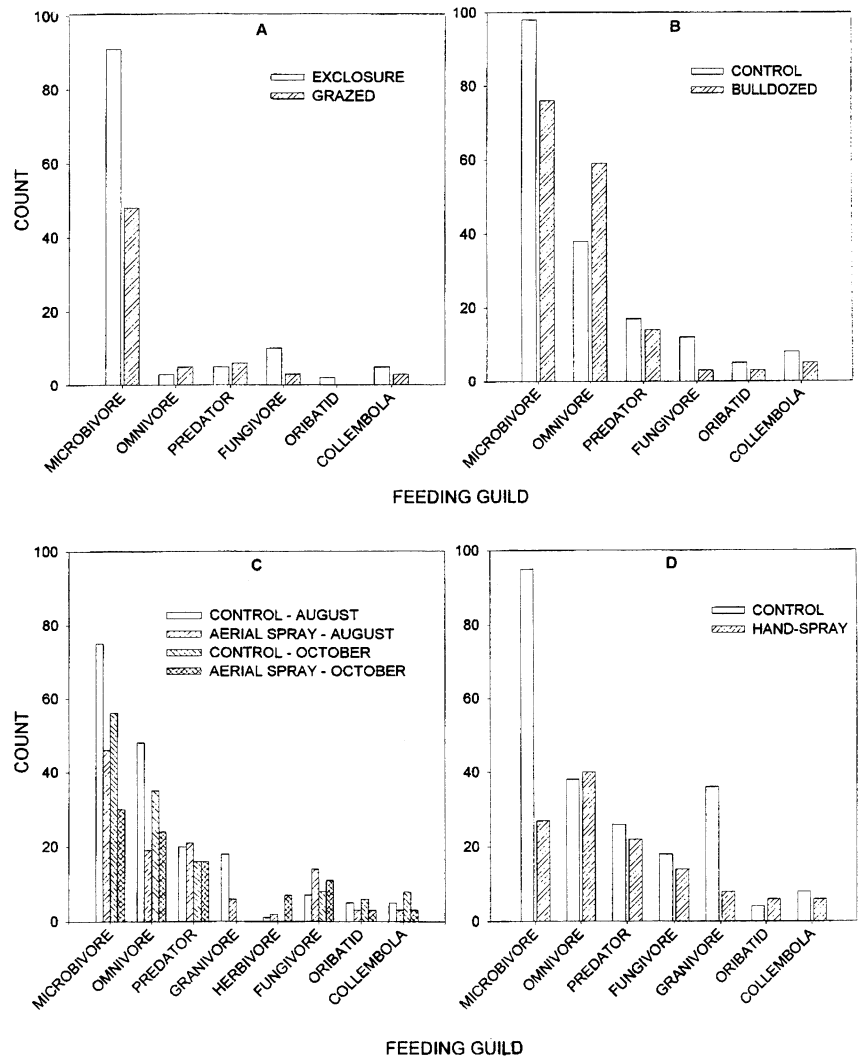
significant difference between dates ($T=398.5$, $P=0.04$) and sprayed and control plots ($T=423.0$, $P=0.005$), and a K-W ANOVA indicated a difference between guilds ($H=136.4$, $df=7$, $P<0.001$). The data differed significantly when analyzed across dates, plots, and guilds ($H=160.1$, $df=31$, $P<0.001$). There were significantly higher median counts of microbivores in August than October and on the control plot (SNK, $P<0.1$). They had higher median values than any other guild in all comparisons (SNK, $P<0.1$). Omnivores did not differ between August and October, but numbers from the control plot were higher than the treatment plot (SNK, $P<0.1$). Omnivores were more abundant than any guild except microbivores in all comparisons (SNK, $P<0.01$).

AS site

The results of the sampling on the AS site are presented in Fig. 2D. The relationship between plot and guild at AS contained significant differences ($H=36.9$, $df=6$, $P<0.001$). Microbivores, predators, granivores, and

fungivores were all significantly higher on the control than the sprayed plot (SNK, $P<0.1$). Microbivores had significantly higher median counts than any other guild on the control plot, but had significantly lower values than omnivores on the treated plot (SNK, $P<0.1$). On the control plot, omnivores had significantly higher median numbers than any other guild except microbivores (SNK, $P<0.1$). Omnivores on the sprayed site had higher values than all other guilds (SNK, $P<0.1$). Predators were ranked significantly higher than collembola and fungivores on the control plot, and were higher than granivores and oribatids on the treated plot (SNK, $P<0.1$). Fungivores had significantly higher median counts than collembola on the control plot, and were higher than granivores and oribatids on the treated plot (SNK, $P<0.1$).

Microbivores

Microbivores were the dominant guild on all plots examined except on the herbicide-treated plots where they showed a decided reduction in numbers (Fig. 2C,

D). Because of the marked response on the herbicide plots, we carried out a separate analysis of microbivores across the treated and control plots (Fig. 3). The same three families of microbivores (Nanorchestidae, Tarsonemidae, and Tydeidae) were found in all samples, including the well gradients (Table 2). There was a significant relationship among microbivores between all treatment and control plots ($H=23.8$, $df=7$, $P=0.001$). Microbivores on both herbicide treatment plots (HS and AS) had significantly lower median numbers than on the exclosure plot (SNK, $P<0.1$). Microbivores on the exclosure plot also ranked higher than the bulldoze treatment and the HS control plots (SNK, $P<0.1$). Other relationships of microbivores within plots were not significant.

Nanorchestidae were the dominant family across all plots ($H=33.7$, $df=2$, $P<0.001$). We tested plots within nanorchestids using a one-way ANOVA (the data were normally distributed) and found a significant effect ($F=3.156$, $df=7$, 60, $P=0.007$). There were significantly fewer nanorchestid mites in the herbicide-treated than in any of the control or other treatment plots, except the grazed plot (SNK on Means, $P<0.1$; Fig. 3). The HS site had more nanorchestids than the AS site (SNK on Means, $P<0.1$; Fig. 3). The relationship between Tarsonemidae and Tydeidae and the plot was more complex and did not show the effects of the herbicide treatment (Fig. 3).
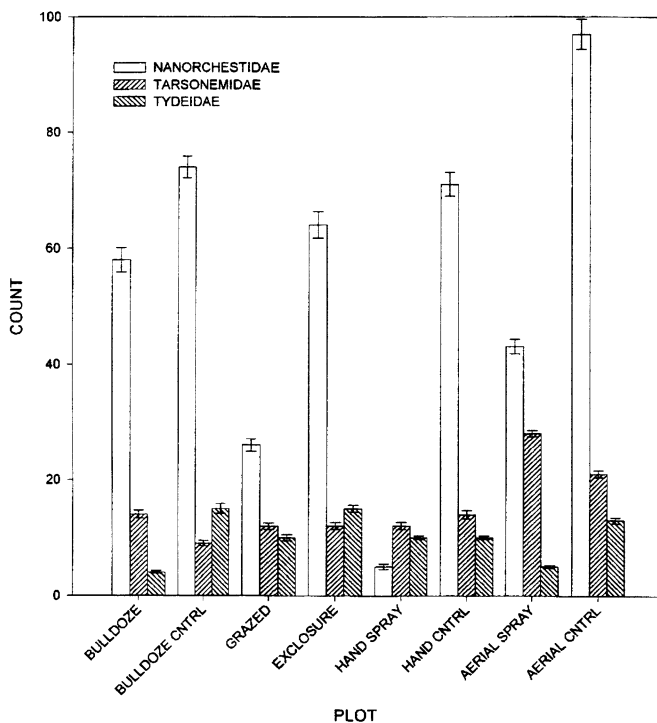

Fig. 3 Responses to four anthropogenic stressors of three microbivorous families of soil mites at experimental sites in a Chihuahuan Desert grassland on the Jornada Experimental Range in southern New Mexico. Data presented as total counts and standard errors of the mean for each family

Discussion

The desert grassland soil mite communities dominated by nanorchestid mites (Fig. 3) differed from those recorded in Chihuahuan Desert shrublands (Santos et al. 1978; Cepeda-Pizarro and Whitford 1989), which were generally dominated by small tydeid mites. The primary difference in desert grassland soils and soil habitats in shrublands was the general absence of litter accumulations in desert grasslands. The major food source of nanorchestid mites in a gypsum sand dune community, which they dominated, was soil algae (Santos and Whitford 1983). There may be higher concentrations of algae in the surface soils of grasslands compared to shrublands.

The variation in the patterns of microbivorous mite abundance on the grazing gradients (Fig. 1) appeared to be a function of topography. The WW gradient crossed a change in elevation at a small escarpment (approximately 10 m differential in elevation) at approximately 700 m from the well. Soil depths varied considerably along the WW gradient with exposed petrocalcic material visible on plot 2 on the gradient. The variation in soil depth along this gradient may have caused the anomalous pattern of abundance on the WW gradient.

Most of the sampling was done during a year when the growing season rainfall was only 47% of the long-term average. Shallow soils or soils with a compacted layer 10–20 cm below the surface may have limited refugia for soil mites during drought. The low abundance of mites on the sites nearest the livestock watering points reflected the presence of a compacted soil layer 5–15 cm below the surface. The surficial soils on sites nearest the livestock watering points were churned by hoof action which mixed large quantities of dried dung with the surface soil. The organic matter content of the plot-0 soils was considerably higher than the organic matter content on any of the more distant plots (unpublished data).

The negative influence of grazing by domestic livestock on the microbivorous mite populations was further documented by the differences in abundance of mites extracted from the soils of a grazing exclosure and from the grazed area outside the exclosure fence (Fig. 2A). Here also the primary factor was probably the presence or absence of a compacted layer that resulted from hoof action.

In a study in tropical Australia, Holt et al. (1996) found that soil Acari populations were significantly lower in the heavily grazed treatments at one of the two sites that they studied. They did not report the soil Acari data by species or functional group. The site where grazing had no effect on the soil Acari populations was a site characterized by higher bulk density soils, higher tree densities, and shorter time duration of exposure to livestock grazing (Holt et al. 1996). The effects of livestock grazing on soils resulted from tram-

pling and removal of protective plant cover, which affected infiltration, and reduced pore sizes and connectivity within the compacted soil layers. In the sandy soils of the Jornada Basin, the compacted layer resulting from concentrated use by livestock varied between 5 cm and 15 cm (measured by penetrometer; J. Herrick, personal communication). Compaction of the soil resulted in negative feedback by reducing the populations of soil organisms that contributed to soil porosity by their activity and by their contribution to carbon turnover.

Grazing by livestock was also shown to reduce below-ground biomass (Pandey and Singh 1992). Root systems and root turnover were the primary sources of carbon and energy for the soil food webs in desert grasslands. Reduction in below-ground biomass would contribute to the reduction in soil microarthropod abundance reported in this study.

Soil microarthropods were very sensitive to chemical and physical changes in the soil. This was clearly true more than a decade after the treatments attempting to reduce shrub cover and restore grasslands. Herbicide residuals may affect the microarthropod populations or the differences observed may simply reflect the change in vegetative composition that resulted from the treatment. There was deflation of dunes in the herbicide-treated areas and a more uniform soil depth. Dune deflation also reduced the patchiness of litter associated with the coppiced mesquite plants. Whatever the factors involved, the reduced populations of microarthropods in the "restoration" sites would have a negative effect on the recovery of soil processes.

We conclude that soil microarthropods are useful indicators of soil disturbance in the sandy basin soils of Chihuahuan Desert rangelands. Nanorchestid mites are the most abundant and most responsive taxa of soil microarthropods in the desert grassland soils. These mites are adversely affected by hoof action that produces a compacted layer in the soil. Also, surface soil that is constantly disturbed by livestock is probably not a good environment for soil algae, the most important food source for those mites.

Soil microarthropods are also useful indicators of the success of restoration efforts. For rangeland restoration to be successful in the long term, soil processes must return to the pre-disturbance state. In the rangeland restoration efforts in the northern Chihuahuan Desert, the attempts to reduce the shrub cover and to increase grasses in areas that had degraded to coppice dunes resulted in marked reductions in nanorchestid mites and some reductions in the populations of tarsonemid and tydeid mites. These are the mite taxa that play a critical role in decomposition and nutrient cycling processes (Santos et al. 1981; Parker et al. 1984). The fate of soil microarthropods in these restoration efforts adds to the evidence that those approaches are not feasible for long-term ecosystem improvement (Whitford et al. 1995).

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