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DYNAMICS OF RODENT ASSEMBLAGES INHABITING ABANDONED PETROLEUM LANDFARMS IN OKLAHOMA

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Abstract. Studies on the effects of anthropogenic contamination on wildlife have largely been focused at the individual level. Biomarkers have been used to monitor changes in the health of individuals exposed to contaminants; however, little attention has been given to the effects of chronic exposure at the population or community levels. We studied rodent assemblages from uncontaminated (reference) sites ($n = 5$) and abandoned petrochemical landfarms ($n = 5$) in Oklahoma to investigate potential alterations in community structure and composition. Rodent assemblages inhabiting landfarms had lower species diversity, lower richness, and a more even distribution of individuals across species. Reference sites showed typical rodent assemblage structure dominated by hispid cotton rats (*Sigmodon hispidus*) and fulvous harvest mice (*Reithrodontomys fulvescens*). Assemblages inhabiting landfarms also were dominated by cotton rats; however, harvest mice were replaced by deer mice (*Peromyscus maniculatus*) on two landfarms. Contaminated sites also were characterized by an increase in house mice (*Mus musculus*) and an absence of voles (*Microtus* spp.). Although landfarms tended to have lower cotton rat densities, we could not separate the effects of contamination from increased bare ground associated with landfarms. The results of this study suggest that rodent assemblages were different on landfarms, when compared with reference sites. However, no direct link between site contamination and rodent community structure could be established.

Key words: contamination; cotton rats; diversity; evenness; landfarms; Oklahoma, USA; petroleum; Reithrodontomys fulvescens; Sigmodon hispidus.

Introduction

Rodent populations fluctuate with variations in environmental conditions. For example, precipitation, which directly affects seed and forage production, has been correlated with rodent population densities (Shelford 1943, Krebs and Myers 1974, Windberg 1998). However, species with different life histories will exhibit different patterns of population growth under similar environmental conditions (Windberg 1998), and have evolved strategies for coexistence with other species in a varying environment. As a result, fluctuations in the population structure of individual species will affect community structure as well. Contamination from anthropogenic sources has been hypothesized to increase the number of stressors that may alter community dynamics (Lochmiller 1996).

Petroleum refining generates a complex and highly concentrated waste product. The use of landfarms in the treatment and disposal of petrochemical waste has increased in recent years, and it is estimated that over half of all waste produced by refineries is treated in landfarms (American Petroleum Institute 1984). During landfarming, petrochemical waste is applied on or into a prepared bed of soil and tilled under where microbes metabolize the organic portion of the waste, decontaminating the site in the process. However, microbes are not effective against certain polyaromatic hydrocarbons and inorganic compounds, leaving residual waste in the soil that may be available for bioaccumulation and toxicity (Schroder et al. 2003).

Contaminants associated with petrochemical refining have been reported to cause a number of adverse effects on rodents inhabiting abandoned landfarms. Effects from petrochemical waste include chromosomal aberrations (McBee et al. 1987), dental lesions (Paranjpe et al. 1994, Rafferty et al. 2000), alterations in immune function and hematology (Rafferty et al. 2001, Wilson et al. 2003), and increased detoxification enzyme activity (Lochmiller et al. 1999, Carlson et al. 2003). Effects of contaminants at the individual level may be translated into changes at the population and community levels.

Because populations are collections of individuals, populations can only change through alterations in the birth/death rate, migration, and/or survival of individuals within a population. Likewise changes within a given population may affect other members of the community by altering population interaction parameters such as competition, predation, and resource partitioning. Congdon et al. (2001) proposed that contaminants

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PLATE 1. View of an abandoned petrochemical landfarm (Unit 1) in southwestern Oklahoma (USA) showing the patchy distribution of plants and bare ground. Photo credit: J. A. Wilson.

may alter populations either directly by causing mortality (toxicity) or inhibiting reproduction, or indirectly through increased energy costs associated with detoxification and elimination of contaminants (Congdon et al. 2001).

Changes in rodent assemblages have been noted on sites exposed to various types of contamination. McMurry (1993) found sites contaminated with heavy metals and hydrocarbons had lower species richness, but increased species diversity due primarily to increased house mouse (*Mus musculus*) populations. In addition, a decrease in the proportion of juveniles found on contaminated sites has been observed (McMurry 1993). Batty et al. (1990) also reported a decrease in the number of juvenile and subadult white-footed mice (*Peromyscus leucopus*) on sites contaminated with polychlorinated biphenyls. Lower densities and species richness in rodent assemblages also were observed on sites contaminated with thallium (Dmowski et al. 1998).

Our objectives were to investigate differences in rodent assemblages inhabiting abandoned petrochemical landfarms compared to uncontaminated reference sites. We measured differences in species diversity, community evenness, and species richness between rodent assemblages living on replicated landfarms and reference sites. In particular, we were interested in the abundance of cotton rats in relation to other rodent species, as cotton rats are the dominant rodent in the system and have been shown to be important in structuring rodent assemblages. We hypothesized that rodent assemblages on contaminated sites would differ from those associated with uncontaminated sites. In addition, cotton rats would be found in lower numbers on petroleum-contaminated sites. As a result of lower cotton rat densities, there would be an increase in rodent species diversity and evenness compared to uncontaminated sites. Finally, we hypothesized that the species composition on petroleum-contaminated sites would change in relation to uncontaminated sites, with sensitive species, such as voles, decreasing in importance, while species associated with disturbance (e.g., *Mus musculus*) increased in importance.

METHODS

This study was conducted on 10 paired sites throughout Oklahoma (Units 1–5; see Plate 1). Five sites were abandoned landfarms that had a history of petrochemical contamination, and five were uncontaminated reference sites. Reference sites were located as close to landfarms as possible to reduce variation from climate and vegetation. Contaminated sites for Units 1, 2, and 3 were abandoned landfarms with no further cleanup. Contaminated sites at Units 4 and 5 were abandoned landfarms that had undergone additional cleanup (removal of contaminated soil to a new landfarm) by the U.S. Environmental Protection Agency. Sites were located in southwestern (Units 1 and 2), north-central (Unit 3), and eastern (Units 4 and 5) Oklahoma. Detailed descriptions of the study sites in the present study, including soil metal and polycyclic aromatic hydrocarbon (PAH) levels, are given by Schroder et al. (2003).

Soil contaminant levels (milligrams per kilogram) measured by Schroder et al. (2003) were used to characterize individual sites using principal components analysis (PCA). PCA was performed using the program CANOCO for Windows 4.0 (Centre for Biometry, Wageningen, The Netherlands) with the data square-root transformed, and the center and standardize option selected to scale soil contaminants with varying concentration levels equally, and rotate component axes to provide the clearest view of the data. Because metals and organics exhibit different modes of toxicity, PCA analyses were performed independently for metal and organic contaminants to characterize sites based on the two classes of contaminants. The 16 priority PAHs listed by the U.S. Environmental Protection Agency were measured on each site and used in this analysis. Plots of the eigenvalues for principal components 1 and 2 as well as the loading vectors for the individual metal and organic contaminants were generated to visualize multivariate site characterization.

Rodent assemblages were sampled on all sites using mark–recapture techniques. Rodent assemblages were surveyed monthly during winter (December–February) and summer (June–August) for two years (June 1999–February 2001), with each seasonal trap session consisting of three four-day periods separated by three-week intervals. Sixty-four Sherman live traps (LFA 9-inch, Sherman Traps Incorporated, Tallahassee, Florida) spaced at 10-m intervals were arranged in a square (8×8) or rectangular (4×16) grid as dictated by the shape of the area to be surveyed. Traps were baited with whole oats, set in the late afternoon, and checked the following morning. Cotton bedding was provided during winter months for added insulation.

Captured individuals for each species were sexed, weighed, given a unique identification number by toe clipping, and released. Because several species were represented by low incidences of capture, the minimum number known alive (MNKA) estimate was used for population abundance (Krebs 1966). Birth, death, and immigration were assumed to be zero for all sites during each 4-day period of trapping. Mean minimum longevity was calculated for each species by averaging the time, in months, between the first and last capture of each individual that was captured at least twice (Wilkins 1995). Mean minimum longevity values were calculated for each site. Monthly species richness was calculated for every landfarm and reference site as the number of species captured during the four-day trapping session.

Rank abundance analysis (Begon et al. 1996) was used to determine differences in the structure of rodent assemblages from landfarms and reference sites. The logarithm of the MNKA was used as the measure of abundance, and species were assigned a rank from 1 (most abundant) to 9 (least abundant). The relationship between species rank and abundance was tested between rodent assemblages inhabiting landfarm and reference sites using linear regression with PROC REG (SAS Institute 1994).

Standard measures of community structure were calculated from live-trap data. Species richness was determined for each site during each season (summer and winter). Shannon's diversity index (H') was calculated from the proportional abundance of individuals of each species. To determine if fluctuations in cotton rat abundance affected species evenness, linear regression was performed on cotton rat density, and Shannon's evenness (J') with and without inclusion of cotton rats in the evenness calculations as described by Brady and Slade (2001). Density was used to calculate diversity indices for species with enough individual captures, whereas minimum number known alive was used for species with low captures. Estimates of population density were made using program MARK (White and Burnham 1999), using the robust design data type.

The proportion of bare ground on each site was measured using 10 randomly placed 1-m^2 quadrats. The percentage of each quadrat that was bare ground was recorded and a mean percentage for each site was used for analysis. Locations for the sampling quadrats were randomly located on one of the 64 potential grid points on the established live-trapping grid. The live-trap grid effectively sampled a 1-ha area within the landfarm or reference site. The size of the landfarms varied from $\sim$2 ha (Unit 3), 50–60 ha (Units 4 and 5), to 162 ha (Units 1 and 2). Reference sites were located on larger contiguous parcels of land.

Results

Although all landfarms were only used to treat petrochemical waste, the composition and concentration of waste applied at each site were different. Contamination remaining on landfarm sites consisted of two major classes: inorganics (heavy metals and fluoride) and polyaromatic hydrocarbons (PAHs). The landfarms at Units 1 and 3 were characterized by increased levels of of As, Cd, Cr, Cu, and Pb; whereas the landfarms at Units 2 and 4 were associated with high levels of F (Fig. 1 top). Although the landfarm at Unit 5 was associated with elevated levels of Al, Ti, and V, a suite of other contaminants were also elevated including As, Cr, Cu, Pb, and F. Reference sites showed variation across a number of metals; however, reference sites had comparatively low levels of As, Cd, Cr, Cu, Pb, and F, with most variation due to differences in the concentration of Al, Ba, Ti, V, and Zn. Mean soil concentrations of inorganics for all landfarms and the mean reference values can be found in Schroder et al. (2003).

Contrary to the high variation of reference sites with respect to metal concentrations, virtually no PAHs were detected on reference sites, resulting in a tight cluster of reference sites (Fig. 1 bottom). The landfarm at Unit 3 had the highest number (15 of 16) and concentration of priority PAHs elevated above reference levels, followed by the landfarm at Unit 1 (11 of 16 priority PAHs, Fig. 1 bottom). The landfarm at Unit 4 showed high levels of acenaphthylene, acenaphthene, and naphthalene, whereas the concentration of PAHs on the landfarms from Units 2 and 5, although still elevated over reference sites, was an order of magnitude lower than on other landfarms (Fig. 1 bottom). Individual site soil concentrations of the 16 priority PAHs and total petroleum hydrocarbon levels measured in this study can be found in Schroder et al. (2003).

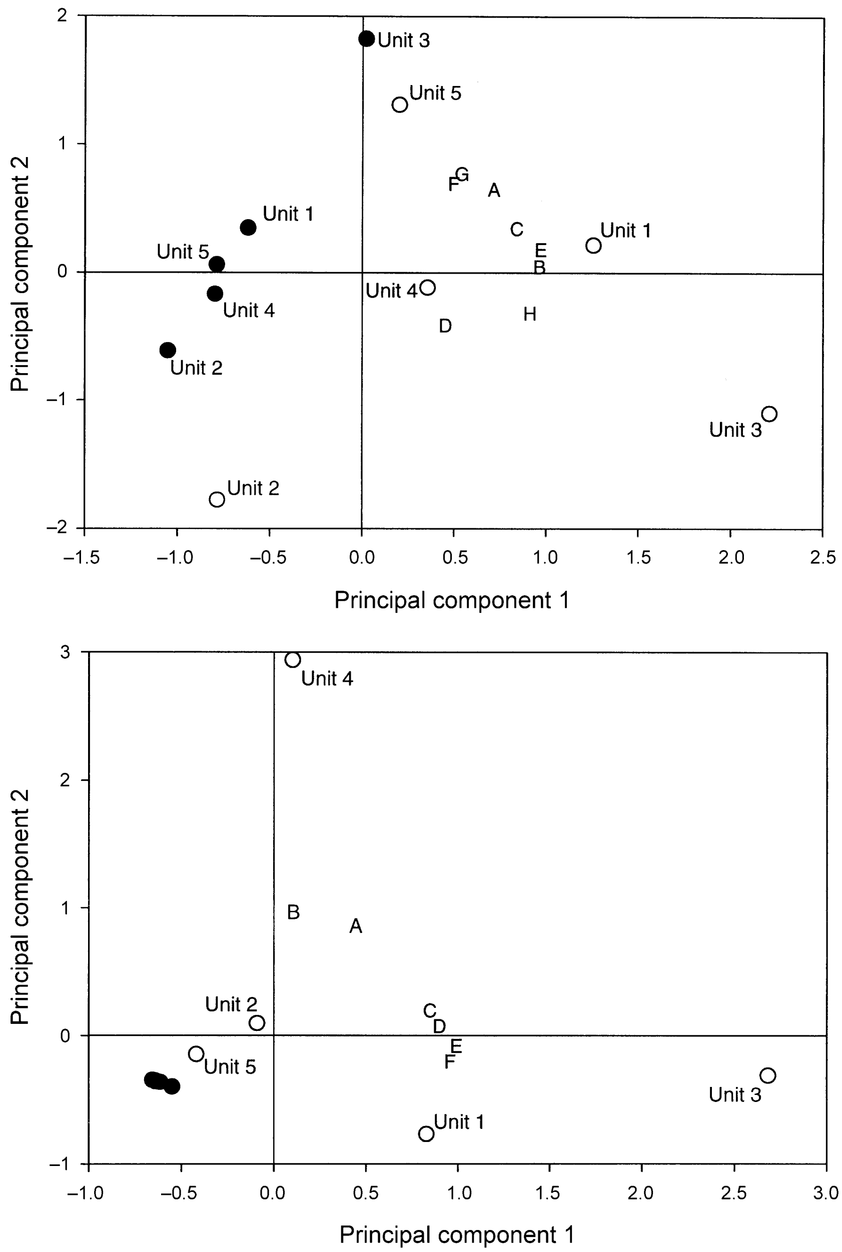

FIG. 1. Plot of the first two principal components for soil metal concentrations (top panel) and soil polyaromatic hydrocarbon (PAH) concentrations (bottom panel) from petrochemical-contaminated landfarms and uncontaminated reference sites. Individual site mean eigenvalues are represented with open symbols for contaminated sites, and closed circles for reference sites. In the top panel, loading values for individual metals are represented by letters: (A) Al, (B) As, (C) Ba, (D) F, (E) Ni, (F) Ti, (G) V, and (H) a combination of Cd, Cr, Cu, Pb, Sr, and Zn. In the bottom panel, loading values for individual PAHs are also represented by letters: (A) acenaphthene, (B) acenaphthylene, (C) naphthalene, (D) combination of benzo(k)fluoranthene, chrysene, and fluorene, (E) benzo(b)fluoranthene, and (F) a combination of all other PAHs. Soil contaminant data were obtained from Schroder et al. (2003).

Rodent assemblages, as described by rank–abundance analysis, differed between landfarms and reference sites (Fig. 2; $F_{2,15} = 3.62$, $P = 0.05$). Rank-abundance analysis, which incorporates species richness, diversity, and evenness, showed rodent assemblages inhabiting landfarms to have a more even distribution of individuals across species (slope $= -0.11$, $R^2 = 0.82$, $P < 0.001$) compared to those from reference sites (slope $= -0.13$, $R^2 = 0.90$, $P < 0.001$). Each component was tested separately to determine if any treatment effects were present for species richness, diversity, and evenness. Species richness showed a treatment effect ($F_{1,96} = 4.86$, $P = 0.03$) but no effects by season, with reference sites having higher mean month-

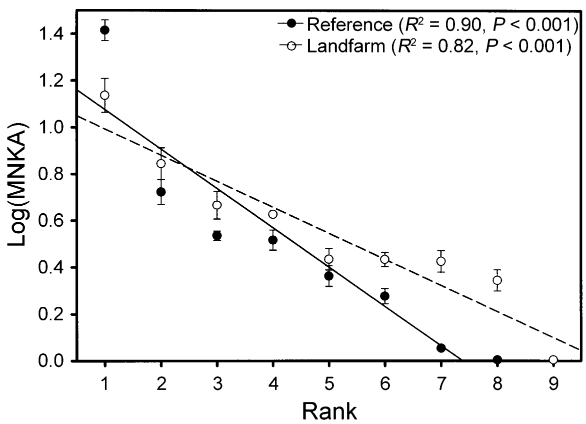

FIG. 2. Rank abundance patterns of rodent communities inhabiting abandoned petrochemical landfarms (dashed line) and uncontaminated reference (solid line) sites in Oklahoma (USA). The log of the minimum number known alive (MNKA) of each species is ranked from most abundant (1) to least abundant (9). Data are means ± 1 SE.

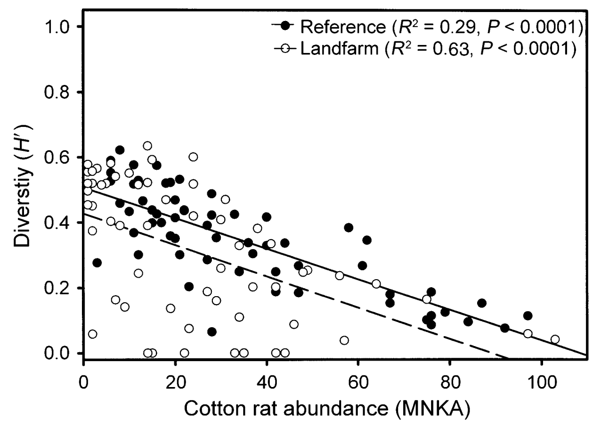

FIG. 3. Shannon's diversity index in relation to cotton rat (*Sigmodon hispidus*) abundance for communities inhabiting abandoned petrochemical landfarms (n = 5) and uncontaminated reference sites (n = 5) in Oklahoma. Abundance was the mark–recapture MNKA estimate based on winter and summer trapping over a two-year period with 64 Sherman live traps per site (see *Methods*).

ly species richness (3.77 ± 0.16 species/mo) than landfarms (3.28 ± 0.16 species/mo). (Data are expressed as mean ± 1 SE.) Species diversity was negatively associated with cotton rat abundance on both reference (slope = −0.005, R^2 = 0.63, P < 0.0001) and landfarm (slope = −0.005, R^2 = 0.29, P < 0.0001) sites (Fig. 3). However, the negative effect of cotton rat abundance on rodent diversity was more intense on landfarms compared to reference sites ($F_{2,\,116}$ = 5.04, P = 0.008).

Cotton rat abundance initially appeared to affect total rodent evenness; however, the effect of cotton rat abundance on rodent evenness was an artifact of the comparatively large number of cotton rat individuals (Fig. 4). Both landfarms (slope = −0.006, R^2 = 0.40, P < 0.0001) and reference (slope = −0.008, R^2 = 0.77, P < 0.0001) sites showed a negative relationship between community evenness and cotton rat abundance when cotton rats were included in the evenness calculations (Fig. 4A). Species evenness is susceptible to bias in communities where individuals of a single species dominate. To correct for this, Brady and Slade (2001) have suggested that evenness calculations in relation to the dominant species be calculated both with and without inclusion of the dominant species. When cotton rats were excluded from the evenness calculations, the effect of cotton rat abundance on evenness disappeared from both reference sites (slope = −0.0004, R^2 = 0.002, P = 0.97) and landfarms (slope = 0.00003, R^2 < 0.001, P = 0.79, Fig. 4B). Similarly, a treatment difference was apparent when cotton rats were included in the evenness calculations ($F_{2,\,108}$ = 3.05, P = 0.05, Fig. 4A); however, treatment differences were no longer significant when cotton rats were excluded from evenness calculations ($F_{2,90}$ = 0.18, P = 0.84, Fig. 4).

Cotton rats were the most abundant species on both reference and landfarm sites (Table 1). Cotton rat abun-

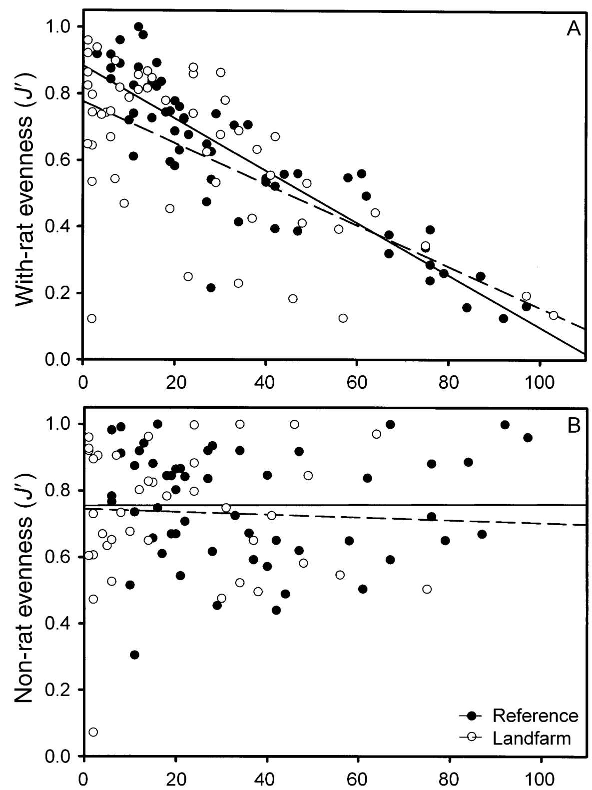

FIG. 4. Shannon's community evenness in relation to cotton rat (*Sigmodon hispidus*) abundance for communities inhabiting abandoned petrochemical landfarms (n = 5) and uncontaminated reference sites (n = 5) in Oklahoma. Community evenness was measured (A) with and (B) without cotton rats included in evenness calculations.

TABLE 1. Total number of individuals, by rodent species, captured in June 1999–February 2001 on reference and petroleum landfarm sites in Oklahoma (USA).

Species	Unit 1 Reference	Unit 1 Landfarm	Unit 2 Reference	Unit 2 Landfarm	Unit 3 Reference	Unit 3 Landfarm	Unit 4 Reference	Unit 4 Landfarm	Unit 5 Reference	Unit 5 Landfarm
Sigmodon hispidus	592	116	431	55	350	420	450	588	264	296
Reithrodontomys fulvescens	56	29	29	21	58	35	97	20	123	42
Reithrodontomys montanus	0	0	0	7	0	0	2	0	0	2
Peromyscus maniculatus	7	189	6	86	62	1	7	4	18	5
Peromyscus leucopus	37	24	88	41	28	4	17	0	32	3
Chaetodipus hispidus	6	21	1	51	0	0	0	0	0	0
Neotoma floridana	0	1	0	0	2	0	0	0	1	0
Mus musculus	1	7	1	1	1	117	0	0	1	2
Microtus ochrogaster	20	0	23	0	1	0	0	0	0	0
Oryzomys palustris	0	0	0	0	0	0	11	17	7	15

Notes: Units 1 and 2 are located in southwestern, Unit 3 in north-central, and Units 4 and 5 in eastern Oklahoma. In total, 30 720 trapnights were evenly distributed among the sites.

dance was greater on reference sites during the first summer, but then remained at a similar level at contaminated sites for the remainder of the study (Fig. 5). Cotton rat abundance peaked during the summer months on reference sites; however, during the second summer, populations peaked at levels less than half that of the previous summer. Similarly, fulvous harvest mice were more abundant on reference sites compared to landfarm sites (Table 1). Fulvous harvest mice had peaks in abundance during winter months, with populations from reference sites reaching greater abundances than those from landfarms (Fig. 6A). Although plains harvest mice (*Reithrodontomys montanus*) were found as incidental species on both landfarms and reference sites, they occurred more frequently on landfarms (Table 1).

Two species of white-footed mice were found among the sites (Table 1), the deer mouse and the white-footed mouse (*Peromyscus leucopus*). Deer mice were found in low to high numbers on both sites, but tended to be more abundant on landfarms, increasing during the winter of 2000–2001 (Fig. 6C). A prominent peak in abundance was observed for *P. maniculatus* inhabiting landfarms during February 2000. White-footed mice also were found in higher numbers on reference sites and showed peaks in their abundance during summer (Fig. 6D). Prairie voles (*Microtus ochrogaster*) were found only on reference sites from Units 1, 2, and 3 (Table 1; Fig. 6E). Conversely, house mice, although trapped on both landfarms and reference sites, were found predominantly on landfarms and had abundances that peaked in winter (Fig. 6B). Pocket mice (*Chaetodipus hispidus*) also were found in higher abundances on landfarms (Table 1) and peaked in summer (Fig. 6F). Rice rats (*Oryzomys palustris*) were not trapped on any site until December 2000, and may represent a temporary range expansion, as they have not been reported previously in Tulsa County, Oklahoma. Eastern woodrats (*Neotoma floridana*) were also occasionally caught as incidentals on both reference and landfarm sites (Table 1).

No differences in mean minimum longevity were observed for most rodent species inhabiting landfarms and reference sites. However, treatment effects for mean minimum longevity were observed in cotton rats and house mice (Table 2). Cotton rats inhabiting petrochemical landfarms had a minimum longevity (2.20 $\pm$ 0.09 mo) that was a month shorter than cotton rats inhabiting reference sites (3.91 $\pm$ 0.15 mo). House mice inhabiting landfarms had longer longevity values (1.84 $\pm$ 0.19 mo) than their counterparts from reference sites (1.00 $\pm$ 0.00 mo).

The proportion of bare ground was $<$5% on all reference sites with the exception of Unit 4, which had an average of 23.5%. The proportion of bare ground varied among the landfarm sites depending on how they were treated. Landfarms at Units 1 and 2 were left for natural succession after completion of landfarming and had the greatest amount of bare ground (68.6% and 33.8%, respectively). The history of the landfarm at Unit 3 is unknown; however, it was intermediate in the proportion of bare ground (21.3%) and consisted of large tracts of Johnsongrass (*Sorghum halapense*) interspersed with bare patches of ground. The landfarms at Units 4 and 5 contained little to no bare ground ($<$5.0%) because they were seeded with fescue (*Festuca arundinacea*) and bermudagrass (*Cynodon dactylon*) upon completion of landfarming (Kelley 1985). This resulted in a dense mat of vegetation that covered the landfarm. Maximal cotton rat densities observed in this study were negatively correlated with the amount of bare ground ($R^2 = 0.51$, slope $= -1.09$, Fig. 7).

DISCUSSION

The structure of rodent assemblages differed between reference sites and abandoned petrochemical landfarms. Rank abundance analyses present a combined measure of diversity, richness, and evenness (Begon et al. 1996). Rodent assemblages inhabiting landfarms showed a trend toward a more even distribution of rodent species compared to those inhabiting reference sites. This difference was primarily due to a re-

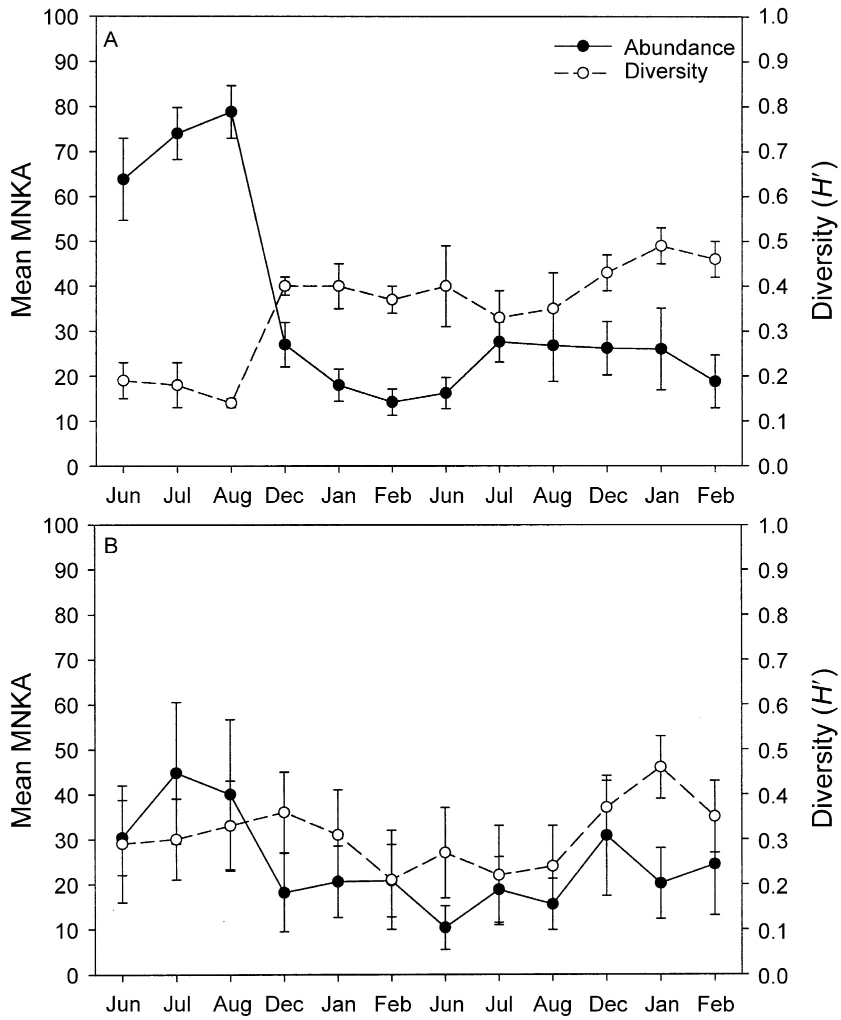

FIG. 5. Shannon's diversity index (dashed line) in association with cotton rat (*Sigmodon hispidus*) MNKA abundance (solid line) for communities inhabiting (A) uncontaminated reference sites and (B) petrochemical landfarms in Oklahoma, 1999–2001. Data are means ± 1 SE.

duction in cotton rat abundance and increased abundances in incidental species found on landfarms, both contributing to increased evenness. Landfarms had fewer rodent species than those found inhabiting reference sites, with the decrease primarily due to an absence of voles on landfarms.

We observed a noticeable decrease in the densities of cotton rats on both reference and landfarm sites between the first and second year. During the first season of trapping (1998–1999) Oklahoma experienced severe high temperatures during August with daily high temperatures remaining over 100°F for 16 consecutive days (Graumann et al. 1998). During the winter following this drought event, temperatures were lower than normal and at least one severe ice storm similar to that observed by Clark et al. (2003) occurred, reducing cotton rat densities. As a result, cotton rat densities observed during the first year of trapping are indicative of normal population levels, whereas densities from the second year may reflect unusual losses from harsh weather.

The results of our study suggest that cotton rat abundance may influence species diversity on both reference and landfarm sites. Rodent diversity was negatively associated with cotton rat density on both reference and landfarm sites in this study. Diversity changed temporally on both landfarms and reference sites, and was correlated with cotton rat abundance. This effect was also observed in rodent assemblages from Kansas, with diversity negatively associated with periods of high cotton rat abundance (Brady and Slade 2001). In this study, rodent species diversity was observed to be lower on contaminated sites, even at the same cotton rat abundance, supporting the hypothesis that reductions in rodent diversity on landfarms may be due to the effects of landfarming. However, we cannot determine if these results are caused by the direct or indirect effects of residual contaminants, or alterations in habitat

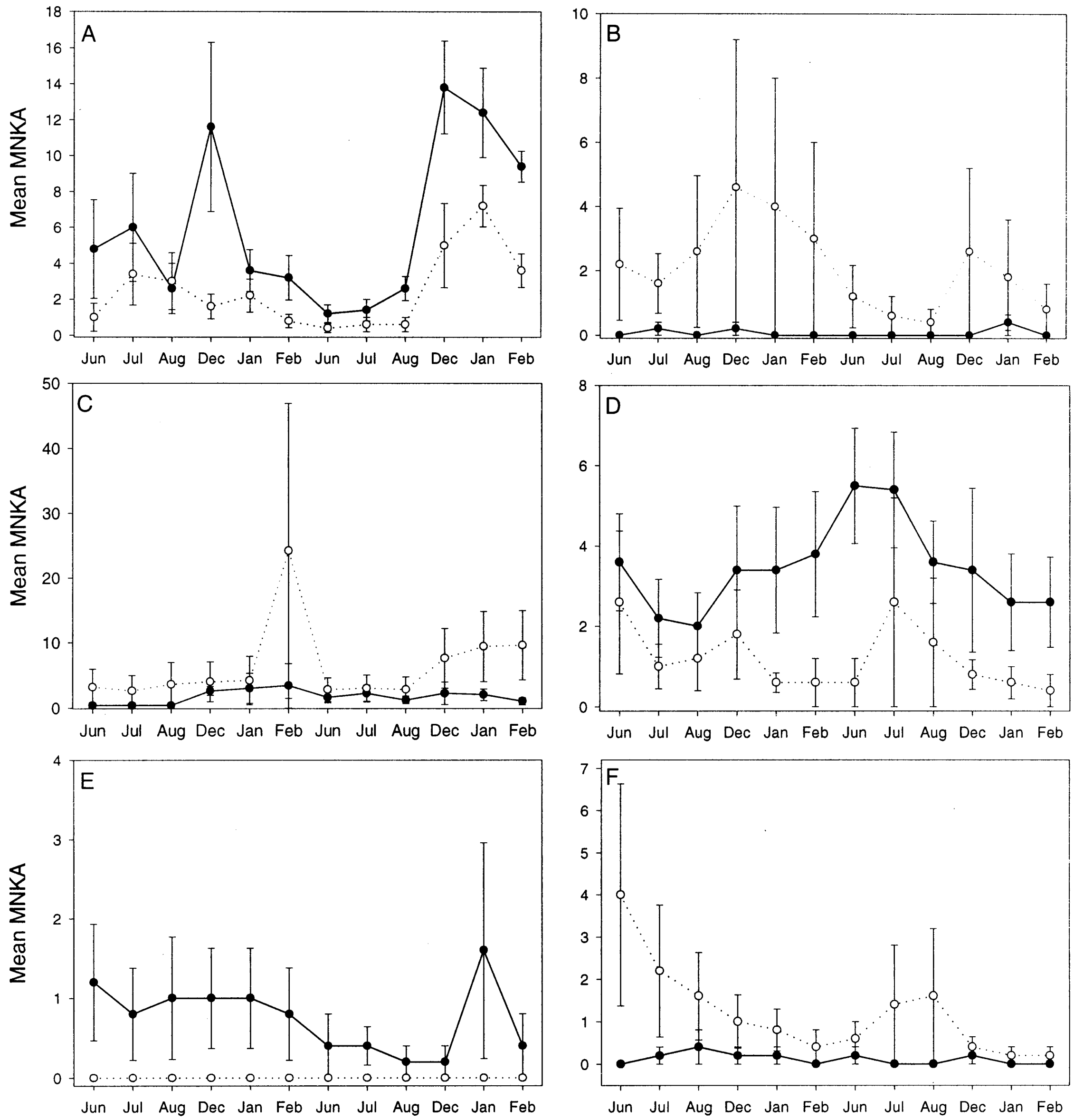

FIG. 6. Mean minimum number known alive (MNKA) for six species of rodent inhabiting abandoned petrochemical landfarms (dotted line, $n = 5$) and uncontaminated reference sites (solid line, $n = 5$) in Oklahoma. Rodent species are (A) *Reithrodontomys fulvescens*, (B) *Mus musculus*, (C) *Peromyscus maniculatus*, (D) *P. leucopus*, (E) *Microtus* spp., and (F) *Chaetodipus hispidus*. *Neotoma floridana*, *Reithrodontomys montanus*, and *Oryzomys palustrus* were trapped as incidentals. Data are means ± 1 SE.

structure, especially an increase in bare ground, associated with the mechanical process of landfarming.

Due to restrictions on land use, no sites were established as controls to separate the effects of contamination from those associated with the mechanical process of landfarming (i.e., control sites with mechanical soil preparation but no contaminant application). Besides the addition of contaminants to the habitat, most landfarms are cleared of all vegetation and experience complete mixing of the topsoil while preparing the landfarm for the application of petrochemical waste. After completion, landfarms are seeded with native or nonnative plant species or are left to invasion by species from surrounding habitats. These physical disturbances may represent a significant confounding factor in determining the structure of rodent assemblages on landfarms.

Although studies of rodent communities inhabiting contaminated sites are rare, studies at the population level have been conducted on free-living species inhabiting contaminated sites. These studies have found alterations in population parameters associated with contaminant exposure and accumulation in several populations of rodents (Batty et al. 1990, Dmowski et al.

TABLE 2. Mean minimum longevity (months) of species captured during the study (June 1999–February 2001).

Species	Reference		Landfarm	
	Mean	1 SE	Mean	1 SE
Sigmodon hispidus	3.91	0.15	2.20*	0.09
Reithrodontomys fulvescens	1.62	0.12	1.60	0.22
Reithrodontomys montanus	1.00	0.00	1.25	0.12
Peromyscus maniculatus	1.51	0.16	1.83	0.14
Peromyscus leucopus	1.90	0.19	1.65	0.31
Chaetodipus hispidus	2.00	1.00	1.59	0.16
Neotoma floridana	1.00	0.00	1.00	0.00
Mus musculus	1.00	0.00	1.84*	0.19
Microtus ochrogaster	1.63	0.26	⋯	⋯
Oryzomys palustris	1.20	0.14	1.10	0.06

Notes: Longevities were calculated as the time in months from first capture to time of last capture and are listed by site for each petrochemical and reference pair (Units 1–5).

* Significant difference from the reference site, at the $\alpha = 0.05$ level.

1998). Batty et al. (1990) found that white-footed mice (*Peromyscus leucopus*) inhabiting polychlorinated biphenol-contaminated sites had fewer juveniles during the reproductive period. In addition, males had reduced testes size and increased liver and spleen size. Dmowski et al. (1998) also found high levels of thallium contamination in rodents inhabiting sites surrounding a zinc smelter and a similar decrease in population numbers compared to noncontaminated sites. Furthermore, Dmowski et al. (1998) also noted a decrease in the juvenile population on contaminated sites. Finally, vole populations inhabiting sites in and around the Love Canal, New York, hazardous waste site showed the same trend described above (Rowley et al. 1983). Populations of voles had lower densities at contaminated compared to reference sites, with individuals inhabiting the contaminated sites showing body burdens of organic contaminants.

Alterations in population parameters are ultimately the result of changes in the fitness of individuals within the population. The additional stress of contaminants may impact individuals through decreased reproduction (Linzey 1987), increased energy costs (Lochmiller and Deerenberg 2000), impaired immune function (Rafferty et al. 2001), or indirectly by reducing plant diversity (Xiong et al. 1997) and biomass (Stoughton and Marcus 2000). In addition, the accumulation and effects of contaminants may vary across species (Dmowski et al. 1998) and may be responsible for differences in the response of species observed at the population and community levels.

Previous studies on our study sites have established that both inorganic and organic contaminants are bioaccumulating in cotton rats inhabiting the landfarms (Carlson et al. 2003, Schroder et al. 2003). Similarly, Wilson et al. (2003) found that cotton rats inhabiting landfarms in this study had impaired immune systems, namely reduced spleen size, altered hematological parameters, and decreased circulating leukocytes during summer. On our study sites, it is apparent that within cotton rats, at least, contaminants are being accumulated, and are producing immunological and physiological effects. In addition, cotton rat populations inhabiting these landfarms also showed the trend for reduced densities and juvenile populations observed in other studies (Wilson 2002). This suggests indirectly that contaminants found on petrochemical landfarms may be exerting an effect at the population and ultimately community level.

Reductions in cotton rat populations and the absence of voles on landfarms also suggest that cotton rats and voles were most affected by contamination in the present study. McMurry (1993) also noted the absence of voles from similarly contaminated sites in Oklahoma. Dmowski et al. (1998) found that of the rodents inhabiting a thallium-contaminated site, voles (*Clethrionomys* sp.) had the highest level of contaminant uptake. Similarly, Rowley et al. (1983) found that voles (*Microtus pennsylvanicus*) inhabiting the contaminated site at Love Canal, New York, experienced increased mortality, and reduced liver and adrenal masses.

In addition to contaminant effects on rodents inhabiting petrochemical landfarms, it is likely that disturbance associated with the mechanical process of landfarming may affect rodents by altering habitat structure. These alterations may then provide additional stressors that can work alone or synergistically with contaminant toxicity. Cotton rat densities are proportional to increasing plant cover (Cameron 1977), and may be due to increased risk of predation associated with open habitats (Lidicker et al. 1992). Landfarms in this study had increased proportion of bare ground compared to reference sites, with the exception of the landfarms at Units 4 and 5. Although cotton rats are able to utilize a more generalized habitat type, they prefer habitats with overhead cover (Swihart and Slade

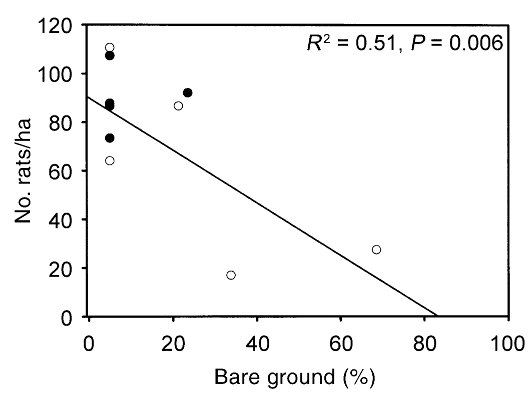

FIG. 7. The relationship between maximum densities of cotton rats reached during summer months and the percentage of bare ground found on a site. The highest cotton rat density is plotted against the mean percent cover by bare ground for each of the sites. Solid circles represent reference sites, and open circles represent landfarms.

1990). As a result, cotton rat populations would be impacted by increased bare ground on landfarms. Decreases in cotton rat abundance were observed in this study on those landfarms that had high proportions of bare ground (Units 1–3), while landfarms with little or no bare ground (Units 4 and 5) had abundances that matched reference sites.

Cotton rats are not the only species reported to be affected by alterations in habitat. Kincaid et al. (1983) showed *Reithrodontomys* to have similar habitat requirements to cotton rats. This may explain why *R. fulvescens* populations also were reduced on landfarms and were replaced by *Peromyscus* as the secondary species on two of the landfarms. *Peromyscus leucopus* has been shown to be associated with woody habitats, whereas *P. maniculatus* is found in more grassy areas (Kaufman and Fleharty 1974). Following landfarming, colonizing plants are typically annuals and grasses, creating a patchy habitat with few woody species. This would tend to favor *P. maniculatus* over *P. leucopus*, as was seen in this study.

Few studies have focused on the effects of contaminants at the population or community level, with most comparing contaminated sites with paired reference sites that have no history of contaminant exposure and represent ''normal'' conditions (Kirkland 1976, Sly 1976, Ma 1989, Flickinger and Nichols 1990, Stansley and Roscoe 1996, Dmowski et al. 1998). Although this provides a useful comparison of contaminated sites with that of representative habitat, confounding variables associated with the process of contamination or the history of contaminated sites may undermine the usefulness of this approach.

Studies comparing contaminated and reference sites were initially used to identify potential hazards to humans and wildlife associated with hazardous waste. Although these studies do not provide direct causal evidence for the differences observed between contaminated and reference sites, they do measure real changes in populations and communities as a result of site contamination. Because sites have historically not been available for study until after they have been contaminated, it has been virtually impossible to set up a study with a proper control, leading to the retrospective nature of most in vivo ecotoxicological studies.

For example, Kirkland (1976) studied the effects of mine wastes on small mammals using data collected from three live-trap grids on old mine-waste terraces. These grids consisted of (1) a 2.6-ha herbaceous field of white sweetclover (*Melilotis alba*) with three clumps of quaking aspen (*Populus tremuloides*) and a patch of red and scotch pine (*Pinus resinosa* and *P. sylvestris*) covering 4% of the grid, (2) a 0.91-ha grid similar to the first in vegetation with old tires, railroad ties, electrical belts, and a small oil spill, and (3) a 0.37-ha field with dense vegetation consisting of grasses and strawberries. These sites were compared to rodent communities inhabiting seven reference sites consisting of a 2-yr-old grassy slope, mixed tree–weed sites, and two isolated forests up to 16 km distant (Kirkland 1976). Kirkland (1976) found small-mammal assemblages inhabiting the mine waste sites to be ''noticeably depauperate compared to that of surrounding forests,'' and suggests that this reduction is due to the difference in habitat structure found on mine sites. In particular, Kirkland (1976) claims the differences are a result of the ''lack of suitable vegetation cover and because of extremes in physical parameters.'' Although this is undoubtedly contributing to the reduction of some populations and elimination of others from the mine sites, other factors, including the multiple sizes, varying degrees of contamination, and different plant communities of the waste sites may also contribute to the observed changes. Without proper control sites and a standardization of contaminated sites, it is impossible for Kirkland to conclude what factors are responsible for the differences he observed.

The problems associated with retrospective studies have been noted by authors, who have attempted to account for them using a paired design (Flickinger and Nichols 1990). Most authors try to choose control sites that reflect the habitat and vegetation characteristics of the contaminated sites. However, as was discovered in this study, the very nature of site contamination alters the habitat structure. Flickinger and Nichols (1990) also found that numerous plant species were found on either the control or waste sites, but not both, leading to uncontrolled differences between their experimental units. In fact, of the 35 plants listed across their six study sites, an average of 28.1% of the plants were found on only one of the paired control–waste sites. The six control–waste site pairs ranged from having only 5.4% of the species differ to a 51.4% difference. It is clear that even when studies are designed to reduce variation in habitat structure, enough variation is inherent to warrant careful interpretation and application of the results.

In our study we observed a measurable difference in the rodent assemblage structure between communities inhabiting petrochemical landfarms and those found on reference sites. Previous studies on our sites have shown that soil contamination levels are elevated on landfarms (Schroder et al. 2003), are being accumulated in cotton rats (Schroder et al. 2003), and have altered their immune systems (Wilson et al. 2003). In addition to the elevated contaminant levels, we also found differences in habitat structure. Specifically, abandoned landfarms had a higher proportion of bare ground than reference sites, unless the landfarm was seeded following waste treatment, as occurred on Units 4 and 5. Because of the limitations of our experimental design we cannot determine if the observed difference in the rodent assemblage structure was due to the residual contaminants or simply from the mechanical disturbance associated with petrochemical landfarming. In future studies it would be beneficial to include sites with no history of contamination where the mechanical process of landfarming was employed. Given the two possible explanations for the difference in rodent assemblages observed on landfarms, it is likely that the true mechanism for change is a combination of both contaminant effects on individual plants and animals and changes in habitat associated with the mechanical process of landfarming.

Landfarming clearly alters the rodent assemblage structure; however, it is not clear what specific factors are driving these differences. Further study is needed to investigate the effects of chronic exposure to contaminants at the population and community level, with careful attention being given to the history of contaminated sites and the physical disturbances associated with site contamination. Specifically, controlled experiments are needed to separate the effects of alterations in habitat structure from contaminant uptake on populations inhabiting these sites.

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