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The influence of land use on desertification processes

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Abstract

Site degradation occurs mainly through deterioration of the soil's capacity to capture and store water, as well as the loss of organic matter or the accumulation of salts or other toxic substances in the soil. This degradation process, leading to the reduction of the biotic potential of the site, is known as desertification. In this study, changes in bulk density, organic matter, and electrical conductivity are used as indicators of desertification in northeast Mexico. The hypotheses put forward here are that degradation processes are affecting extensive areas of the region, and that the type of processes and their magnitude differ according to specific land uses. Thirty-one sites under different land use systems (agriculture, rangeland, induced grassland, and a protected site) were sampled for bulk density, organic matter, and salinity. Soil samples for bulk density estimation were collected in 1996, 1997, and 1999, while those for organic matter and salinity were taken in 1993, 1997, and 1999. Soil bulk density and organic matter showed significant changes across time in rangeland sites. None of the sites showed significant changes in salinity. Organic matter was similar in agriculture, rangeland, and grassland sites across dates. Soil bulk density was similar in grasslands and rangelands and lower in agriculture sites. Values of organic matter were lower and those of soil bulk density were higher when compared to a protected native vegetation site.

Key Words: soil bulk density, organic matter, land use, Northeast Mexico, land degradation

Resumen

La degradación de un sitio ocurre principalmente a través del deterioro de la capacidad del suelo para captar y almacenar agua, la pérdida de nutrientes o la acumulación de sales u otras sustancias tóxicas en el suelo. Este proceso de degradación, que conduce a la reducción del potencial biótico del sitio, se conoce como desertificación. En este estudio, la densidad aparente del suelo, contenido de materia orgánica y valores de salinidad son utilizados como indicadores de desertificación en el Noreste de México. Las hipótesis planteadas son que los procesos de degradación están afectando extensas áreas en la región y que el tipo de procesos, así como la magnitud de éstos, difieren dependiendo del uso del suelo. Se muestrearon treinta y un sitios bajo diferentes usos de suelo (agricultura, agostadero, pastizal y un sitio protegido) para determinar la densidad aparente, contenido de materia orgánica y salinidad. Las muestras para evaluar densidad del suelo fueron colectadas en 1996, 1997 y 1999; mientras que las de materia orgánica y conductividad eléctrica se tomaron en 1993, 1997 y 1999. La densidad aparente del suelo y la materia orgánica mostraron cambios significativos a través del tiempo en los sitios de agostadero. Ninguno de los sitios evaluados mostró cambios significativos en salinidad. La materia orgánica fue similar en los sitios de agricultura, agostadero y pastizal. La densidad aparente fue similar en agostadero y pastizales y menor en sitios de agricultura. Los valores de materia orgánica fueron menores y los de densidad aparente del suelo mayores que los del sitio de vegetación nativa protegido.

Desertification is a global phenomenon with serious human and environmental repercussions affecting the livelihood of today's human population and that of generations to come (Grainger 1992, Arnalds 2000). In spite of the controversial history of the term 'desertification' (Medellín-Leal 1978, Landa et al. 1997), there is general agreement that it includes a series of processes leading to the impoverishment of soil and vegetation, such as soil erosion, loss of soil fertility, and decline of productivity (Medellín-Leal 1978, Dregne 1983, Grainger 1992, Mainguet 1994, CONAZA-SEDESOL 1994, Toulmin 1995, Pando et al. 1996).

Land degradation occurs mainly through deterioration of the soil's capacity to capture and store water, the loss of nutrients or the accumulation of salts or other toxic substances in the soil (Smith 1989, Friedel 1991, National Research Council 1994). This degradation process, leading to the reduction of the biotic potential of a site, is known as desertification.

Soils may lose their capacity to capture and store water by compaction of the soil, loss of organic matter or loss of soil depth. In addition, increases in salinity reduce water availability for plants. Soil compaction due to use of heavy machinery in agricultural land (Hartge 1988) and livestock trampling (Manzano and Navar 2000, Yates et al. 2000) usually results in undesirable changes in the hydrological processes of the soil, such as reduced water infiltration capacity (Brady and Weil 2002). Loss of organic matter in turn is associated with soil compaction, decline in fertility and a general deterioration of soil quality through destabilization of aggregates and reduction of cationic exchange capacity (Bohn et al. 1993, Fassbender 1993).

Salinity reduces the ability of plants to extract water from the soil; it has been recognized as a source of land degradation due to irrigation practices (Thomas and Middleton 1993) and as one of the factors leading to the fall of the Mesopotamian culture 6,000

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years ago (Jacobsen and Adams 1958). It has also been documented that replacing a natural vegetation community with crops or grassland for grazing can be significant for salinization (Bettenay 1986).

Land use in northeast Mexico is characterized by practices that are commonly associated with desertification, such as extensive land clearing (Maldonado and Pando-Moreno 1994, Jurado et al. 2001), poor agricultural practices, and overgrazing (Manzano et al. 2000, Mellado et al. 2003). It is possible that land degradation is occurring in this area even though it may be at an early stage that is only revealed by laboratory tests (Pando et al. 1996). In this study we evaluated desertification based on changes in the physical, chemical and biological conditions of the soil, which, to some extent, determine its biotic potential. Changes over the last decade in soil compaction, organic matter content and salinity were analyzed in agriculture, rangelands, and induced grasslands (seeded after clearing native vegetation) of northeast Mexico. The hypotheses put forward are that degradation processes are affecting extensive areas of the region, and that the type of processes and their magnitude differ according to specific land uses.

Materials and Methods

Research site

The study was conducted in the area surrounding Linares, Nuevo Leon (24° 47' N, 99° 32' W), in northeast Mexico. Soils in the area are silt clay, clay or silt clay loam, mostly Vertisols and Regosols, following FAO's classification (1998). The most common landforms are plains and gently undulating slopes interspersed with hills up to 50 m above the terrain. On gentle hills and upper slopes, outcrops of Upper Cretaceous shale occur, often overlain by silty clay loams. Scattered Pliocene and Quaternary terraces of conglomerate, often consolidated in a limestone matrix (caliche) are also present throughout the region (Ruiz 1990).

Climate of the area has been classified as (A)C(W_0) (García 1981), semi-warm, subhumid, with a summer rainfall regime. Average annual rainfall is 761.2 mm and mean annual temperature 22.4° C with summer temperatures often reaching 40° C.

The vegetation is a Tamaulipan thornscrub plant community (Muller 1947), known locally as "matorral". This native vegetation is a diverse, spiny, sometimes dense scrub dominated by woody plants (Heiseke 1986) with some 80 species of shrubs and trees ranging in height from 1 to 15 meters (Reid et al. 1990). Thorny shrubs (e.g. *Acacia berlandieri* Benth., *Acacia farnesiana* (L.) Willd., *Acacia greggii* Gray, *Acacia rigidula* Benth., *Havardia pallens* (Benth.) Britton & Rose) and trees (e.g. *Ebenopsis ebano* (Berl.) Barneby, *Prosopis laevigata* (Humb. & Bonpl. ex Willd.) M.C. Johnst., *Prosopis glandulosa* Torr. var. *torreyana* M.C. Johnst.) dominate the natural vegetation, but grasses (e.g. *Eragrostis mexicana* (Horn.) Link., *Bouteloua curtipendula* (Michx.) Torr., *Bouteloua barbata* Lag.), forbs (e.g. *Croton ciliato-glandulosus* Ort., *Lantana camara* L., *Verbesina encelioides* (Cav.) A. Gray, *Waltheria indica* L.) and succulents (e.g. *Opuntia engelmannii* Salm-Dyck, *O. leptocaulis* DC., *Opuntia phaeacantha* Engelm.) are also prominent (González-Medrano 1972).

The area has been grazed by introduced livestock since the Spanish conquest in the latter part of the 16th century (Rojas-Mendoza 1965, del Hoyo 1979). Selective logging and cutting for timber and firewood has occurred in the area for centuries (Reid et al. 1990), while extensive land clearing for agriculture or cattle grazing in induced grasslands became extensive in the 1970's (USFWS 1983, Vázquez and González 1999). Native vegetation is still being converted to non-irrigated maize and sorghum and more often to induced grasslands of buffel grass (*Pennisetum ciliare* (L.) Link) for cattle grazing.

Methods

Sites were selected as homogeneous areas of land use, ranging from 20 to 100 ha, in the same climate. Distance between sites ranged from 5 km to 50 km. At the centre of each site a circular plot of 100 m diameter was located in which samples were taken for soil bulk density, salinity and organic matter. Sampling was done in the fallow period during the dry season (late June and early July).

Samples have been collected as part of a long-term research on desertification at the School of Forest Science, in Linares, Nuevo Leon, Mexico. All samples were collected and analyzed using the same procedures (described below). Early results have been presented as part of unpublished dissertations (Maldonado and Pando 1994, Gutiérrez 1997, Reyes 2000, and Pando 2002).

A total of 33 sites on 4 land uses (agriculture, rangelands, induced grasslands, and areas protected from grazing) were sampled for organic matter and salinity in 1993, 1997, and 1999. Sampling for soil bulk density was carried out in 1996, 1997 and 1999. Two out of 3 protected sites were cleared and thus not included in later evaluations. Thus, statistical tests were only done for land uses with sufficient number of replicates: 17 rangeland sites, 10 agricultural sites, and 3 grassland sites. The remaining protected site was used only for visual comparisons.

Sampling sites were precisely located using GPS. Samples for organic matter were taken from the top 30 cm once the covering litter was removed. Organic matter was indirectly estimated through multiplication of organic carbon concentration by 1.724. Carbon concentration was determined using the wet combustion Walkley-Black method (Nelson and Sommers 1982). Salinity was determined by electrical conductivity of the solution extracted from a 1:5 soil-water mixture, after half an hour of shaking (Rhoades 1982). Soil bulk density was estimated using the core method to a soil depth of 10 cm (3.5 cm in diameter) (Blake and Hartge 1986).

Five samples from each of 10 randomly selected sites were collected and used for pre-sampling analysis for soil bulk density, organic matter and electrical conductivity. The number of plots required for 95% confidence was determined using Bonham's equation (1980):

$$N = \frac{(t^2)\,(s^2)}{(k * \bar{X})^2}$$

where N is the computed sample size, t is the tabulated value for the specified confidence level and the degrees of freedom of the sample, s^2 is the variance of the initial sample, k is the accepted error (0.1) and $\bar{X}$ is the mean.

Results from the pre-sampling test indicated that the minimal number of samples required for $\alpha \leq 0.05$ were: 5 samples per site for bulk density, 4 samples for organic matter, and 2 samples for electrical conductivity. Hence, for practical reasons, 5 samples were taken for all the parameters. Samples were taken at the center of the site and 50 meters apart in the North, South, East, and West. All samples were analyzed separately, thus an average result of 5 samples was obtained for each site.

Paired t-tests were run to evaluate changes through the periods 1993–1997, 1996–1997, 1997–1999, and 1993–1999 for the entire area, using the average value of the sites. Paired t-test, known as the "before and after" design, is the kind of analysis recommended when the same individual is measured more than once; the data are continuous variables, and have, at least approximately, a normal distribution (Dythman 1999).

A t-test was also applied to compare bulk density, electrical conductivity and organic matter land use values from the first sampling (1996 for soil bulk density, and 1993 for the other 2) to the last one (1999). The same analysis was also used to evaluate changes at each individual site.

Results and Discussion

Significant changes ($P \leq 0.05$) on soil bulk density and organic matter were only detected across the longest period. About 67% of the sites had detrimental changes either in soil bulk density or organic matter and 27% of the sites had detrimental changes in both parameters. None of the sites showed significant levels of salinity (< 200 µS/cm) or changes in this parameter during the 6-year evaluation period.

Soil bulk density

Spatial distribution of soil bulk density in the upper 5 cm was very homogeneous within each site. The highest variation coefficient was 8.7% (n = 5) for a rangeland site. This figure is similar to those of Martínez and Zinck (1994) who reported a variation coefficient of 9% (n = 15) for the 0–15 cm layer in induced grasslands in the Amazon, and 13% for a tropical forest.

Soil bulk density had a tendency to increase with time (Fig 1) implying that soils in the area are in a process of compaction. Soil bulk density values significantly increased from 1996 to 1999 (P = 0.020), but not between 1996 and 1997 (P = 0.073) nor between 1997 and 1999 (P = 0.255). From 1996 to 1999 soil bulk density increased for 13 sites ($P \leq 0.05$), with only 1 site decreasing in soil bulk density and 16 remaining constant. Bulk density increased in 10 out of the 30 sites for both periods (Table 1).

The average increase in soil bulk density, for those sites that showed a significant difference from 1996 to 1999, was 0.163 g cm^{-3} (12.8%). This percentage is similar to that found by Van Haveren (1983) for fine textured soils, of 13.4% for heavily grazed pastures compared to those lightly grazed. A similar soil bulk density increase (0.2 g cm^{-3}) was found after an experimental heavy overgrazing event in northeast Mexico by Manzano and Navar (2000).

Soil bulk density was lower ($P < 0.05$) for agricultural sites than for rangeland and grassland sites (Table 2). Because no heavy machinery is used on agricultural soil and the latter is ploughed at least once a year in this region, lower soil bulk density values were expected. Evidence for soil compaction was found for rangeland sites, as soil bulk density was higher ($P < 0.05$) in 1997 and 1999 than in 1996. Soil bulk density values were consistently lower across time for the protected site used as reference (Table 2).

Table 1. Soil bulk density, organic matter values and land use by site, at each evaluation date.

	Soil bulk density			Organic matter		
	1996	1997	1999	1993	1997	1999
	(g cm^{-3})			(%)		
rangeland	1.14	1.21	1.31	3.71	1.96	2.57
rangeland	1.31	1.44	1.47	3.14	1.98	1.08
rangeland	1.10	1.24	1.42	5.42	3.84	4.21
rangeland	1.28	1.30	1.22	3.57	4.11	2.45
rangeland	1.33	1.47	1.56	2.61	0.96	0.72
rangeland	1.37	1.41	1.40	2.18	2.44	2.61
rangeland	1.41	1.45	1.45	3.92	1.4	1.77
rangeland	1.40	1.32	1.42	2.07	2.07	2.21
rangeland	1.41	1.43	1.40	2.58	2.74	2.54
rangeland	1.40	1.45	1.43	1.21	2.26	1.72
rangeland	1.36	1.39	1.42	2.28	3.93	3.76
rangeland	1.24	1.31	1.37	3.09	2.49	3.39
rangeland	1.35	1.42	1.48	2.75	1.70	1.72
rangeland	1.29	1.29	1.43	3.94	1.73	2.25
rangeland	1.32	1.49	1.47	2.3	1.58	1.43
rangeland	1.46	1.54	1.54	2.09	2.84	1.40
rangeland	1.32	1.35	1.36	3.8	2.15	3.17
agriculture	1.20	1.24	1.38	2.04	3.00	2.92
agriculture	1.18	1.18	1.32	1.99	1.34	1.83
agriculture	1.27	1.26	1.22	2.41	2.72	1.65
agriculture	1.21	1.24	1.21	4.47	4.23	4.10
agriculture	1.27	1.29	1.18	3.43	4.48	3.68
agriculture	1.08	1.11	1.07	3.16	2.97	2.80
agriculture	1.28	1.30	1.29	2.62	2.04	1.69
agriculture	1.27	1.16	1.17	3.59	2.28	2.28
agriculture	1.28	1.27	1.35	2.62	2.42	2.47
agriculture	1.25	1.26	1.48	2.80	2.95	1.92
grassland	1.40	1.42	1.42	2.97	2.61	3.31
grassland	1.25	1.34	1.27	2.32	3.00	2.36
grassland	1.44	1.47	1.45	1.90	1.94	2.05
protected site	1.07	1.09	1.05	16.43	12.89	15.32

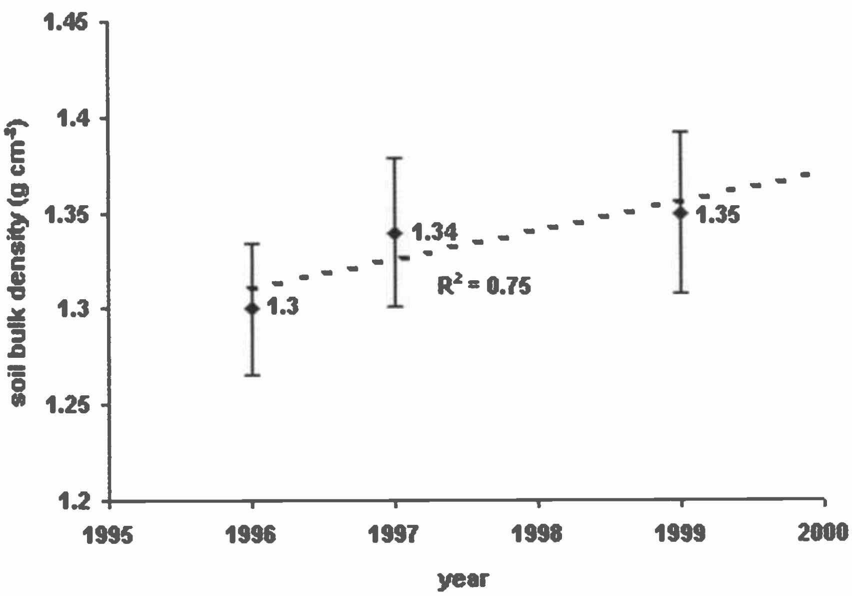

Fig. 1. Average soil bulk density values (n = 30) for the study area. Error bars are for confidence intervals ($\alpha = 0.05$).

Table 2. Average soil bulk density (g cm^{-3}) for the 3 evaluation periods, grouped by land use.

Year	Rangeland (17)	Agriculture (10)	Grassland (3)	Protected site (1)
	(g cm^{-3})			
1996	1.323^a A[1]	1.228^b A	1.361^a A	1.073
1997	1.384^a B	1.232^b A	1.407^a A	1.09
1999	1.421^a B	1.266^b A	1.381^a A	1.053

[1]Means within rows with different lower case letters differ ($P \leq 0.05$). Means within columns with different upper case letters differ ($P \leq 0.05$). Numbers in parenthesis indicate number of sites. Due to loss of replicates for protected sites, the remaining value is shown for comparative purposes.

Table 3. Average organic matter values (%) for the 3 evaluation periods, grouped by land use.

Year	Rangeland (17)	Agriculture (10)	Grassland (3)	Protected site (1)
	(%)			
1993	2.98^a A[1]	2.91^a A	2.40^a A	16.43
1997	2.36^a B	2.84^a A	2.51^a A	12.89
1999	2.29^a B	2.53^a A	2.57^a A	15.32

[1]Different lower case letters (in lines) are for significant differences ($P \leq 0.05$) between land uses. Different upper case letters (in columns) are for significant differences ($P \leq 0.05$) between evaluation periods. Numbers in parenthesis are number of sites for the analysis. Due to loss of replicates for protected sites, the remaining value is shown for comparative purposes.

Organic matter

Organic matter coefficient of variation ($n = 5$) averaged for the 30 sites was 17.7% and only 1 site showed a very high coefficient of variation (53%). This variation was less than that reported by Martínez and Zinck (1994) who found a coefficient of variation ($n = 15$) of 24.5% for the upper 10 cm in a tropical forest and 24% in induced grasslands.

Organic matter significantly diminished from 1993 to 1999 ($P = 0.016$) while no changes were registered from 1993 to 1997 ($P = 0.06$), nor from 1997 to 1999 ($P = 0.275$). The trend (Fig. 2) calculated for the average values, indicates a reduction in soil fertility in the area. During the 1993–1999 period, 15 out of 30 sites showed a significant ($P \leq 0.05$) decline in their organic matter content, while the other 15 sites remained constant (Table 1).

Organic matter was similar for rangeland, agricultural and grassland sites (Table 3). Organic matter for the protected site used as reference was about 4 times higher than those of other land uses. Rangeland sites had lower ($P < 0.05$) organic matter in 1997 and 1999 when compared to 1993 (Table 3), which is consistent with increased soil bulk density values for these sites.

The decrease in organic matter in rangelands from 1993 to 1999 may well be the result of a lack of management, combined with use exceeding carrying capacity (Manzano et al. 2000, Narjisse 2000). There were no changes in the organic matter content of induced grasslands; however low values were presumably a result of removal of native vegetation, as has been found elsewhere (Nair 1984). Agricultural sites did not show a higher content of organic matter than other land uses. This is in line with expectations, as in these sites crop residues are used as fodder and not incorporated into the soil. The protected site had the highest content of organic matter (Table 3), which is in agreement with findings of Bravo (1999), for similar ecosystems in northeast Mexico, in which areas with native vegetation and no-use had the highest levels of organic matter.

Evidence of desertification was found for rangelands, which showed a significant increase in soil bulk density from 1996 to 1999 and a significant decrease in organic matter from 1993 to 1999, while grassland and agricultural sites did not differ through time. It has been shown that removal of native vegetation results in the loss of organic matter and soil compaction (Young 1990, King and Campbell 1994). However, in this study we have found that overgrazing without clearing the land also results in soil degradation.

While organic matter and soil bulk density for induced grasslands and agricultural sites did not change within this study, values for both parameters were poorer when compared to a protected site. Thus, it is possible that soil degradation in these sites occurred prior to our first evaluation dates. Results presented here should not be used out of context to promote land use changes leading to the clearing of thornscrub without specific studies.

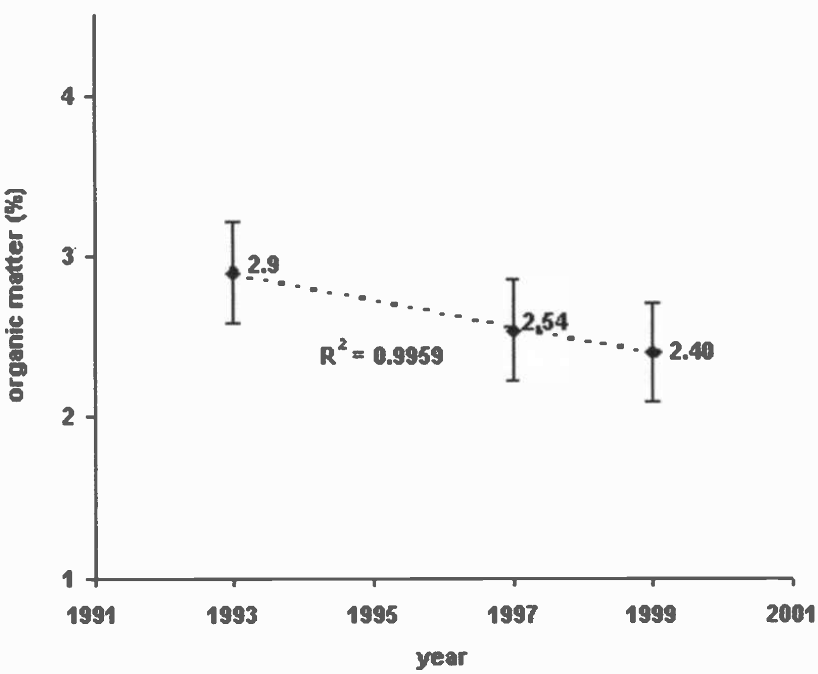

Fig. 2. Average organic matter values ($n = 30$) for the study area. Error bars are for confidence intervals ($\alpha = 0.05$).

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