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Soil Erosion of an Indurated Volcanic Soil from the Semiarid Area of the Valley of Mexico

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ABSTRACT

In the Valley of Mexico, the presence of volcanic soils with indurated horizons is associated with semiarid conditions. The hardened subsurface layers, locally called "tepetates", appear at the soil surface due to erosion of overlying topsoil. The extensive areas of tepetate are not only a significant source of sediments affecting off-site areas, but also marginal lands of low productivity. This study was conducted to evaluate soil erosion of a tepetate with different soil management practices under natural and simulated rainfall. We found that the traditional methods of reclaiming tepetates with deep ripping and cultivation increased soil erosion. Soil loss of reclaimed tepetates had annual values of 46.7 Mg ha^{-1}, while the naturally undisturbed tepetate produced 8.4 Mg ha^{-1}. The use of a cover crop in conjunction with conventional methods of reclamation reduced total soil loss about 85%. Surface cover reduced soil erosion from 57 to 65% in reclaimed tepetates. However, no significant reduction was found when soil cover was used in the naturally undisturbed tepetate.

Surface application of gypsum consistently increased infiltration and reduced runoff, soil loss, and sediment concentration under simulated rainfall conditions. In addition, soil aggregates significantly resisted physical and chemical disintegration reducing the amount of surface sealing and promoting greater infiltration. The use of soil amendments to reduce surface sealing, increase infiltration and reduce soil erosion appears to be a viable management method for reclaiming highly erodible indurated volcanic soils from the Valley of Mexico at a lower cost.

INTRODUCTION

The Valley of Mexico is an extensive (9,000 km²), naturally closed-high mountain valley at approximately 2,200 meters elevation located in Central Mexico, which is surrounded by mountains of volcanic origin that reach altitudes of over 5,000 meters above sea level. The average annual rainfall of 700 mm is concentrated in a few severe storms from June through September with little or no precipitation the remainder of the year. Soils in the area are of volcanic origin and are very susceptible to soil erosion.

In the piedmont zone of the valley, extensive areas have lost the overlying topsoil due to soil erosion and have exposed indurated horizons to the soil surface, which are locally called "*tepetates*". Tepetate is a Mexican folk term adopted from Nahuatl, the language spoken by the Aztecs (Williams, 1972), and it has been generically translated as "rock-like" or "soft rock". The pressure of increasing population has forced cultivation onto steeper and more marginal lands of low productivity with tepetate exposed to the soil surface.

Land reclamation in areas where the fertile soil has been eroded and the tepetate has been exposed on the surface is essential to restore the original soil productivity. A common practice to reclaim tepetates in the Valley of Mexico is deep ripping of the tepetates with heavy equipment followed by plowing and disking. This highly recommended practice by the Mexican government is not only an expensive and high-energy consuming practice (Sánchez, 1992), but also seems to affect negatively the susceptibility of the tepetate to erosion.

The use of appropriate tillage, soil covers and soil amendments may be an alternative to the reclamation of areas with tepetate exposed. Surface application of gypsum for the purpose of increasing infiltration and reducing runoff and soil erosion has been studied by several authors in soils from semiarid regions (Agassi et al., 1981; Shainberg and Singer, 1985), highly weathered and high-clay soils (Miller, 1987; Norton et al., 1993; Reichert et al., 1994; Reichert and Norton, 1994) and soils from the Midwest of the United States (Reichert, 1993; Dontsova, 1998). However, no studies have been reported for indurated volcanic ash soils.

Some research has been performed to evaluate total soil erosion in tepetates under natural rain (Oropeza et al., 1995), but there is also a lack of information on the sub-processes of interrill and rill erosion in tepetates that deserves attention. Since field observations have indicated that the mechanical approach has been an expensive alternative for reclaiming tepetates, a different approach is necessary to reduce soil erosion and to improve the properties of tepetates. The new approach needs to consider that soil erosion is a surface boundary process, which is dependent upon the characteristics of the soil-fluid interface as well as on the dynamic interactions between rain and soil phases.

Under this consideration, the primary objective of this study was to evaluate the magnitude of soil erosion of an

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indurated volcanic soil from the Valley of Mexico as affected by different soil management treatments under natural and simulated rainfall. Another goal was to study the sub-processes of interrill and rill erosion and, to study the effect of surface application of gypsum ($CaSO_4.2H_20$) on soil erosion, runoff and infiltration.

MATERIALS AND METHODS

An indurated volcanic soil, locally called "yellow tepetate", was selected for this study. This tepetate was found exposed to the soil surface in extensive areas nearby the town of Texcoco, Mexico and was representative of the area of study. In remnants of naturally undisturbed soil profiles, the yellow tepetate was located at a depth of about 3 meters.

For the experiment under natural rain, plots 2 m by 20 m long were established on a 5% slope field. The soil treatments studied included: chisel plowing to a depth of 50 cm followed by disc plowing to a depth of 30 cm (Ch + Dp), fallow with tillage operations every 15 days (F), soil cover with geo-textile (Co), barley (*Hordeum vulgare* L.) as cover crop (Cc), and undisturbed tepetate (Un). The treatments were combined as follows: (1) Ch + Dp + Co + F; (2) Ch + Dp + Co; (3) Ch + Dp + F; (4) Ch + Dp; (5) Ch + Dp + Cc; (6) Un + Co; (7) Un. Three replicates were studied for each experimental unit. No crop was planted in the plots, except for treatment 5, in which barley was planted following a crop management similar to the one used by local farmers. The amount and intensity of rainfall was recorded on a daily basis using a rain gauge recorder. The erosivity factor (R) factor of the Universal Soil Loss Equation (USLE) was computed using the equation reported by Foster et al. (1981) for SI units. Total runoff and sediments were collected after every rain in large barrels and the soil loss and runoff were obtained from the total sample by gravimetric methods.

For the rill and interill experiments in the field, three plots each of reclaimed and natural undisturbed tepetate were subjected to simulated rainfall using a modified Purdue Programmable simulator (Foster et al., 1982). Methods to determine rill and interrill erodibilities are described in detail in Norton and Brown (1992). The reclaimed plots were prepared by first removing any biomass and tilling with a rotovator to a depth of 20 cm immediately prior to rainfall. The natural tepetate was undisturbed and received only minimal disturbance from placement of the plot borders.

Two sizes of plots were studied: 1 m x 7 m long and 1 x 1 m to separate rill and interrill processes. In addition, three rill erodibility ridge furrow plots were studied using the procedures of Norton and Brown (1992) to collect rill erodibility (K_r) and critical hydraulic shear (τ_c) values. Rainfall was applied to all plots at a rate of 38 mm hr^{-1} until steady state runoff was maintained. The intensity was increased to 85 mm hr^{-1} and maintained until steady state runoff was obtained and then reduced to 27 mm hr^{-1} until equilibrium. Water losses were determined by collection the discharge in a large bucket in 3 to 5-minute intervals and measuring the weight in the field. Sediment losses were obtained by gravimetric methods taking a 1L sample immediately following the discharge measurement. Total discharge and soil loss were computed by integration of the discharge rates over the time of the run and normalizing them to one-hour duration. Interrill erodibility was determined following the procedures of Elliot et al. (1989).

To measure rill erodibility, rainfall was applied to preformed ridge furrows until steady state runoff occurred and then inflow was added to simulate longer slopes and to increase flow shear stress. The maximum shear imposed at the slope of the rills was 5 Pa. At each of the flow levels, 4 samples were measured for soil and water discharge rates. Flow velocity was measured using the dye trace technique (Abrahams et al., 1988) for each soil and water measurement along with flow top width to compute hydraulic shear. Mean velocity was computed from the leading edge dye velocity using a factor of 0.687 (Elliott et al., 1989).

For the laboratory experiments, soil samples were collected at field moisture conditions from an undisturbed soil profile. After air-drying, the soil was gently passed through a 4-mm sieve and then packed to depth of 3 cm at a density of 1.5 Mg m^{-3} in an erosion pan 32-cm wide, 45-cm long, and 20-cm deep. The pan had a 14-cm bottom layer of gravel, and a 3-cm intermediate layer of silica sand to control moisture tension. The soil then was pre-wetted by capillary rise action with deionized water, at a level position. After saturation, the pan was set at 5% slope and allowed to drain for about 30 min. A 5-cm tension, measured at the center of the soil erosion pan, was set and kept during the drainage and the simulated rainfall events. Rain was applied for one hour at a target rate of 75 mm h^{-1} using a programmable rain simulator with four 80-100 Veejet nozzles (Neibling et al., 1981) located 3 m above the center of each erosion pan. A constant pressure of 6 psi was maintained at each nozzle. Gypsum was applied just before the rainfall event to the soil surface at a rate of 5 Mg ha^{-1}. The gypsum used had composition of 83% $CaSO_4.2H_2O$, 19.3% Calcium equivalent and 15.4% sulfate equivalent. The EC of a 1:1 gypsum/nanopure-water solution was 2 mS cm^{-1}, and the pH 7.7. Infiltrating water was collected from the bottom, while runoff plus sediments were sampled at the bottom edge of the pan using wide-mouth bottles. Samples were taken every five minutes Soil loss was evaluated in g m^{-2} and sediment concentration in g L^{-1} of runoff by traditional gravimetric methods. Additionally, after the rain was applied, tepetate samples were taken to prepare soil thin sections following the procedures by Norton (1987) and Ventura (1998).

Particle size analysis was determined on the <2 mm fraction by the pipette method (Franzmeier et al., 1977); bulk density was determined by the clod method (Blake and Hartge, 1986); soil pH was measured in a 1:1 soil: solution ratio in water and 0.01M $CaCl_2$. Total carbon and nitrogen were determined by dry combustion with a LECO CHN-600 analyzer with soil samples passed through a 60-mesh sieve. Cations (Ca, Mg, Na, and K) were extracted from the <2 mm fraction using the ammonium acetate method (Thomas, 1982). Concentrations of the same were determined by atomic absorption using a Perkin-Elmer 2280 spectrophotometer. Extractable acidity was determined using the Barium Chloride-Triethanolamine method (Thomas, 1982).

Table 1. Selected soil properties of the yellow tepetate.

BD†	WDC‡	CDC§	Silt	Sand	Total C	Total N	pHw¶	pHs#	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	H^{+}
---------- $Mg\ m^{-3}$ ----------			---------------- % ----------------						-------------- $cmol_c\ kg^{-1}$ --------------				
1.58	32.4	35.4	37.3	27.2	0.065	0.050	6.52	6.38	10.0	8.1	1.5	1.1	8.6

†Bulk density
‡Water-dispersible clay
§Chemically-dispersible clay
¶ pH in water
\# pH in 0.01 *M* CaCl2.

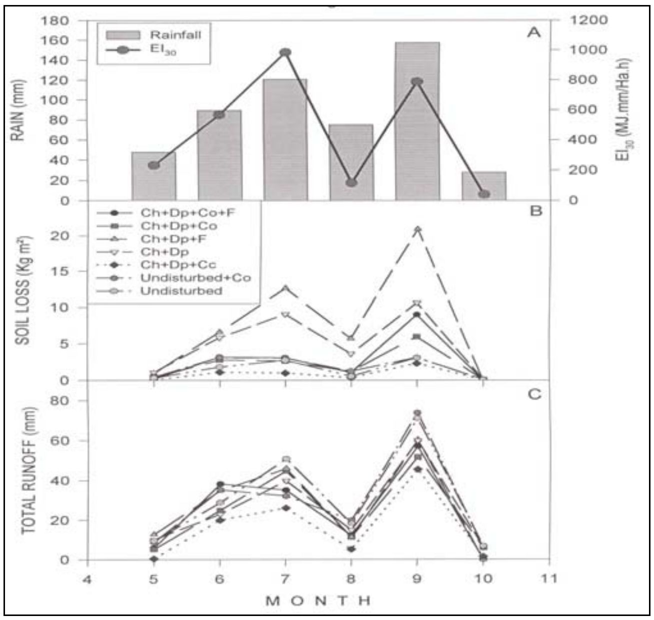

Figure 1. Monthly rainfall and erosivity distribution during 1996 at San Miguel, Mexico (A). Total soil loss (B) and total runoff (C) for different soil management treatments of the yellow tepetate under natural rain during the 1996 rainy season.

RESULTS AND DISCUSSION

Selected soil properties of the yellow tepetate are presented in Table 1. High bulk density, high silt and clay content, low organic matter content and a high sodium content are noticeable characteristics that may contribute significantly to the high susceptibility of this indurated soil to erosion, as indicated by the WDC/CDC ratio of 0.92.

Natural Rainfall Experiment

During the 1996 rainy season, a bimodal distribution of the rainfall and erosivity was observed (Fig. 1). The greater erosivity peak corresponded to the beginning of the growing season when, under natural conditions, the soil has practically no cover. This indicates that the soil needs to be protected during this time in order to provide a soil surface cover to limit the impact of rainfall on soil erosion. Practices such as the use of surface residues or fast-growing cover crops may be adequate for this conditions.

The major erosivity peak occurred before the rainfall peak. In fact, the greatest amount of rain fell during September, indicating a difference in the rainfall intensity distribution patterns of the storms. For the same amount of rain, the intensity of storms was higher during the first part of the rainy season and lower during the second. The study area is located in a tropical-temperate zone, and a mix of orographic and convective storms is expected (Garcia, 1978). It is possible that the rain during the first peak corresponded to the orographic storms, while during the second peak more intense convective storms were dominant. The peak of erosion for the majority of the treatments coincided with the peak rainfall rather than with the peak erosivity (Fig. 1). A closer correlation with the peak of soil erosivity was expected since some studies in the area have demonstrated that annual erosivity, as defined by the EI_{30} index, has a good correlation with soil loss from USLE plots (Ventura and Rios, 1989). However, lower correlations have been obtained when individual storms are analyzed (Moreno-Sanchez, 2000). More soil loss during the rainfall peak rather than during erosivity peak may reflect the influence of the antecedent soil moisture content and runoff on soil erosion. Total runoff was in agreement with the trend of soil loss, indicating that runoff may be a factor contributing significantly to erosivity and total soil loss.

The greatest soil loss was produced when a combination of deep ripping, disc plowing and fallow was used (Fig. 1), with a total annual value of about 46.7 Mg ha^{-1}. This practice significantly increased the amount of soil loss as compared to naturally undisturbed tepetates, which had a total annual soil loss of 8.4 Mg ha^{-1}. Surface cover significantly reduced total soil loss in the treatments including some type of tillage. However, no significant effect was observed on the naturally undisturbed tepetates. The results indicate that the presence of some type of soil surface cover, such as crop residues or cover crops, should be essential as part of the reclamation programs in tepetate soils. Chisel and disc plowing was an alternative for controlling soil loss only when used in conjunction with barley as cover crop. This treatment reduced the total soil loss from 30.3 to 4.8 Mg ha^{-1} as compared to the same treatment without cover crop. The naturally undisturbed tepetate produced small values of soil loss with and without cover. This indicates that naturally undisturbed tepetates resist soil erosion before runoff gets concentrated in small channels or gullies and their strength is exceeded. Under the experimental conditions, soil erosion measurements from USLE plots included sheet and rill erosion (Foster et al., 1981) but did not consider other type of concentrated flow erosion, such as gully erosion, which seemed to be the dominant form of erosion in tepetates, as observed in the field.

Total annual runoff was significantly reduced for the cover crop treatment with a value about 100 mm, as compared to values ranging from 144 to 185 mm for the rest of the soil management practices (Fig. 1). These values were not statistically different, and indicate that for both naturally undisturbed and reclaimed tepetates, water infiltration needs to be increased to reduce the amount of runoff and keep it from getting concentrated.

Rill and Interrill Erosion

The rill erodibility factor (K_r) for the naturally undisturbed tepetate was undefined under the maximum inflow conditions available for the experiment indicating the natural tepetate had a high τ_c (>5 Pa) and low K_r. The rill erodibility and critical hydraulic shear were definable for the reclaimed tepetate and the data are presented in Fig. 2. The reclaimed tepetate had a K_r of 34.1 x 10^{-3} s m^{-1} and a τ_c of 2.37 Pa. These values are comparable to those obtained for the WEPP cropland data (Elliot et al., 1989). The results from this field experiments supported the fact that reclamation of tepetate using mechanical techniques increases the potential of these lands to erode by concentrated flow as compared to the natural tepetate.

Interill erosion, as observed in the 1x1m plots, was greater in the naturally undisturbed than the reclaimed tepetate. The average value of interrill erodibility (Ki x 10^6 kg s m^{-4}) for the natural tepetate was 0.23 as compared to a value of 0.16 for the reclaimed tepetate, which indicates that reclamation of tepetate lands significantly lowered both soil and water losses due to interrill erosionHowever, when erosion was evaluated in the 1x7m plots, the water loss was roughly one half that of the natural plots while the soil loss is nearly equal. Runoff was 13.5 kg m^{-2} h^{-1} for the reclaimed tepetate and 28.0 kg m^{-2} h^{-1} for the natural one. Soil loss in g m^{-2} h^{-1} had a value of82.5 for the disturbed tepetate as compared to a value of 84.0 for the natural tepetate. This is due to the fact that the larger plots have a combination of rill and interrill processes occurring and the increase in the erosion rate over the smaller plots is largely due to rill erosion. In the 1 x 7 m plots, the natural tepetate had similar sediment loss at 85 mm hr^{-1} as at 38 mm hr^{-1} indicating that it is a detachment limited system. The reclaimed tepetate however, produced significantly more sediment at 85 mm hr^{-1} intensity than at 27 mm hr^{-1} indicating a threshold exists whereby; the reclaimed tepetate may be more erodible than the natural (Fig. 3). The results corresponded to 19 min. of simulated rain. The disturbed plot was tilled up before rain was applied. Soil porosity and roughness conditions were changed and as a result, runoff decreased and so did the amount of soil being transported. The undisturbed plot produced runoff more than four times faster than the disturbed plot. In the natural rainfall experiments, however, after soil consolidation occurred over a longer period of time, the disturbed tepetate proved to be more erodible than the undisturbed tepetate. Variations in the results can also be explained due to the effect of temporal variations in soil interrill erodibility (Kinell, 2000).

Reclamation of tepetate considerably reduced the time to runoff and the amount of runoff, but increased the rill erodibility (K_r) and decreased τ_c. Therefore, reclamation efforts should be used in conjunction with erosion control practices such as residue management to further prevent runoff from occurring or to slow it when it does occur. Once rill erosion begins, considerable amounts of soil may be lost.

Effect of gypsum on soil erosion, runoff and infiltration

The yellow tepetates is considered highly dispersible as indicated by the percentage of water-dispersible clay (WDC) and chemically dispersible clay (CDC) content. Values of WDC/CDC close to unity suggest that the soil is highly dispersible. The application of gypsum on the soil surface, however, reduced considerably the final runoff rate from 61.3 to 46.7 mmh^{-1}, and increased significantly the final infiltration rate after one hour of rain from 12.8 mm h^{-1} to 26.3 mm h^{-1} (Fig 4).

Total soil loss after one hour of rainfall is presented in Fig. 4. Gypsum reduced soil erosion significantly. Total soil erosion dropped from 360 g m^{-2} to 197 g m^{-2} in the yellow tepetate when gypsum was applied. This significant

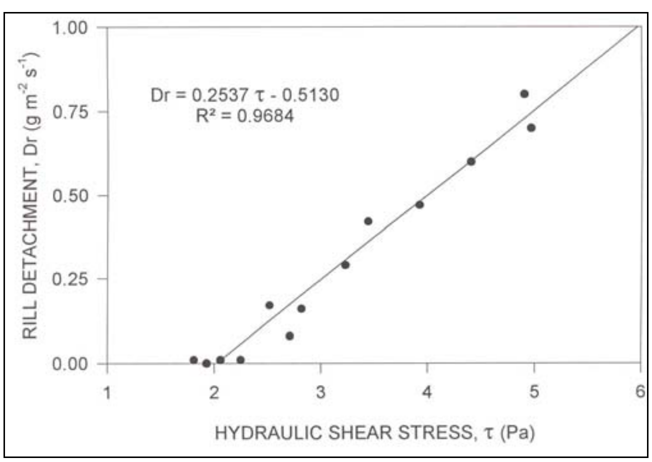

Figure. 2. Rill detachment vs. hydraulic shear stress for the reclaimed yellow tepetate on a wetted perimeter basis.

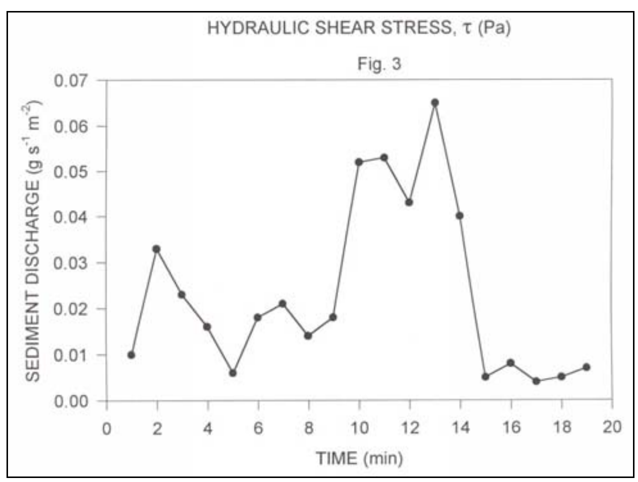

Figure 3. Soil loss as a function of rainfall intensity in the reclaimed and natural yellow tepetate for the 1 x 7 m plots. The first 9 min. the intensity was 38 mm h^{-1}, then 85 mm h^{-1} and after 14 min. 27 mm h^{-1}.

reduction corresponded to a relative reduction in soil loss of 55%. The presence of a greater amount of exchangeable Na and Mg in the soil may explain the high susceptibility of this soil to erosion. The mechanical plus the chemical action of destroying and dispersing the soil clays particles played an important role in the surface sealing of the non-treated soil. Surface application of gypsum prevented soil aggregates from being destroyed (Fig. 5) reducing the effect of raindrop impact in surface sealing. It has been reported that the effect of gypsum was to flocculate the water dispersible clay (Kazman et al., 1983) by providing electrolytes to the soil solution.

Positive effects of gypsum or gypsum-like products in some high-clay and high dispersible soils has been reported by several authors (Miller, 1987; Warrington et al., 1989; Norton et al., 1993; Reichert et al., 1994; Reichert and Norton, 1994; Reichert and Norton, 1996; Dontsova, 1998). Soil structure in yellow tepetates was very susceptible to the detrimental effects of the low electrolyte concentration of the rainwater and chemical composition of the soil exchange complex. Clay dispersion followed by clay migration with the infiltrating waters and plugging of the soil pores finally enhances surface sealing and promotes soil erosion. Surface application of gypsum effectively reduced runoff by increasing the electrolyte content of the water (Agassi et al., 1982; Norton et al., 1993; Reichert, 1993). The mechanisms responsible for the reduction of runoff and soil loss and the increase in the final infiltration with gypsum application is related to the increase in electrolytes and ionic strength in the soil solution and runoff (Agassi et al., 1982; Miller, 1987, Norton et al., 1993). A greater ionic strength and concentration of Ca^{2+} in the soil solution decreases clay dispersion and promotes flocculation according to the electrical double layer theory (van Olphen, 1977). The diffuse double layer is compressed towards the clay surface when the electrolyte concentration is increased, decreasing clay particle separation. Due to the compression of the double layer, the range of repulsive forces is considerable reduced (van Olphen, 1977), promoting flocculation.

Gypsum provided electrolytes to the soil solution of the highly dispersive tepetate and limited soil aggregate disintegration, stabilized surface soil structure and maintained greater infiltration rates and lower runoff and soil loss.

The sediment concentrations in the runoff were consistently less with gypsum application. Average sediment concentrations were reduced from 8.47 g L^{-1} to 6.05 g L^{-1}. Similar results have been reported by Reichter and Norton (1994), Reichert and Norton (1996), and Dontsova (1998).

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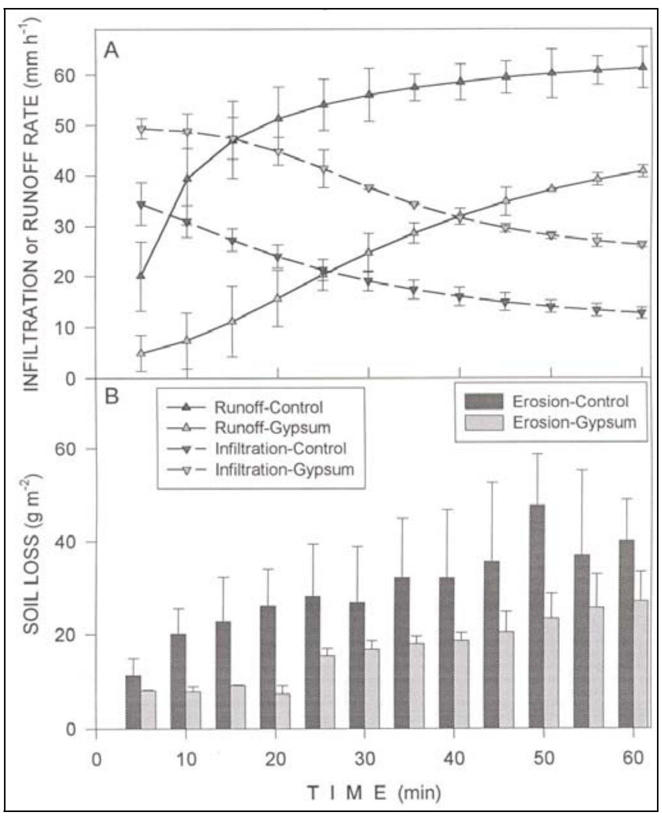

Figure 4. Average infiltration and runoff rate (A), and soil loss for one hour of simulated rain as affected by surface application of gypsum in the yellow tepetate. Vertical bars correspond to one standard deviation.

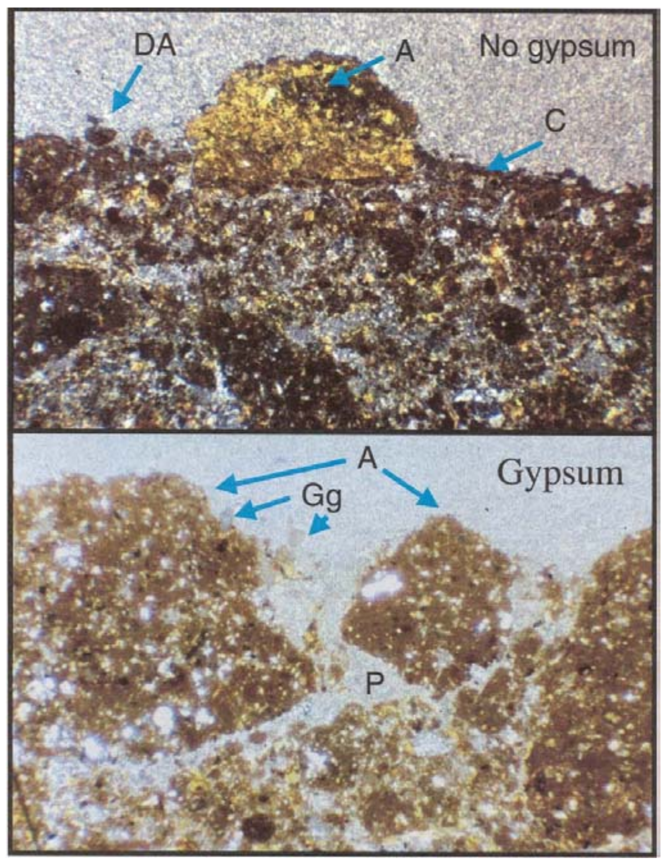

Figure 5. Aggregate disintegration and surface crusting after one hour of simulated rain in a reclaimed indurate volcanic soil (No gypsum). Surface application of gypsum prevented surface crusting and aggregate disintegration (gypsum) for the same rainfall conditions. DA = disintegrated aggregate; A = aggregate; C = surface crust; Gg = gypsum grain, P = pore space.

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CONCLUSIONS

Natural rainfall experiments demonstrated that the traditional practice of reclaiming tepetate increased soil erosion as indicated by the low critical shear stress and high rill erodibility when reclamation was performed. The combination of deep ripping and disking for reclaiming tepetates can only be used in conjunction with other practices such as cover crops or some other type of soil surface cover like crop residues.

Runoff has to be reduced or prevented from occurring since soil erosion by concentrated flow seems to be the dominant form of soil erosion in areas with tepetate exposed. Surface application of gypsum consistently increased infiltration and reduced runoff, soil loss, and sediment concentration in the yellow tepetate under simulated rainfall conditions. In addition, soil aggregates significantly resisted physical and chemical disintegration reducing the amount of surface sealing and promoting greater infiltration. The results are related to the effect of gypsum on maintaining high ionic strength and the supply of Ca to the soil solution and exchange sites, which decreases soil dispersion and promotes flocculation. The use of gypsiferous amendments to reduce surface sealing, increase infiltration and reduce soil erosion appears to be a viable management method for reclaiming highly erodible indurated volcanic soils from the Valley of Mexico at a lower cost.

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