Assessment of erosion rates during rehabilitation of hardened volcanic soils (tepetates) in Tlaxcala

Mathieu Haulon[1,*], Gerd Werner[1], Gustavo Flores-García[2], Andrea Vera-Reyes[2], and Peter Felix-Henningsen[1]

[1]Justus-Liebig-University of Giessen. Institut für Bodenkunde und Bodenerhaltung, Heinrich-Buff-Ring 26-32 (IFZ), D-35392 Giessen, Germany.
[2]Universidad Autónoma de Tlaxcala. Centro de Investigación en Ciencias Biológicas, Km 10.5 Autopista Tlaxcala-San Martín, 90120 Ixtacuixtla, Tlaxcala, Mexico.
** mathieu.haulon@googlemail.com*

ABSTRACT

The emergence of tepetates (hardened volcanic ash layers) on the surface after erosion of the overlying horizon is widespread all over the Trans-Mexican Volcanic Belt, and in particular in the State of Tlaxcala where it covers 15% of the state surface. The rehabilitation of tepetates can be a solution to the lack of arable land and to environmental problems related to surface runoff and soil erosion. The purpose of this investigation was to evaluate the effect of organic farming on erosion rates and to determine the relationship between runoff, soil loss, rain erosivity (EI30), soil organic carbon (SOC), vegetation cover (V) and aggregate stability (AS), by multiple regression analysis performed for individual erosive events (36) and for cumulative annual values.

Erosion and runoff rates were measured from 2003 to 2005 in five farmer's plots (580 to 2,020 m^2) of 3% slope inclination. Two plots were reclaimed and cultivated since 2002 and three since 1989. Three different management techniques were applied in plots reclaimed in 1989: "conventional", "improved" and "organic", corresponding mainly to increasing incorporation of organic matter. Soil loss in plots reclaimed in 2002 ranged from 8.6 to 19.1 $ton{\cdot}ha^{-1}{\cdot}year^{-1}$ under conventional management and from 5.5 to 14.1 $ton{\cdot}ha^{-1}{\cdot}year^{-1}$ under organic farming. In plots reclaimed in 1989 the erosion rates are up to three times smaller than in recently reclaimed tepetates, with soil losses ranging from 1.1 to 5.6 $ton{\cdot}ha^{-1}{\cdot}year^{-1}$ and no significant ($P<0.05$) differences between management techniques. For individual events, runoff and soil loss are significantly dependant on EI30, SOC and V ($r^2=0.73$ and 0.54 respectively). For annual values, the model accounted for an even larger proportion of the variance ($r^2=0.94$ and 0.87, respectively). Even moderate incorporation of fresh organic matter significantly increased aggregate stability in both recently and older reclaimed tepetates. However, the percolation stability index was not correlated to SOC nor to erosion rates as we expected. In recently reclaimed tepetates, organic management enhanced carbon accumulation and vegetation cover, reducing runoff and soil loss in relation to conventional management.

Key words: tepetate, erosion, runoff, rehabilitation, organic management, Tlaxcala, Mexico.

RESUMEN

El afloramiento de tepetates (capas endurecidas de cenizas volcánicas) en la superficie es un fenómeno muy extendido en la Faja Volcánica Transmexicana, y en particular en el Estado de Tlaxcala donde estos materiales ocupan 15% de la superficie del estado. La rehabilitación de los tepetates y su incorporación a la actividad agrícola se ha vuelto una necesidad social desde hace unas décadas para dar respuesta a una demanda creciente por nuevas tierras de cultivo, así como una necesidad ambiental *para mitigar los problemas relacionados con los escurrimientos superficiales. El objetivo principal de este estudio fue evaluar el efecto del manejo orgánico sobre las tasas de erosión del suelo y determinar la relación entre pérdida de suelo, erosividad de las lluvias (EI30), escurrimientos, cobertura vegetal (V), carbono orgánico (COS) y estabilidad de agregados (EA) en tepetates en rehabilitación, mediante un análisis de regresión múltiple por evento (36 eventos seleccionados) y por año.*

Durante los ciclos agrícolas de 2003 a 2005, se midieron las tasas de erosión en Santiago Tlalpan, Tlaxcala, en cinco parcelas campesinas (de 580 a 2,020 m^2) con una pendiente de 3%. Dos de las parcelas fueron roturadas en 2002 y tres en 1989. Se evaluaron tres manejos diferentes: "convencional", "mejorado" y "orgánico" que corresponden a tres niveles de incorporación de materia orgánica. En las parcelas rehabilitadas en 2002, las tasas de erosión fueron significativamente ($p<0.05$) mayores en el manejo convencional (de 8.6 a 19.1 ton·ha^{-1}·$año^{-1}$) que en el orgánico (de 5.5 a 14.1 ton·ha^{-1}·$año^{-1}$). En las parcelas rehabilitadas en 1989, las tasas de erosión son hasta tres veces menores a las de los tepetates recién rehabilitados, variando entre 1.1 y 5.6 ton·ha^{-1}·$año^{-1}$, sin diferencia significativa entre manejos. Para eventos individuales, el escurrimiento y la pérdida de suelo se relacionaron con EI30, COS y V (r^2= 0.73 y 0.54 respectivamente). Para valores anuales, el modelo explicó una proporción mayor de la varianza (r^2= 0.94 y 0.87 respectivamente). La incorporación de materia orgánica al suelo, aun en dosis moderadas, incrementó significativamente la estabilidad de agregados, independientemente de los años de rehabilitación. Sin embargo, este parámetro no se relacionó satisfactoriamente con el contenido de carbono orgánico ni con la pérdida de suelo. En tepetates recién roturados, el manejo orgánico fomenta la acumulación de COS y garantiza mejor cobertura vegetal, lo que permite reducir las perdidas de suelo y agua.

Palabras clave: tepetate, erosión, escurrimiento, rehabilitación, manejo orgánico, Tlaxcala, México.

INTRODUCTION

Emergence of tepetates in Tlaxcala

Tepetate is a vernacular Mexican term referring to hardened layers formed from pyroclastic materials, either exposed to the surface after erosion of the overlying soil, or part of the soil profile at variable depth (Zebrowski, 1992; Etchevers *et al.*, 2003).

The causes of induration of tepetates are controversial: some authors state that the induration of tepetates is due to the accumulation of silica in the subsoil under ustic isomesic soil climate with 6–7 humid months. After erosion of the overlying soil, cycles of wetting and drying compact and indurate the Si-enriched horizon (Miehlich, 1992). For other authors, pedogenic processes only consolidate the initial induration that resulted from the partial alteration of a volcanic ash into a tuff (Quantin, 1992; Hidalgo *et al.*, 1997).

In Mexico, indurated volcanic soils cover 30,700 km^2 and represent 27% of the Trans-Mexican Volcanic Belt (Zebrowski *et al.*, 1991). The state of Tlaxcala is one of the most affected by tepetates. Indurated volcanic soils cover 2,175 km^2, of which 598 km^2 are superficial tepetates (Werner, 1988). This area represents 15% of the state surface, and 21% of the arable lands.

The widespread emergence of tepetates is due to successive accelerated erosion periods which occurred when the environment was affected by climatic, demographic, social or political events over the last 4,000 years. Several studies showed evidence of accelerated erosion during prehispanic times in the Puebla-Tlaxcala region (Lauer, 1979), and in central Mexico (O'Hara *et al.*, 1993).

According to Aliphat-Fernández and Werner (1994), most of the erosion that led to the widespread emergence of tepetates in the Puebla-Tlaxcala region mainly occurred after the Spanish colonization and is the result of 1) the abandonment of the traditional intensive agriculture in terraces and the sophisticated irrigation system (Pimentel-Bribiesca, 1992) after the decline of indigenous population; 2) the introduction of extensive cattle grazing; 3) the introduction of the plough and the abandonment of inserted crops (beans, squashes) in maize cropping; 4) the intensive deforestation to supply haciendas with building timber and industries in the 19^{th} century with charcoal and firewood for steam machinery.

Rehabilitation of tepetates

The rehabilitation of tepetates for agriculture is well known since prehispanic times. This practice has developed in the last few decades to cope with the demand for arable land by the increasing population. The advent of heavy machinery to break up the hardened layer has promoted the expansion of this practice.

Rehabilitation of tepetates combines two actions: fragmentation and the subsequent management. Fragmentation consists of breaking up and loosening the hardened layer by subsoiling, deep ploughing and harrowing. This operation radically modifies the physical properties of the tepetate within a few hours (Table 1). These physical changes create the necessary conditions for water circulation and storage and for root development, but the fertility of the newly-formed material is still reduced because of the lack of carbon and nitrogen (Etchevers and Brito, 1997).

The *rehabilitation management* aims at turning the almost sterile material into a productive soil by improving the physical, chemical and biological properties of the soil to ensure sustainable crop production.

Results of previous studies on soil erosion on tepetates and under natural conditions in the states of Tlaxcala (Baumann and Werner, 1997; Fechter-Escamilla *et al.*, 1997) and Mexico (Prat *et al.*, 1997) are reported in Table 2. Values greatly depend on the size of the plot and on the meteorological conditions of the years the erosion was measured. The results show that bare tepetates produce high runoff rates (up to 90%), but moderate soil loss *in situ* due to its strong cohesive properties. Once fragmented, but not cultivated, soil loss increases considerably, whereas runoff rate decreases as a result of greater infiltration. Under cultivation, runoff and erosion rates decrease.

The results of these previous studies and field observations led to the development of a conceptual scheme of the evolution of erosion, runoff and fertility during the process of rehabilitation (Figure 1). The consequences of the physical changes of the tepetate as a result of the fragmentation (Table 1) on fertility, runoff and erosion are instantaneous. The management applied after fragmentation will determine the evolution of runoff, erosion and fertility over time. In the case of sustainable and ideal management, the improvement of physical properties ensures rapid decrease of erosion and runoff rates, which will guarantee, together with the improvement of chemical properties and biological activity, the progressive increase of soil fertility (Figure 2).

However, if the management technique is inappropriate, or if the fragmented plot is abandoned, the benefit of fragmentation on runoff will rapidly decrease because of sealing and compaction. The high erosion rates induced by fragmentation will remove within a few years the loosened layer, until the hardened horizon emerges again (Figure 3). This scenario has been observed in Tlaxcala for several rehabilitation programs, due to the lack of rehabilitation strategy and assessment for farmers.

Table 1. Selected significant physical properties of tepetate (t3) in Tlalpan, Tlaxcala, before and after fragmentation. Source: Baumann *et al.* (1992); Fechter-Escamilla and Flores (1997).

	Before fragmentation	**After fragmentation**
Bulk density ($g \cdot cm^{-3}$)	1.47	1.15 to 1.24
Total pore volume	45 %	55%
Macro pores (>10 μm)	12 %	20%

Between the two extreme scenarios, there is a range of possible situations. The knowledge of the effects of cultivation practices on the hydrodynamics of tepetates is a key factor for successful rehabilitation, since it determines the water supply for the crop, and the conservation of the newly formed production potential.

The beneficial effect of organic farming on soil structure and erodibility has been widely reported (Watts *et al.*, 2001; Shepherd *et al.*, 2002; Bronick and Lal, 2005). Nevertheless, in the case of tepetates, the use of organic amendments during rehabilitation has been repeatedly recommended (Zebrowski *et al.*, 1991; Arias, 1992; Márquez *et al.*, 1992; Pimentel-Bribiesca, 1992; Etchevers and Brito, 1997), but its effect on erodibility under field conditions has not been reported nor quantified. Moreover, there is little data available on erosion and runoff rates on rehabilitated tepetates at farmer plot scale and under natural climatic conditions.

Table 2. Soil loss and runoff on bare, fragmented and cultivated tepetate in the states of Tlaxcala and Mexico.

	Plot (m^2)	**Soil loss ($ton \cdot ha^{-1}$)**	**Runoff Coef. (erosive rain)**	**Period**	**Place**
Bare tepetate					
Baumann and Werner (1997)	44	42.3	-	1991 to 1994	Tlalpan, Tlaxcala
Fechter-Escamilla *et al*. (1997)	44	17.3	90%	1995	Tlalpan, Tlaxcala
Prat *et al*. (1997)	1800	22.5	48%	1994 to 1996	Tlaixpan, Edo. Mex.
Fragmented tepetate, not cultivated					
Baumann and Werner (1997)	44	103.5	-	1991 to 1994	Tlalpan, Tlaxcala
Fechter-Escamilla *et al*. (1997)	44	66.6	58%	1995	Tlalpan, Tlaxcala
Cultivated tepetate					
Baumann and Werner (1997)	44	7.4	-	1991 to 1995	Tlalpan, Tlaxcala
Fechter-Escamilla *et al*. (1997)	44	1.1	3%	1995	Tlalpan, Tlaxcala
Fechter-Escamilla *et al*. (1997)	1200	3	25%	1995	Tlalpan, Tlaxcala
Prat *et al*. (1997)	750	6.2	32%	1994 to 1996	Tlaixpan, Edo. Mex.

The objectives of this study are to 1) assess the erosion rates of reclaimed tepetates in the short and medium term during the rehabilitation process; 2) evaluate the effect of management and age of rehabilitation on erosion rates; and 3) determine the main factors responsible for the erodibility of reclaimed tepetates.

MATERIALS AND METHODS

A medium-term erosion study is being conducted in Santiago Tlalpan, Tlaxcala; the study was established in 2002. This paper considers the results obtained from 2003 to 2005.

Tlalpan experimental site

The site was established in two stages: in 1989, a large area of bare tepetate, adjacent to a deep ravine and with 15% natural slope, was fragmented and six terraces of 3% diagonal slope were formed (A, B, C, D, E, and F). In 2002, two smaller plots were established at the head of the ravine (R1 and R2). All plots have the same slope, and were formed on the same tepetate formation, which has been identified as t3 (Werner, 1989). Five plots are equipped with erosion measurement systems (Figure 4).

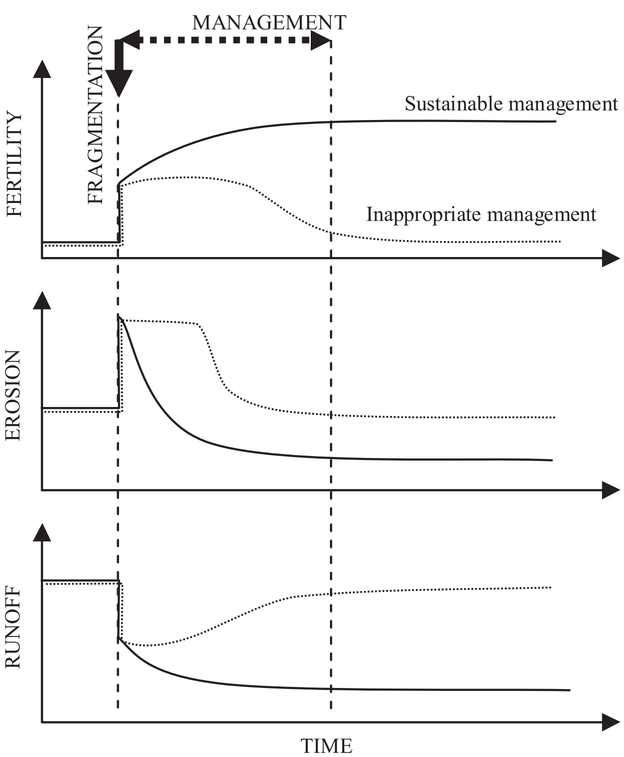

Figure 1. Expected evolution of fertility, runoff and erosion during the rehabilitation process under two extreme management scenarios.

Management techniques

Three different management techniques are being evaluated: conventional, conventional improved, and organic.

C*onventional management* is the one applied by the farmers in the study area: soil preparation with disc plough and harrow (additional operations are done depending on the crop), use of synthetic fertilizers, and use of phyto-protection products when necessary. The crop residues (straws) are sold or used for cattle pasture in spite of their poor nutritional value. Inputs are self-moderated because of economic restrictions. The incorporation of organic matter is limited to the decomposition of roots and part of the crop residues, since cattle usually graze the land after the harvest.

Improved management is based on conventional management without any restrictions of inputs (all inputs required by the crop are applied), and use of associated crop (legumes). All crop residues are incorporated to the soil. The intention is to incorporate all organic matter available on the plot after harvesting, without any addition of external sources such as manure or compost, and with a minimum of time and work requirement.

Organic management involves the same soil cultivation practices as the other systems, but exclusively uses organic fertilizers (manure or compost) and includes an associated crop. Crop residues are composted with additional farm manure and then reincorporated to the plot providing more organic matter than the other management techniques (Table 3).

Plots fragmented in 1989 were cultivated using conventional management until 2002. The main crops were maize and wheat, without any external application of organic matter (only crop residues). The crops and fertilization applied during the three cycles of this study are presented in Table 3.

Assessment of soil loss and runoff

The erosion measurement system (Haulon *et al*., 2003) comprises an H-flume equipped with a water level recorder that measures the total runoff discharge, which is then channelled to a high capacity rotating tank (2,000 to 4,500 liters). In case the runoff volume exceeds the tank capacity, a hose connected to a plastic reservoir collects an aliquot of the overflow. Samples of the suspended and settled fraction of the soil particles in the tank are taken and their concentration is determined in the laboratory to calculate soil loss. After each storm, the tank is emptied and cleaned by rotation. In total, 76 erosive events were recorded over the 2003-2005 period. ANOVA was performed on Log10(E+1) and Log10(R+1) with E equals the soil loss ($ton \cdot ha^{-1}$) and R the runoff (mm) per event to compare erosion and runoff rates between plots. For the latter we used the Duncan test at 0.05 significance level.

Figure 2. Sustainable management of reclaimed terraced tepetate in Tlaxco, Tlaxcala.

Figure 3. On the same hillside, neo-emergence of the tepetate as a result of the abandonment of the terrace.

Rain erosivity

Rainfall was registered by an event recorder connected to a tipping-bucket rain gauge allowing a precise calculation of rainfall intensity and kinetic energy (KE). A daily pluviograph ensures the continuity of records in case of failure of the electronic device. Kinetic energy was computed using the equation used for the RUSLE (Renard *et al.*, 1997):

$KE = 11.9+8.73 \text{ Log10}(I)$ if $I \leq 76 \text{ mm·h}^{-1}$

$KE = 28.3$ if $I > 76 \text{ mm·h}^{-1}$

The erosivity factor EI30 was calculated for each event and annually.

Aggregate stability

Aggregate stability was assessed using the percolation stability index (PS) according to the method developed by Becher and Kainz (1983). This index corresponds to the amount of deionised water that percolates through a column (length: 10 cm; diameter 15 mm) of 10 g of calibrated air-dried aggregates, during 10 minutes and at a pressure of 20 cm water column. Aggregates of higher stability are assigned a higher PS value. Three replicates were performed.

The original test is performed on 1-2 mm diameter air-dried aggregates. In this study, the method is widened

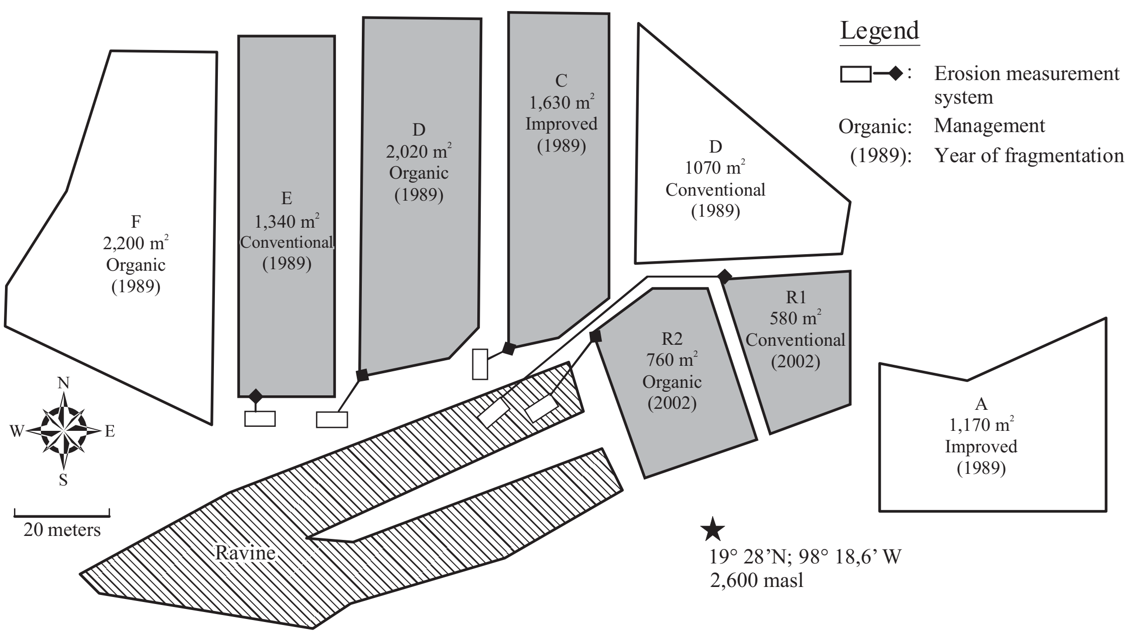

Figure 4. Map of Tlalpan experimental site and selected characteristics of the plots.

Table 3. Crops and fertilization from 2002 to 2005.

Plot		C	D	E	R1	R2
Management		Improved	Organic	Conventional	Conventional	Organic
Fertilization (N-P-K, kg/ha)	2002	60-100-34	compost	23-00-00	23-46-00	21t/ha (FM) + crop incorporation*
	2003	23-60-00	15 t/ha (FM)	23-00-00	23-00-00	15 t/ha (FM)
	2004	90-40-00	2.9 t/ha (DC)	81-00-00	81-00-00	2.6 t/ha (DC)
	2005	82-23-00	2.1 ton/ha (DC)	62-23-00	62-23-00	1.9 ton/ha (DC)
Crop	2002	Broad bean	Broad bean	Broad bean	Broad bean	Broad bean
	2003	Oat + vetch	Oat + vetch	Oat	Oat	Oat + vetch
	2004	Maize + bean	Maize + bean	Maize + bean	Maize + bean	Maize + bean
	2005	Wheat	Wheat	Wheat	Wheat	Wheat

FM: fresh manure; DC: dry compost; Vetch: *Vicia sativa*. * broad bean was not harvested and the whole biomass was incorporated.

as the test is performed on several aggregate sizes: 0.59–1 mm, 1–2 mm, and 2–3.15 mm. The interest is to evaluate the stability of a wider range of aggregate sizes so that the sample tested is more representative of the whole soil behavior. Based on this consideration, the weighted PS (PS*w*) was calculated to take into account the relative proportion of each aggregate size class.

$$PSw = \sum PSx \cdot \%x$$

where PS*x* is the percolation stability index for aggregate size *x*, and %*x* is the fraction of aggregate size *x* in relation to the other aggregate sizes tested.

Organic carbon

In each plot, two composite samples from 10 subsamples were taken at 0–10 cm depth at the end of the rainy season. Soil organic carbon was measured by dry combustion (TOCA). Samples were measured once. The precision of the measurements was verified by running standard control samples regularly.

Vegetation cover

In 2003, vegetation cover was measured by a modified version of quadrat sighting frame (Stocking, 1994), which consisted of a board perforated with fifty 2 mm-diameter holes at 2 cm interval. In 2005, a new method based on digital photographs taken at 7 meters height and processed by image analysis software was used. In 2004, only visual observation was performed at maximum development stage of the crop. Repeated measures ANOVA was performed and Tukey HSD at 0.05 confidence level was used to compare means between treatments.

Statistical analysis

SOC and vegetation cover are the parameters most influenced by management and age of rehabilitation in our study. Using 36 selected erosive events, a multiple regression analysis was performed to explore the relationship between soil loss (E), runoff (R) rainfall erosivity (EI30), soil organic carbon (SOC) vegetation cover (V) and aggregate stability (AS). The same analysis was performed for annual values.

RESULTS

Rainfall erosivity, runoff and soil loss

Annual precipitation ranged from 577 mm in 2005 to 805 mm in 2003. The R factor (EI30) ranged from 1953 to 3767 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$ (Table 4). Annual precipitation and erosivity measured between 2003 and 2005 are in the range of those previously reported by Baumann and Werner (1997).

In recently reclaimed tepetates, erosion rates ranged

Table 4. Rainfall characteristics at Tlalpan experimental site from 2003 to 2005 (annual means).

	Mean annual precipitation (mm)	Kinetic energy ($MJ \cdot ha^{-1}$)	EI30 ($MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$)	Most erosive month
2003	805	157	3449	June
2004	756	151	3767	September
2005	577	110	1953	July

Table 5. Soil loss and runoff from 2003 to 2005 in reclaimed tepetates at Tlalpan, Tlaxcala. Different letters indicate significant differences between plots (P<0.05).

Plot		**R1**	**R2**	**C**	**D**	**E**
Management		Conventional	Organic	Improved	Organic	Conventional
Year of fragmentation		2002	2002	1989	1989	1989
Runoff (mm)	2003	265	160	51	49	70
	2004	207	146	58	82	99
	2005	177	149	27	31	39
Soil loss	2003	19.1	14.1	4.5	5.5	4.6
(ton·ha^{-1}·year^{-1})	2004	16.2	10.2	2.3	4.2	5.6
	2005	8.6	5.5	1.1	1.4	1.3
	P<0.05	a	a	a	b	c
Mean sediment discharge	2003	72.0	88.2	87.9	111.5	65.2
(kg·mm^{-1})	2004	78.3	70.0	39.6	51.6	56.7
	2005	48.6	36.9	40.1	44.6	33.4
Runoff coefficient	2003	45%	28%	10%	10%	14%
(from erosive events)	2004	52%	37%	17%	23%	28%
	2005	50%	41%	10%	10%	14%
% of annual soil loss caused	2003	19%	38%	72%	67%	53%
by major event	2004	24%	40%	39%	26%	29%
	2005	24%	27%	45%	30%	48%

from 5.5 to 19.1 ton·ha^{-1}·year^{-1} depending on the annual rainfall amount (Table 4) and the management, with a mean value of 12.3 ton·ha^{-1}·year^{-1} over the period of study (Table 5). Soil loss under conventional management was significantly (P<0.05) greater than under organic management, with a difference of 3.1 to 5 ton·ha^{-1}·year^{-1}. In tepetates reclaimed in 1989, erosion rates ranged from 1.1 to 5.5 ton·ha^{-1}·year^{-1}, with a mean value of 3.4 ton·ha^{-1}·year^{-1} and no significant difference between management techniques. The same trend is observed in runoff, with annual values ranging from 146 to 265 mm in recently reclaimed tepetates, and from 27 to 99 mm in older reclaimed plots.

Soil properties and vegetation cover

Aggregate stability

There is a strong annual variability in PSw values (Table 6). The time elapsed between the date of sampling and the date of testing differs from one year to another. In 2005, samples were analyzed a few weeks after they were air dried whereas samples from 2004 cycle were stored for more than a year before they were analyzed. This may have increased aggregate cohesion (Kemper and Rosenau, 1986; Díaz-Zorita *et al.*, 2002). Also, variation of structural stability within a treatment over a growing season can be as large, or larger, than the changes observed between treatments over a number of years (Perfect *et al.*, 1990). Since variability between years can not be controlled in this study, the discussion of results only focuses on differences between plots within a year.

Management had a significant effect on PSw (p<0.001), independent of the year of rehabilitation. As expected, the lowest PSw values were obtained in the plot recently reclaimed under conventional management (R1) and the highest ones in the plot reclaimed in 1989 under organic management (D). Organic management in newly rehabilitated tepetate (R2) yielded similar PSw values than conventional and improved management in plots reclaimed in 1989 (C and E).

Vegetation cover

Vegetation cover depends on crop characteristics, which varies between years, and crop development, which is mainly responsible for differences between plots within a year. In turn, crop development depends on plant nutrition and water supply. Hence, water loss by runoff both affects and is affected by vegetation cover (Table 5).

In average, improved management provided significantly (P<0.05) greater vegetation cover than organic and conventional management in plots reclaimed in 1989, reaching up to 18% (Table 6). In these plots, vegetation cover is also larger than in plots recently cultivated in both recently and older reclaimed plots.

Soil organic carbon

Just after fragmentation, tepetates contained 1.05 mg·g^{-1} of SOC (R1 and R2). After 4 years of cultivation, SOC content increased to 2.2 mg·g^{-1} under organic management, and to 1.5 mg·g^{-1} under conventional management.

At the beginning of the experiment in 2002, SOC content was 3.3 mg·g^{-1} in all plots reclaimed in 1989. The organic management provided more accumulation of SOC over the period studied, from 3.4 to 4.0 mg·g^{-1}.

Table 6. Selected soil properties and mean vegetation cover from 2003 to 2005 in reclaimed tepetates at Tlalpan, Tlaxcala. Different letters indicate significant differences between plots (P<0.05).

Plot		R1	R2	C	D	E
Management		Conventional	Organic	Improved	Organic	Conventional
Year of fragmentation		2002	2002	1989	1989	1989
Soil organic carbon	2002	1.05	1.05	3.3	3.3	3.4
($mg \cdot g^{-1}$)	2003	0.8	2.0	3.4	4.5	4.1
	2004	1.5	2.35	3.5	4.5	3.8
	2005	1.5	2.2	3.3	4.0	3.6
Vegetation cover	2003	39.2%	69.8%	83.9%	73.6%	60.9%
(%)	P<0.05	d	c	b	c	a
	2004	35.0%	70.0%	87.5%	79.0%	77.5%
		±5%	±5%	±5%	±5%	±5%
	2005	32.2%	37.2%	69.0%	65.9%	54.2%
	P<0.05	c	c	b	b	a
Aggregate stability	2003	170.2	254.0	302.4	442.1	236.5
PSw	P<0.05	a	a	a	b	a
	2004	323.5	739.5	545.0	874.4	425.9
	P<0.05	a	bc	ac	b	a
	2005	45.3	94.4	114.4	139.9	98.1
	P<0.05	c	a	ab	b	a

Unexpectedly, SOC content in improved management remained almost stable at 3.3 $mg \cdot g^{-1}$, whereas a small increase was observed in conventional management, from 3.3 up to 3.6 $mg \cdot g^{-1}$. The ANOVA showed that over the period R1<R2<C=E<D (P<0.05). However, further replicates would be necessary to increase the significance of the differences between plots.

Statistical analysis

For individual events, runoff and soil loss are significantly dependant on EI30, SOC and V (R^2=0.73 for runoff and R^2=0.54 for soil loss, n=161). Their relationship can be formulated as follows:

$$E = 1.096 + 0.0027(EI30) - 0.203(SOC) - 0.977(V)$$

$$R = 12.7 + 0.033(EI30) - 3.09(SOC) - 3.39(V)$$

The erosivity factor (EI30) alone accounts for 59.5% of the variance in runoff and 39.3% in soil loss. Vegetation cover and SOC explain respectively another 0.9% and 12.8% of the runoff variance and 9.7% and 4.7% of the soil loss variance (Table 7). Therefore, among the factors affected by management and age of rehabilitation, runoff is most affected by SOC, whereas soil loss is more affected by vegetation cover.

As expected, soil loss is strongly correlated with runoff (R^2=0.75, n=161), such as:

$$E = -0.126 + 0.088(R)$$

These equations are valid for erosive rainstorms only and for soil conditions found during the rainy season and after the crops were established. Their extrapolation to other circumstances or to other ranges of SOC content is not advised and should be avoided.

The models adjusted to cumulative annual runoff and soil loss explain a larger proportion of the variances than the models adjusted to individual events, although the contribution of each variable differs in the various models. For runoff (R^2=0.94, n=15) and soil loss (R^2=0.87, n=15), SOC is the main contributor, explaining respectively 79.8% and 65.3% of the variance (Table 7). Vegetation cover did not make any significant unique contribution to soil loss prediction. No significant relationship was found between PS and SOC (r^2=0.14) nor between PS and soil loss (R^2=0).

DISCUSSION

Erosion rates and erosivity

Rainfall characteristics recorded over the period are consistent with those reported previously at the same location from 1991 to 1995 (Baumann and Werner, 1997; Fechter-Escamilla *et al.*, 1997).

In the study area, and more generally in semi-arid areas, the major part of total soil loss is caused by a small number of rainstorms (Baumann and Werner, 1997; Prat *et al.*, 1997). This is particularly true for the year 2003. The most erosive rainstorm occurred at the end of June when the soil was only 35% covered by vegetation, and caused between 53% and 72% of the total soil loss in plots reclaimed in 1989.

Erosion rates measured during this study are also in the range of those reported previously in reclaimed tepetates under natural conditions (Table 2). There are no studies available on soil loss tolerance in the case of tepetates, but for agronomic concerns such rates are acceptable and reclaimed tepetates cultivated for more than 13 years can be considered as stable. In recently reclaimed tepetates, organic management contributed to reducing erosion rates to between 3.1 and 5 ton·ha^{-1}·year^{-1}. The major concern of erosion may not be soil loss but water loss which represents a serious limitation for crop production in Tlaxcala.

Factors affecting erodibility of reclaimed tepetates

The area of the plots reclaimed in 1989 is two to three times larger than that of recently reclaimed tepetate plots. The possible effect of plot size on soil loss is however uncertain: on one hand, plot length could increase flow velocity and particle detachment and as a result increase soil erosion; on the other hand, larger plots might present more depositional areas and, hence, reduce net erosion. In this study, we assume plot size effect is negligible.

In soils not affected by sodicity (Agassi *et al.*, 1981; Barzegar *et al.*, 1997), organic matter (OM) content is one of the main soil properties influencing aggregate and structure stability (Le Bissonnais, 1996). OM increases aggregate cohesive strength by bonding and/or holding particles together (*e.g.*, Oades, 1984; Six *et al.*, 2000) and decreases the wettability of aggregates because of its hydrophobic properties (Chenu *et al.*, 2000; Goebel *et al.*, 2005). In turn, aggregate stability reduces particle detachment, soil crusting, runoff and soil loss (Le Bissonnais, 1996). Vegetation cover provides direct protection to the soil and reduces aggregate breakdown from raindrop impact.

Multiple regression analysis clearly highlighted the role of SOC and vegetation cover in erosion of reclaimed tepetates. However the relationship we expected between SOC and PS and between PS and soil loss or runoff was non existent in our study. Other studies report that PS is a good indicator of structural stability to assess soil erosion (Mbagwu and Auerswald, 1999), and that it is significantly correlated with soil erosion (Auerswald, 1995).

Several hypothesis are suggested to explain this result: 1) SOC and PS are not correlated because only part of the OM is responsible for the formation and stability of aggregates (Tisdall and Oades, 1982; Golchin *et al.*, 1995; Tisdall *et al.*, 1997); 2) the methodology used is a source of bias: SOC and PS were measured independently on different samples taken at different dates. SOC should have been measured on the same aggregates used to measure PS; 3) the percolation stability index measures slaking potential (Auerswald, 1995; Mbagwu and Auerswald, 1999) and might not reflect the main mechanism of aggregate breakdown in reclaimed tepetates. This last suggestions is considered the least likely, but should be confirmed by clay mineralogy and electrolyte concentration studies to check on possible aggregate breakdown by differential swelling and physico-chemical dispersion.

Effect of management and age of rehabilitation on erosion rates

The difference between SOC just after fragmentation (1.05 mg·g^{-1}) and after 13 years of cultivation (3.3 mg·g^{-1}) gives an indication of the accumulation of organic carbon in cultivated tepetates under conventional management. Since the incorporation of crop residue is minor, the accumulation of SOC in the conventional system is mainly due to root decomposition. These results are consistent with those of Báez-Pérez *et al.* (2002), who showed that organic carbon concentration in reclaimed tepetates increases rapidly in the first years of rehabilitation and tends to stabilize naturally around 5 mg·g^{-1} in monocropping systems after the first decade of rehabilitation, and over 10 mg·g^{-1} in systems with frequent manure applications and conservation tillage.

The addition of fresh organic matter (Table 3) is a way to magnify the accumulation of SOC in the soil during the first years of rehabilitation. In four years the accumulation of SOC in organic management (1.15 mg·g^{-1}) was 2.5 times higher than in conventional management (0.45 mg·g^{-1}). Considering that increasing SOC content by 1 mg·g^{-1} may prevent a soil loss of 3.5 ton·ha^{-1}·year^{-1} and save 40 mm of water, the accumulation of SOC must be a primary objective in rehabilitation strategies. In plots reclaimed for more than a decade, the accumulation rate is smaller and a larger amount of organic matter will be required to achieve a substantial increase in SOC.

Results of percolation stability suggests that aggregate stability is the result of the combination of a long lasting stability that develops with time during the rehabilitation process, and of a temporary stability that depends on management and is able to develop rapidly after incorporation of OM, even in recently fragmented tepetates.

When fresh organic material is incorporated into the soil matrix, it is rapidly colonized by microbial decomposers which induce the formation and stabilization of aggregates (Golchin *et al.*, 1994; Puget *et al.*, 2000). Fungal hyphae mechanically bind the soil particles that surround the organic resource, and extracellular polysaccharides stick them to cells of bacteria and fungi (Oades, 1993). Puget *et al.*(1995) also demonstrated that the SOM responsible for the stability of macroaggregates was younger than the one present in microaggregates, which explains why organic management in recently reclaimed tepetate can reach a similar or higher level of PS than plots with more years of rehabilitation.

However, macroaggregate stability (measured by the percolation method) did not seem to be responsible for the difference in erosion rates we observed. It suggests that soil structure improvement related to SOC rather than aggregate stability related to incorporation of fresh organic matter plays a major role in erosion processes in reclaimed tepetates.

Fertility limitations are responsible for lower crop development and vegetation cover in recently reclaimed

Table 7. Model summary and coefficients of the regression analysis between soil loss, runoff, erosivity, SOC and vegetation cover. Units: E (ton·ha^{-1}), R (mm), EI30 (MJ·mm·ha^{-1}·h^{-1}), V (%), SOC (mg·g^{-1}).

Dependent	Predictors	Unstandardized Coeff. B	Unstandardized Coeff. Std. Error	Standardized Coeff. Beta	Sig. P	Model R^2
Soil loss (E) event	(Constant)	1.096	0.171		0.000	0.54
	EI30	2.73E-03	2.32E-04	0.64	0.000	
	V	-0.977	0.200	-0.27	0.000	
	SOC	-0.203	0.051	-0.22	0.000	
Runoff (R) event	(Constant)	12.673	1.287		0.000	0.73
	EI30	3.30E-02	1.75E-03	0.78	0.000	
	SOC	-3.085	0.382	-0.34	0.000	
	V	-3.394	1.509	-0.09	0.026	
Soil loss (E) event	(Constant)	-0.126	0.054		0.021	0.75
	R	0.088	0.004	0.87	0.000	
Soil loss (E) annual	(Constant)	9.854	2.855		0.005	0.87
	SOC	-3.529	0.753	-0.74	0.001	
	EI30	3.36E-03	7.83E-04	0.49	0.001	
	V(mean)	-4.388	5.547	-0.13	0.446	
Runoff (R) annual	(Constant)	223.390	25.780		0.000	0.94
	SOC	-39.568	6.799	-0.65	0.000	
	EI30	3.22E-02	7.07E-03	0.36	0.001	
	V(mean)	-163.631	50.092	-0.37	0.008	
Soil loss (E) annual	(Constant)	-0.763	1.023		0.469	0.86
	R	0.072	0.008	0.93	0.000	

tepetates. However, the study demonstrated that such limitations can be partly overcome by the use of associated crops and better nutrition. In 2003, the associated crop (vetch) resulted in increased vegetation cover from 61% (conventional management) to up to 84% (improved management) in plots reclaimed in 1989, and from 39% to 70% in plots reclaimed in 2002. The following year, in these plots the residual effect of the previous leguminous crop (vetch) along with the organic manure applied in the organic management provided better plant nutrition, resulting in greater vegetation cover (70%) than the conventional management (35%). In 2005, however, the vegetation cover over the period was equal for both management techniques, because of a nutrition deficit in the organic management attributed to a large C/N ratio of the compost that caused a lack of N for the plant. Such observation stresses the pertinence of the combination of organic and mineral fertilization to ensure optimum plant nutrition and vegetation cover. This is supported by the vegetation cover results obtained under improved management in plots reclaimed in 1989.

CONCLUSIONS

This study conducted over 3 years made clear that erosion rates and their evolution in reclaimed tepetates depends on SOC content and vegetation cover. After 14 years of rehabilitation, cultivated tepetates reached up to three times lower erosion rates than recently fragmented tepetate. In recently reclaimed tepetates, organic management enhanced carbon accumulation and vegetation cover, reducing runoff and soil loss in relation to conventional management. In tepetates reclaimed for more than 13 years, there is no significant effect of higher incorporation of organic matter on erosion rates, because of lower SOC accumulation rates.

The incorporation of fresh organic matter, even moderate, did increase significantly aggregate percolation stability in both recently and older reclaimed tepetates. However, percolation stability index was not satisfactorily correlated to SOC or to erosion rates as we expected.

Results obtained in this study confirm recommendations about the use of organic matter to improve soil fertility and conservation. Sustainable rehabilitation of tepetates depends on the ability of the management applied after fragmentation to promote SOC accumulation and provide vegetation cover.

AKNOWLEDGEMENTS

This study was part of the REVOLSO project funded by the European Comission within the FP5 INCO/DEV program, contract ICA4-2001-10052, and was also supported by the Fundación Produce Tlaxcala from 2002 to 2005. We would like to thank Sara Covaleda from the University of

Salamanca and the team of Jorge Etchevers from the Colegio de Postgraduados for providing the soil organic carbon data. We are also grateful to the editors and two anonymous referees for their valuable suggestions to improve the manuscript.

REFERENCES

Agassi, M., Shainberg, I., Morin, J., 1981, Effect of electrolyte concentration and soil sodicity on infiltration and crust formation: Soil Science Society of Amercia Journal, 45, 848-851.

Aliphat-Fernández, M., Werner, G., 1994, The tepetates of the Mexican Central Highlands: Prehispanic and Modern impact of agriculture and water managment, *in* 15th World Congress of Soil Science, Transactions, Acapulco, Mexico, July 1994: Chapingo, México, Sociedad Mexicana de la Ciencia del Suelo (SMCS), International Society of Soil Science (ISSS), v. 6a, 528-540.

Arias, H., 1992, Rehabilitación de tepetate: una alternativa para la producción agropecuaria y forestal: Terra, 10 (numero especial), 309-317.

Auerswald, K., 1995, Percolation stability of aggregates from arable topsoils: Soil Science, 159(2), 142-148.

Báez-Pérez, A., Etchevers-Barra, J.D., Hidalgo-Moreno, C., Prat, C., Ordaz-Chaparro, V., Núñez-Escobar. R., 2002, Organic C and Olsen-P in cultivated tepetates of México: Agrociencias, 36, 643-653.

Barzegar, A.R., Nelson, P.N., Oades, J.M., Rengasamy, P., 1997, Organic matter, sodicity, and clay type: Influence of soil aggregation: Soil Science Society of Amercia Journal, 61, 1131-1137.

Baumann, J., Werner, G., 1997, Erodibility of volcanic ash soils in the Central Mexican Highlands, *in* Zebrowski, C., Quantin, P., Trujillo, G., (eds.), Suelos Volcánicos Endurecidos, III Simposio Internacional, Quito, December 1996: Quito, Ecuador, Unión Europea (UE), Institut Français de Recherche Scientifique pour le développement en Coopération (ORSTOM), Pontificia Universidad Católica del Ecuador (PUCE), Universidad Central del Ecuador (UCE), 343-350.

Baumann, J., Werner, G., Muñoz, H., Vera, A., Flores, G.F., 1992, Mediciones preliminares de la erosión hídrica en el bloque de Tlaxcala, Mexico: Terra, 10 (numero especial), 347-354.

Becher, H.H., Kainz, M., 1983, Auswirkungen einer langjährigen Stallmistdüngung auf das Bodengefüge im Löβgebiet bei Straubing: Zeitschrift für Acker und Pflanzenbau, 152, 152–158.

Bronick, C.J., Lal, R., 2005, Soil structure and management: a review: Geoderma, 124(1-2), 3-22.

Chenu, C., Le Bissonnais, Y., Arrouays, D., 2000, Organic matter influence on clay wettability and soil aggregate stability: Soil Science Society of America Journal, 64(4), 1479-1486.

Díaz-Zorita, M., Perfect, E., Grove, J.H., 2002, Disruptive methods for assessing soil structure: Soil & Tillage Research, 64(1-2), 3-22.

Etchevers, J.D., Brito, H., 1997, Levantamiento nutrimental de los tepetates en los estados de Mexico y Tlaxcala, *in* Zebrowski, C., Quantin, P., Trujillo, G. (eds.), Suelos Volcánicos Endurecidos, III Simposio Internacional, Quito, December 1996: Quito, Ecuador, Unión Europea (UE), Institut Français de Recherche Scientifique pour le développement en Coopération (ORSTOM), Pontificia Universidad Católica del Ecuador (PUCE), Universidad Central del Ecuador (UCE), 202-212.

Etchevers, J.D., Hidalgo, C., Prat, C., Quantin, P., 2003, Tepetates of Mexico, *in* Lal, R. (ed.), Encyclopedia of Soil Science: New York, Marcel Dekker, 1745-1748.

Fechter-Escamilla, U., Flores, G., 1997, Propiedades físicas de suelos volcánicos endurecidos (tepatetes t3) después de su rehabilitación, en Tlaxcala (Mexico), *in* Zebrowski, C., Quantin, P., Trujillo, G. (eds.), Suelos Volcánicos Endurecidos, III Simposio Internacional, Quito, December 1996: Quito, Ecuador, Unión Europea (UE), Institut Français de Recherche Scientifique pour le développement en Coopération (ORSTOM), Pontificia Universidad Católica del Ecuador (PUCE), Universidad Central del Ecuador (UCE), 162-169.

Fechter-Escamilla, U., Vera, A., Werner, G., 1997, Erosión hídrica en un suelo volcánico endurecido (tepetate t3) en el bloque de Tlaxcala, Mexico, *iin* Zebrowski, C., Quantin, P., Trujillo, G. (eds.), Suelos Volcánicos Endurecidos, III Simposio Internacional, Quito, December 1996: Quito, Ecuador, Unión Europea (UE), Institut Français de Recherche Scientifique pour le développement en Coopération (ORSTOM), Pontificia Universidad Católica del Ecuador (PUCE), Universidad Central del Ecuador (UCE), 351-358.

Goebel, M.-O., Bachmann, J., Woche, S.K., Fischer, W.R., 2005, Soil wettability, aggregate stability, and the decomposition of soil organic matter: Geoderma, 128(1-2), 80-93.

Golchin, A., Oades, J.M., Skjemstad, J.O., Clarke, P., 1994, Soil structure and carbon cycling: Australian Journal of Soil Research, 32(5), 1043-1068.

Golchin, A., Clarke, P., Oades, J. M., Skjemstad, J. O., 1995, The effects of cultivation on the composition of organic matter and structural stability of soils: Australian Journal of Soil Research, 33(6), 975-993.

Haulon, M., Werner, G., Bravo-Espinoza, M., Prat, C., Flores, G., Fechter-Escamilla, U., 2003, Sediment laden runoff measurement system on deteriorated volcanic ash soils in Mexico, *in* Gabriels, D., Cormelis, W. (eds), 25 Years of Assessment of Erosion: Ghent, Ghent University, 303-304.

Hidalgo, C., Quantin, P., Elsass, F., 1997, Caracterización mineralógica de los tepetates tipo fragipán del valle de México, *in* Zebrowski, C., Quantin, P., Trujillo, G. (eds.), Suelos Volcánicos Endurecidos, III Simposio Internacional, Quito, December 1996: Quito, Ecuador, Unión Europea (UE), Institut Français de Recherche Scientifique pour le développement en Coopération (ORSTOM), Pontificia Universidad Católica del Ecuador (PUCE), Universidad Central del Ecuador (UCE), 65-72.

Kemper, W.D., Rosenau, R.C., 1986, Aggregates stability and size distribution, *in* Klute, A. (eds.), Methods of Soil Analysis, Part 1. Physical and mineralogical methods: Madison, WI, American Society of Agronomy (ASA), Agronomy Monographs 9(1), 2nd ed., 425–442.

Lauer, W., 1979, Medio ambiente y desarrollo cultural de la región de Puebla Tlaxcala: Puebla, Mexico, Fundacion Alemana para la Investigación Científica, Proyecto Puebla-Tlaxcala, Comunicaciones, 16, 29-54.

Le Bissonnais, Y., 1996, Aggregate stability and assessment of soil crustability and erodibility, I. Theory and methodology: European Journal of Soil Science, 47(4), 425-437.

Márquez, A., Zebrowski, C., Navarro, H., 1992, Alternativas agronómicas para la recuperación de tepetates: Terra, 10 (número especial), 465-473.

Mbagwu, J.S.C., Auerswald, K., 1999, Relationship of percolation stability of soil aggregates to land use, selected properties, structural indices and simulated rainfall erosion: Soil and Tillage Research, 50(3-4), 197-206.

Miehlich, G., 1992, Formation and properties of tepetate in the Central highlands of México: Terra, 10 (número especial), 137-144.

O'Hara, S.L., Street-Perrott, F.A., Burt, T.P., 1993, Accelerated soil erosion around a Mexican highland lake caused by prehispanic agriculture: Nature, 362(6415), 48-51.

Oades, J.M., 1984, Soil organic matter and structural stability: mechanisms and implications for management: Plant and Soil, 76, 319-337.

Oades, J.M., 1993, The role of biology in the formation, stabilization and degradation of soil structure: Geoderma, 56(1-4), 377-400.

Perfect, E., Kay, B.D., Vanloon, W.K.P., Sheard, R.W., Pojasok, T., 1990, Rates of Change in Soil Structural Stability under Forages and Corn: Soil Science Society of America Journal, 54(1), 179-186.

Pimentel-Bribiesca, L., 1992, Como hacer productivos a los tepetates en México: Terra, 10 (numero especial), 293-301.

Prat, C., Báez-Pérez, A., Márquez-Ramos, A., 1997, Erosión y escurrimiento en parcelas de tepetate t3 en Texcoco, México, *in* Zebrowski, C., Quantin, P., Trujillo, G. (eds.), Suelos Volcánicos Endurecidos, III

Simposio Internacional, Quito, December 1996: Quito, Ecuador, Unión Europea (UE), Institut Français de Recherche Scientifique pour le développement en Coopération (ORSTOM), Pontificia Universidad Católica del Ecuador (PUCE), Universidad Central del Ecuador (UCE), 371-383.

Puget, P., Chenu, C., Balesdent, J., 1995, Total and young organic matter distributions in aggregates of silty cultivated soils: European Journal of Soil Science, 46, 449-459.

Puget, P., Chenu, C., Balesdent, J., 2000, Dynamics of soil organic matter associated with particle-size fractions of water-stable aggregates: European Journal of Soil Science, 51(4), 595-605.

Quantin, P., 1992, L'induration des materiaux volcaniques pyroclastiques en Amérique Latine: processus géologiques et pédogiques: Terra, 10 (numero especial), 24-33.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C., 1997, Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE): United States Department of Agriculture (USDA), Agriculture Handbook 703, 404 p.

Shepherd, M.A., Harrison, R., Webb, J., 2002, Managing soil organic matter - implications for soil structure on organic farms: Soil Use and Management, 18, 284-292.

Six, J., Paustian, K., Elliott, E.T., Combrink, C., 2000, Soil structure and organic matter, I. Distribution of aggregate-size classes and aggregate-associated carbon: Soil Science Society of Amercia Journal, 64(2), 681-689.

Stocking, M.A., 1994, Assessing vegetation cover and management effects, *in* Lal, R. (eds), Soil Erosion Research Methods: Delray Beach, Soil and Water Conservation Society and St. Lucie Press, 211-232.

Tisdall, J.M., Oades, R. L., 1982, Organic matter and water stable aggregates in soils: European Journal of Soil Science, 33, 141-163.

Tisdall, J.M., Smith, S.E., Rengasamy, P., 1997, Aggregation of soil by fungal hyphae: Australian Journal of Soil Research, 35(1), 55-60.

Watts, C.W., Whalley, W.R., Longstaff, D., White, R.P., Brooke, P.C., Whitmore, A.P., 2001, Aggregation of a soil with different cropping histories following the addition of organic materials: Soil Use and Management, 17(4), 263-268.

Werner, G., 1988, Die Böden des Staates Tlaxcala im Zentralen Hochland vom Mexiko. Das Mexiko Projekt der Deutschen Forschungsgemeinschaft 20: Stuttgart, BDR, 207.

Werner, G., 1989, Los suelos en el Estado de Tlaxcala, Altiplano Central Mexicano. Investigaciones relacionadas con su desarrollo, extensión, erosión y su utilización bajo la influencia de actividades agrícolas en 3000 años (con Aportaciones de G. Miehlich): Tlaxcala, Gobierno del Estado de Tlaxcala, Universidad Autónoma de Tlaxcala, 92 p.

Zebrowski, C., 1992, Los suelos volcánicos endurecidos en America Latina: Terra, 10 (numero especial), 15-23.

Zebrowski, C., Quantin, P., Arias, H., Werner, G., 1991, Les "tepetates", récupération et mise en valeur des terres volcanicques indurées au Mexique: Paris, Institut Français de Recherche Scientifique pour le développement en Coopération (ORSTOM), Actualités, 33, 13-18.

Manuscript received: November 4, 2005
Corrected manuscript received: March 7, 2007
Manuscript accepted: May 20, 2007