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Effect of organic farming on soil erosion and soil structure of reclaimed *Tepetates* in Tlaxcala, Mexico

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Zusammenfassung

In den Hochländern Mexicos werden Landschaften, in denen durch Kieselsäure verhärtete, sterile Schichten (Tepetates) als Folge von Bodenerosion frei gelegt wurden, rekultiviert, um neue landwirtschaftliche Nutzflächen zu gewinnen. Um die Nachhaltigkeit der Rekultivierungsmaßnahmen zu verbessern, wurde der Einfluss der organischen Landwirtschaft auf das Bodengefüge und die Bodenerosion von rekultivierten Tepetateflächen im Feldmaßstab unter natürlichen Bedingungen untersucht. Organische Festsubstanz (SOC) stellt den bedeutendsten Faktor dar, der die jährlichen Erosionsraten der rekultivierten Tepetateflächen kontrolliert. Neben einer kurzfristig zunehmenden Gefügestabilität führt die organische Düngung zu einer dichteren Vegetationsdecke, was wiederum die Bodenerosion im Mittel von 3 Jahren nach der Krustenfragmentierung auf 9,9 t ha-1a-1 reduziert, im Vergleich zu 14,6 t ha^{-1} a^{-1} bei Mineraldüngung. In 16 Jahren seit der Rekultivierung unter konventioneller Landbewirtschaftung sanken die Erosionsraten auf 1,1 bis 5,6 t ha^{-1} a^{-1} ab. Die Etablierung der organischen Landwirtschaft steigerte zwar den Gehalt an organischer Substanz der Böden, hatte im Vergleich zu anderen Bewirtschaftungsweisen jedoch keinen nachweisbaren Effekt auf die Bodenerosion. In stärkerem Maße als die organische Landwirtschaft per se, garantieren die regelmäßige Einarbeitung von organischem Material und eine dichte Vegetationsdecke eine Erosionskontrolle und nachhaltige Rekultivierung der Tepetateflächen.

Abstract

In Mexican highlands, vast areas are covered by hardened and sterile volcanic layers (tepetates) that showed up to the surface after erosion of the overlying soil. The rehabilitation of tepetates is a way to increase arable land and combat desertification. In order to develop sustainable rehabilitation strategies, the effect of organic farming on soil erosion and soil structure in reclaimed tepetates was investigated at field scale and under natural condition. In addition to short term structural improvement, organic farming provided higher vegetation cover and increased carbon accumulation rates, resulting in a decrease of soil erosion to 9.9 t ha^{-1} yr^{-1} on average over a period of 3 years after fragmentation compared to 14.6 t ha^{-1} yr^{-1} with conventional management (mineral fertilization). In reclaimed tepetates cultivated for more than 16 years, erosion rates ranged between 1.1 and 5.6 t ha^{-1} yr^{-1}. SOC was the main parameter controlling annual erosion rates and their evolution over time in reclaimed tepetates. More than organic farming per se, it is the regular incorporation of organic material and the development of high vegetation cover which will guarantee erosion control and sustainable rehabilitation of tepetates

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List of abbreviations

ANOVA	Analysis of Variance
ASD	Aggregate Size Distribution
C	Carbon
CT	Conventional Tillage
ER	Enrichment Ratio
FAO	Food and Agriculture Organization
FYM	Farmyard Manure
HSD	Honestly Significant Difference
INEGI	Instituto Nacional de Estadística Geografía e Información
K	Potassium
LD	Laser Diffraction
masl	Meters above sea level
MWD	Mean Weight Diameter
N	Nitrogen
NT	No Tillage
OC	Organic Carbon
OM	Organic matter
P	Phosphorus
PIDS	Polarization Intensity Differential of Scattered light
POM	Particulate Organic Matter
PS	Percolation Stability
PSA	Particle Size Analysis
PSD	Particle Size Distribution
PSw	Weighted Percolation Stability
REVOLSO	Alternative Agriculture for the Sustainable Rehabilitation of Deteriorated Volcanic Soils in Mexico and Chile
RMA	Reduced Major Axis
SOC	Soil Organic Carbon
TDR	Time Domain Reflectometry
TMVB	Trans-Mexican Volcanic Belt
USDA	United State Department of Agriculture

1. Introduction

1.1. Tepetates and erosion

1.1.1. *Tepetates*: hardened volcanic horizons with agriculture potential

1.1.1.1.Definition

Etymologically, the term *tepetate* derives from the Nahuatl *tepetlatl* composed from “tetl” (stone, rock) and “petlatl” (bed, mat), meaning “stone mat”. *Williams* (1972), suggested that instead of true rock, *tepetlatl* was a lexeme labelling an earth material intermediate in consistency between hard consolidated rock and unconsolidated material.

Nowadays, *tepetate* is a vernacular Mexican term referring to a wide range of hardened infertile material (*Etchevers et al.*, 2006), perceived locally as arable or non arable soil, or even as non soil depending on the type of *tepetate* (*Williams*, 1992). The scientific definition of *tepetate* is a hardened layer formed from pyroclastic materials, either exposed to the surface after erosion of the overlying soil, or part of the soil profile at variable depth (*Etchevers et al.*, 2003; *Quantin*, 1992; *Zebrowski*, 1992). This definition excludes other type of hardened horizons such as petrocalcic or petrogypsic (*IUSS*, 2006) which are common in northern and central Mexico under arid climate (*Guerrero et al.*, 1992), and restrains the presence of *tepetates* to volcanic areas.

1.1.1.2.Distribution

In Latin America, indurated soil horizons from volcanic parent materials are found in many countries adjacent to the Pacific shore and under the influence of volcanic activity. Such formations are called by different vernacular names (*talpetate*, *cangahua*, *ñadis*, *sillares*, *trumaos*) but their total extension is only partially known and restricted to countries where they have been studied, such as Nicaragua, Ecuador, Chile, Peru and Mexico (*Etchevers et al.*, 2003; *Zebrowski*, 1992).

In Mexico, hardened volcanic ash soils cover 30,700 km^2, representing 27 % of the Trans-Mexican Volcanic Belt, according to *Zebrowski* et al. (1991), and 37,250 km^2 according to *Guerrero* et al. (1992). In the States of Tlaxcala and Mexico, they are located in piedmont areas between 2250 and 2800 m.a.s.l (*Peña and Zebrowski*, 1992b), and can be found under ustic isomesic soil climate with 6 to 7 humid months (*Miehlich*, 1992).

The state of Tlaxcala is one of the most affected by the presence of *tepetates*. Indurated volcanic ash soils covers 2175 km^2, of which 598 km^2 are superficial *tepetates* (*Werner*, 1988). This area represents approximately 15 % of the State surface, and 25 % of the arable lands.

1.1.1.3.Origin, hardening and conditions of formation

The origin of the hardening, of *tepetates* depends on the nature of the original material and conditions of deposition and can vary, as a consequence, from one location to another. To avoid confusion, we will focus on the hardening of the *tepetates* of Mexico valley and Tlaxcala which are of interest in this study, and which have been more extensively studied.

Quantin et al. (1992) showed that the parent material is a “Toba sediment” which consists of a fine ash, that suffered a strong alteration of its glasses and a certain fragmentation of its minerals. This conclusion would discard the interpretation made initially by *Heine* and *Schönhals* (1973) according to whom the deposit that originated *tepetates* could be a loess. However, for *Poetsch* and *Arikas* (1997), the presence of phytoliths in most Toba sediments they studied in Tlaxcala suggest that the Toba is the result of a re-deposition of volcanic ash. According to *Miehlich* (1992), the formation of hardened horizon is a pedogenic process that occurs in four steps:

1. Deposition of volcanic ashes is required. The T3 series identified by the author in the Sierra Nevada are ashes from the Popocatepetl volcano aged 21000 year BP.
2. Development of an Eutric Ustept rich in clay and opal-A, by weathering of the volcanic ash under ustic isomesic soil climate with 6-7 humid months. This particular climatic condition induces the release of considerable amount of silicon into the soil solution. One part of the silicon released is incorporated into clay minerals and the other part, because of low leaching, is retained and accumulated in the Eutric Ustept horizon of the Toba sediment. Under udic regime, Miehlich assumed that the silicone released in mainly leached to groundwater, whereas under ustic regime with only 4-5 months humid period, the weathering rate is too low and only minute amount of opal-A is accumulated in the soil. Under both soil climate regimes, no *tepetates* are formed. The higher clay content found in the subsoil, in relation to topsoil was not attributed to clay illuviation, but to stronger weathering and clay formation arising from a longer moist period in the subsoil.
3. Erosion of topsoil, typically by gully erosion.

4. The subsoil, enriched in opal-A, is then affected by alternate cycle of humectation and desiccation. This mechanism would cause the compaction and hardening of the *tepetate*.

For other authors, the pedogenic process only consolidate, in a posterior stage, the initial hardening of the horizon which would be the result of the partial alteration of a volcanic ash into a tuff (*Hidalgo et al.*, 1992; *Hidalgo et al.*, 1997; *Quantin*, 1992).

Hidalgo et al. (1992) studied the silicification of *tepetates* and concluded that free silica was present in the matrix and in the clay fraction. They also found free silica in clay coatings, especially in the lower part of the profile, attributed to recent pedogenic processes. However, for these authors, the fact that most part of the silica remains diffuse in the matrix and that its amount is limited shows that the pedogenic silicification does not justify *per se* the cementation of *tepetates*. For *Quantin* (1992) and *Hidalgo* et al.(1992), although the signs and role of pedogenesis is undeniable, the diffuse and discrete presence of silica in the matrix suggests that the silica enrichment occurred after a prior alteration of volcanic glasses at the moment of their deposit, and that the main hardeness of the *tepetates* is inherited from the parent material. This conclusion is supported by recent work of *Poetsch* (2004), whose thin section taken at Tlalpan, Tlaxcala, showed very good preservation of the microlamination of the fabric elements. This observation suggests that the sediment of the *tepetates* must have been more densely packed, in comparison to its corresponding overlying non-indurated horizons, from the outset (*Poetsch*, 2004).

In further studies, *Hidalgo* et al. (1997) confirmed that fragipan-type *tepetate* was formed by pyroclastic material partially altered, as demonstrated by the important amount of residual primary minerals and the predominance of fine silts and clay in the particle size distribution. However, Hidalgo concluded that the arrangement and accumulation of the products of alteration in the matrix porosity (pores and cracks), also observed by several authors (*Poetsch and Arikas*, 1997; *Oleschko et al.*, 1992), contributed to the consolidation of the *tepetate*, but do not constitute a stable cementation. The plasma of the matrix (finer fraction) consists in clay minerals interstratified 1:1/2:1, Fe and Mn oxides and hydroxides, silica gels and opal-A (*Hidalgo et al.*, 1997; *Hidalgo et al.*, 1992). The composition of the plasma would give the fragipan-type *tepetate* its ability to shrinking and swelling (between 5 and 15 % of its volume) and its reversible character: hard when dry and friable when moist. *Oleschko* et al.(1992) studied the micromorphological patterns of clay assemblages in *Tepetates* and concluded that it was not possible to assure that pedogenic silicification was the main process of cementation of *tepetates*.

1.1.1.4.Emergence due to erosion

The emergence of hardened horizon is caused by erosion of the overlying soil. It is widely accepted that this erosion phenomenon was anthropogenic, but there is a controversy on whether the erosion occurred during the pre-hispanic period or after the Spanish conquest (*Quantin and Zebrowski*, 1995).

The study of “Codex” reveals the existence and importance of *tepetates* in the pre-hispanic society (*Williams*, 1972). According to *Williams* (1992), cultivated *tepetates* represented 52 % of arable lands at this period in the Texcoco area. This information proves that: 1) exposed *tepetates* existed at this time, and 2) indigenous people had the knowledge and the necessity to restore and cultivate this kind of material.

Lauer (1979; cited by *Quantin and Zebrowski*, 1995), defined two pre-hispanic periods of accelerated erosion and formation of deep ravine (barrancas) in the Puebla-Tlaxcala region. They are both linked to climate variation (*Heine*, 1976) and to evolution of rural society (*García-Cook*, 1978): increase of rainfall coupled to an increase in population in the case of the first event (around 2100 to 2000 BP) and aridification coupled to a new increase of population and intensification of agriculture in the case of the second (between 1350 and 1000 BP).

Based on palaeolimnological investigation from different lakes in Central Mexico, *Metcalfe* et al (1989) and *O'Hara* et al.(1993) demonstrated evidence of several phase of disturbance and accelerated erosion in the region. The onset of anthropogenic accelerated erosion was induced by the introduction of sedentary maize (*Zea Mays*) agriculture in 3500 yr BP. Subsequent phases of erosion are linked to fluctuation in indigenous population and civilization development. The works of *Metcalfe* et al.(1994) and *O'Hara* et al.(1994) both highlighted the complex relationship between climate, human occupation and soil erosion. They found no evidences that climatic change have had a significant direct impact on erosion rates. Instead, they stressed out that climate changes have a direct impact on human settlement, agriculture and land use, which in turn affect soil erosion.

Werner (1988) and *García-Cook* (1986) also mentioned early human-induced erosion in the State of Tlaxcala due to conversion of forested areas into agricultural lands as a result of dense indigenous population (*García-Cook*, 1978). However, *Aliphat* and *Werner* (1994) attributed the main erosion process that led to the widespread emergence of *tepetates* in the Puebla-Tlaxcala region to the consequences of Spanish colonization and specifically to the results of: i) the abandonment of the traditional intensive agriculture in terraces and the sophisticated irrigation system (*Romero*, 1992; *Pimentel*, 1992), after the decline of indigenous population following Spanish conquest; ii) the introduction of extensive cattle grazing; iii) the introduction of plough and the forsaking of inserted crops (beans, squashes) in maize cropping; iv) the intensive deforestation to supply haciendas with building timber and industries with charcoal and firewood for steam machinery in the 19th century.

In the Patzcuaro Basin, *O'Hara* et al.(1993) did not observed accrued erosion during the Hispanic period and contested the idea that modification of agriculture after Spanish colonization had led to increased erosion rates.

It is important to notice that conditions may vary to a great extent from one region to another depending on local history and environment. Either pre-hispanic, colonial or modern, we can conclude from the mentioned studies that the emergence of *tepetates* is due to a succession of accelerated erosion periods which occurred when the environment of civilization were affected by climatic, demographic, social or political events over the last 4000 years.

1.1.1.5.Properties

Tepetates are almost sterile materials due to strong physical, chemical and biological limitations.

Physical characteristics

The first and major limitation of *tepetates* is its hardness and compaction. In Tlalpan, Tlaxcala, *Werner* (1992) reported *tepetates*' bulk density of 1.47 g cm^{-3} with a total porosity of 45 %. The amount of pores >10 μm is low (~10 %), and porosity is often disconnected. As a consequence, infiltration rates are almost nil (4.2 10^{-4} cm s^{-1}). The hardness of *tepetate* may vary according to the location, presence of $CaCO_3$ and time of exposure to the surface. *Miehlich* (1991) reported penetration resistance of 366 kg cm^{-2} on a *tepetate* t3 in the Sierra Nevada, and *Peña* et al. (1992) values of up to 153 kg cm^{-2}.

Such physical properties reduce or avoid roots penetration and water infiltration. Once *tepetates* show up on the surface, no vegetation develops, unless the area is stabilized and protected from runoff.

Chemical characteristics

As mentioned before, the parent material of *tepetates* is rich in volcanic glasses and plagioclase highly susceptible to weathering. *Tepetates* are hence rich in bases with a prevalence of calcium, magnesium and specially potassium (*Etchevers et al.*, 1992; *Etchevers and Brito*, 1997). The cation exchange capacity is relatively high, ranging from 20 to 40 cmol kg^{-1} of fine earth, due to the abundance of 2:1 clays. The percentage of base saturation is high and pH is slightly alkaline, ranging from 7 to 8. *Etchevers* et al (1992) showed that the most limiting factors for *tepetates* fertility were the extremely low content of soluble phosphorus (<3 mg kg^{-1}), due to the absence of phosphate minerals in the parent material and nitrogen (0.04-0.07 %). Part of the N deficiency is caused by the lack of organic carbon (~0.1 %), which indicates that *tepetates* layers have never been disturbed by any biological activities.

Biological characteristics

The lack of carbon in *tepetates* entails very low biological activity. An inventory of the micro flora in *tepetates* carried out in Tlalpan by *Alvarez* et al. (1992) showed limited microbial population in natural (not fragmented) *tepetate* (2.2 10^4 g^{-1} bacteria, 11.8 10^3 g^{-1} actinomycetes and 6.6 10^1 g^{-1} fungi), compared to adjacent cultivated soil (4.6 10^7 g^{-1}, 2.1 10^5 g^{-1}, 3.9 10^3 g^{-1} respectively). Once ripped off, the increase of microbial population in *tepetates* is enhanced by organic matter incorporation, especially green manure (*Alvarez et al.*, 2000; *Alvarez et al.*, 1992).

1.1.1.6.Tepetate rehabilitation

The rehabilitation of *tepetates* for agriculture is a well known practice since pre-hispanic times (*Williams*, 1972; *Pimentel*, 1992). In the last few decades, the advent of heavy machinery to break up the hardened layer promoted the expansion of such practice. The first experiences were carried out in the State of Mexico to reforest and restore the Texcoco lake basin, greatly affected by erosion and infilling (*Pimentel*, 1992; *Llerena and Sanchez*, 1992). The technique was then extended to other areas to confront the lack of arable land and to restore deteriorated areas (*Llerena and Sanchez*, 1992; *Pimentel*, 1992; *Werner*, 1992; *Arias*, 1992).

The rehabilitation process of *tepetates* is a combination of the fragmentation and the subsequent management practices.

The fragmentation consists of breaking up and loosening the hardened layer by subsoiling, deep ploughing and harrowing. This operation modifies radically the physical properties of the *tepetate*, turning the hardened and cohesive *tepetate* into a fragmented and porous material within a few hours (Table 1).

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

	Bulk density (g cm^{-3})	Total pore volume	Volume of macro pores (>10 µm)
Before fragmentation	1.47	45 %	12 %
After fragmentation	1.15 to 1.24	55 %	20 %

Those physical changes create the necessary conditions to air and water transfer in soil, to water storage and to root development. However, the fertility of the newly-formed material is still reduced because of nutrimental deficiencies (*Etchevers et al.*, 1992).

Hence, the management practices applied after fragmentation aims at turning the almost sterile material into a productive soil, by improving the physical, chemical and biological properties of the soil to ensure a sustainable crop production.

Effect of fragmentation and management on erodibility

Previous studies of erosion on *tepetates* and under natural conditions in the states of Tlaxcala (*Baumann and Werner*, 1997a; *Fechter-Escamilla et al.*, 1997a) and Mexico (*Prat et al.*, 1997a) clearly show that bare *tepetates* produce high runoff rates (up to 90 %), but moderate soil loss *in situ* due to strong cohesive properties. Once fragmented, but not cultivated, soil loss increases considerably, whereas runoff rate decreases as a result of a better infiltration. Under cultivation, runoff and erosion rates decrease to tolerable levels.

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).

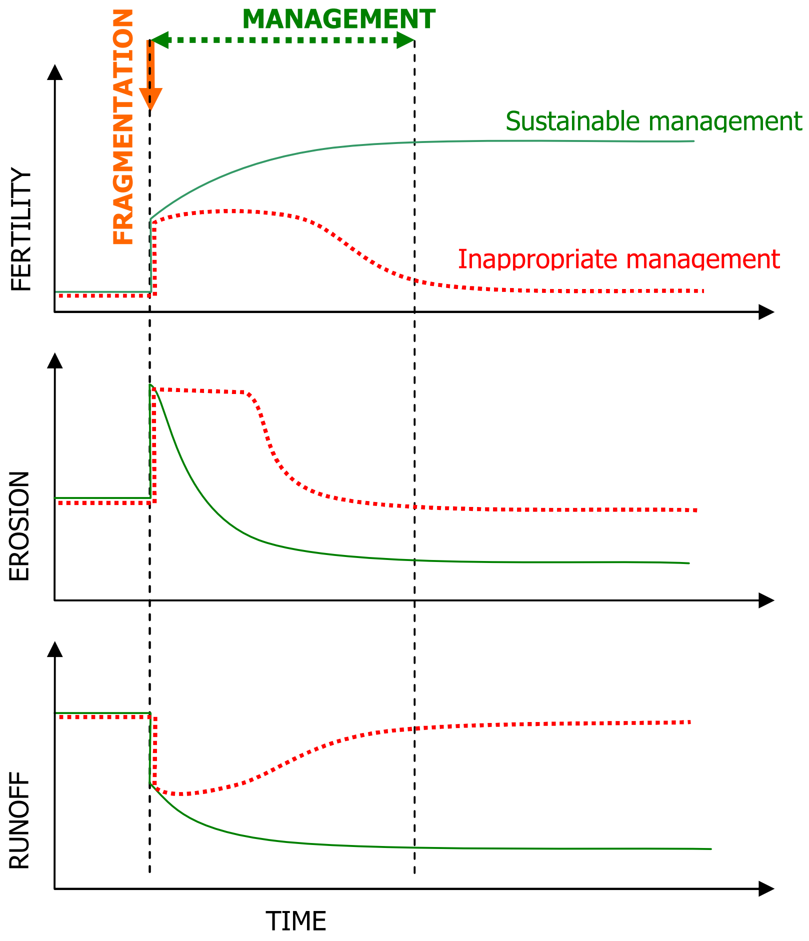

Figure 1: Conceptual evolution of fertility, runoff and erosion during the rehabilitation process under two extreme scenarios.

The consequences of fragmentation on fertility, runoff and erosion are immediate. The management applied after the fragmentation influences the evolution of runoff, erosion and fertility over time. In the case of a sustainable management, the improvement of physical properties ensures fast 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.

However, if the management is inappropriate, or if the fragmented plot is abandoned, the benefit of fragmentation on runoff will rapidly decrease because of sealing and compaction. High erosion rates induced by fragmentation will remove the loosened layer within a few years, until the hardened horizon emerges again. In extreme cases, inappropriate management lead to a return to the initial natural *tepetate* situation. Such scenarios have been observed in

Tlaxcala with several rehabilitation programs, because of the lack of clear rehabilitation strategy and guidance to farmers.

Although most tepetate rehabilitations are more likely to be between the “best case” and “worst case” scenarios, soil conservation and erosion control are always a critical issue to achieve a successful, sustainable and profitable rehabilitation of tepetates to agriculture. Knowledge of the effects of cultivation practices on soil erosion is thus a key factor to develop suitable rehabilitation strategies.

1.1.2. Structure, erosion and organic farming

Soil structure can be defined as the arrangement of particles and pores in soils (*Oades*, 1993). It refers to the size, shape and arrangement of solids and voids, the continuity of pores and voids, their capacity to retain and transmit fluids, organic and inorganic substances, and to the ability of soil to support root growth and development (*Lal*, 1991). It can be evaluated by determining the extent of aggregation, the stability of the aggregates, and the nature of the pore space (*Jury and Horton*, 2004). Soil structure and its stability mediates many biological (*Oades*, 1993) and physical processes in soils, such as porosity and infiltration (*Kutilek*, 2004), and is hence a determinant factor for water availability to plants and erosion susceptibility (*Six et al.*, 2000a; *Lin et al.*, 2005).

In agriculture, the soil physical properties after optimization of the chemical soil conditions are more and more agreed to be the limiting factor of the productivity because the water, air and heat regime of the soils is governed by them (*Schneider and Schroder*, 1995). Soil structure development and improvement is then a focal point to implement sustainable agriculture systems and restore degraded lands (*Lal*, 1991).

Structure and erosion

The relationship between soil structure and erosion has been identified and extensively studied from the beginning of the century (e.g works of *Yoder*, 1936). Structural stability, measured by a wide range of techniques (*Le Bissonnais*, 1996; *Diaz-Zorita et al.*, 2002), governs aggregate breakdown mechanisms and particle detachment, and is an indicator widely used to predict soil erodibility (e.g.: *Le Bissonnais and Arrouays*, 1997; *Mbagwu and Auerswald*, 1999; *Barthes and Roose*, 2002).

Organic carbon and soil structure

SOM is the focal point of soil structure dynamic and contribute, directly or indirectly, to aggregate formation and stabilization. At microaggregate scale, primary particles are bound together by persistent binding agents such as humified organic matter, polyvalent metal cation complexes, oxides and highly disordered aluminosilicates (*Tisdall and Oades*, 1982). At macroaggregate scale, POM acts as a nucleus for macroaggregates formation (*Puget et al.*, 2000). When fresh OM is incorporated into the soil matrix, it is colonized by microbial decomposers. The by-products of the microbial activity mechanically bind soil particles that surround the organic resource (*Tisdall et al.*, 1997), whereas exudates and polysaccharides stick them to cells of bacteria and fungi (*Oades*, 1993). Microaggregates are then formed within macroaggregates (*Oades*, 1984) and are stabilized by more recalcitrant organic carbon compounds (*Oades*, 1984; *Degens*, 1997).

The effect of organic matter on soil structure is well documented (e.g.*Becher*, 1996; *Six et al.*, 2000b). Recently, several reviews highlighted the role and dynamic of carbon in soils: Mechanisms of aggregation in soils and its effect on soil structure have been reviewed by *Six* et al. (2004); The impact of management on soil aggregation and soil structure have been reviewed by *Bronick* and *Lal* (2005); and the mechanisms of aggregate dynamic and carbon sequestration has been reviewed by *Blanco-Canqui* and *Lal* (2004).

Structure and organic management

Soil management (agricultural practices) can affect soil structure in many ways, depending on i) the type and amount of fertilization applied, ii) the management of crop residues, iii) the choice of crops and crops rotation, iv), the frequency or intensity of tillage.

Promoting organic matter management is a fundamental principle of soil conservation strategies in many part of the world (e.g. *Roose and Barthes*, 2001; *Morgan*, 2005). However, the literature related to the effect of organic management on soil physical properties in reclaimed volcanic ash soils are differing:

i. In Mexico, *Acebedo* et al (2001) studied the effect of manure and plant species on the formation and stability of aggregates in fragmented *tepetates* under greenhouse conditions. They concluded that the application of manure and presence of plants did not increase the amount of water-stable aggregates and that roots activity and development had greater effect on structure than application of manure. Similar results were obtained by Velazquez et al. (2001), who concluded that in greenhouse conditions plants increased organic matter content which in turn promoted the aggregation and structure of fragmented *tepetates*.

ii. *Alvarez* et al.(2000) showed that incorporation of green manure and plant residues to reclaimed *tepetates* enhanced microbiological activity and that previous incorporation of cattle manure favoured the mineralization of crop residues. They concluded that incorporation of organic materials to reclaimed *tepetates* contributes to the rehabilitation of *tepetates* thanks to its beneficial effects on microbial activity. However, the authors did not link their results to quantitative measurements of soil physical parameters.

iii. In Ecuador, *Podwojewski* and *Germain* (2005) found that incorporation of organic material did not improve significantly the structural stability of reclaimed cangahuas (hardened volcanic ashes similar to *tepetates*), after 4 years of cultivation, even at high incorporation rates (up to 80 t/ha of fresh cattle manure).

iv. *Prat* et al. (1997a) found that crop association (maize + broad bean) reduced erosion rates in comparison to monoculture (maize), but did not find any significant differences in erosion rates between farmyard manure application (40 t ha^{-1} the first year and 20 t ha^{-1} the following years) and mineral fertilization, suggesting that vegetation cover, more than organic farming, influence erosion rates.

v. It is often considered that SOC affect soil structure when SOC concentration amounts more than 2 % (*Greenland et al.*, 1975). In *tepetates* under maize mono-cropping, SOC content hardly amount more than 1 % (*Baez et al.*, 2002). In reclaimed *tepetates* under reduced tillage and frequent farmyard manure application, SOC can reach 2 % after 80 years of cultivation (*Baez et al.*, 2002). Only in greenhouse conditions with intensive incorporation of organic material can SOC reach approximately 4 % (*Baez et al.*, 2002). There is thus a question whether organic matter can affect soil structure in soils with strong OC deficiencies such as tepetates.

In reclaimed hardened volcanic ash soils, the use of organic amendments to improve soil fertility after fragmentation has been repeatedly recommended (*Zebrowski et al.*, 1991; *Pimentel*, 1992; *Arias*, 1992; *Marquez et al.*, 1992; *Etchevers and Brito*, 1997). However, there is no consensus about the effect of organic amendments on soil structure and erodibility in reclaimed volcanic ash soils. Besides, although previous studies (*Baumann and Werner*, 1997a; *Fechter-Escamilla et al.*, 1997a; *Prat et al.*, 1997a) outlined the effect

of fragmentation and cultivation practices on erosion, there is still too little data available on erosion and runoff rates in reclaimed tepetates at farmer plot scale and under natural climatic conditions, and no information on the evolution of erosion rates during the rehabilitation process and its relationship with soil structure.

Therefore, there is a need to increase the knowledge on how and to what extent organic farming can affect soil structure and soil erosion and be a sustainable alternative to reclaim deteriorated volcanic ash soils.

1.2. Objectives

The aim of this research is to ***evaluate the effect of organic management on soil structure and soil erosion in reclaimed tepetates***, at field scale and under natural conditions. It is part of a pluridisciplinary project whose overall objective is to develop alternative technologies to reclaim deteriorated volcanic ash soils.

The specific objectives are:

i. To assess and quantify erosion rates in *tepetates* in the short and medium term during the rehabilitation process

ii. To evaluate the effect of organic management on soil structure and soil erosion rates, compared to other type of managements

iii. To assess the role and dynamic of organic carbon in reclaim *tepetates* at different stages of the rehabilitation

iv. To determine the main factors involved in the erodibility of reclaimed *tepetates*, in order to establish priorities in soil conservation strategies.

2. Tlaxcala: a state affected by *tepetates*

2.1. Physiographic overview

The State of Tlaxcala is located in the central Mexican highlands between 97°37’07’’ and 98°42’51’’ W and 19°05’43’’ and 19°44’07’’ N. It belongs to the Trans-Mexican Volcanic Belt (TMVB) which stretches from the Volcano of Colima on the Pacific shore to the Orizaba peak on the Atlantic side along the 19°N parallel. It is the region of highest volcanic influence in the country.

With an extension of 3991 km^2 (*INEGI*, 2005b), Tlaxcala is the smallest State of the Mexican Republic and represents 0.2 % of the country’s area (1 959 248 km^2). The average elevation in the State is 2230 m.a.s.l., ranging from 2100 m.a.s.l. in the Atoyac river alluvial plain in to 4461 m.a.s.l. at the summit of La Malinche volcano.

The southern part of the State is dominated by La Malinche Volcano. In the North East, the Taxco Sierra forms a natural boundary with the State of Puebla. The Western part of the State is occupied by the piedmont of the Northern part of the Sierra Nevada and the Tlaxcala block (“Bloque de Tlaxcala”). This hilly region is cut by deep canyons (“barrancas”) and is greatly affected by erosion. In the center part of the State, following a Northwest to Southeast direction, the plains of Calpulalpan, Apizaco and Huamantla lie at approximately 2500 masl.

2.2. Climate

94 % of the State of Tlaxcala is under temperate sub-humid climate (*INEGI*, 2006). Annual precipitations range from 600 to 1200 mm with winter precipitations inferior to 5 % of the annual amount. However, climate in Tlaxcala has great spatial variability due to orography (*Conde et al.*, 2006).

Figure 2 presents meteorological records from Hueyotlipan (19°28’10’’N and 98°20’53’’), located at 4 km from Tlalpan experimental site. Statistics are based on records from 1961 to 1998. In this area, climate is temperate sub-humid. Mean annual precipitation is 772 mm distributed during rainfall season from May to October (90 % of the annual precipitation). Rainfalls are mainly continental, but there is an oceanic influence during the hurricanes season in September-October. Mean annual temperature is 13.9°C, ranging from 10.9°C in January to 15°C in May. Frost risk period stretches from November to February.

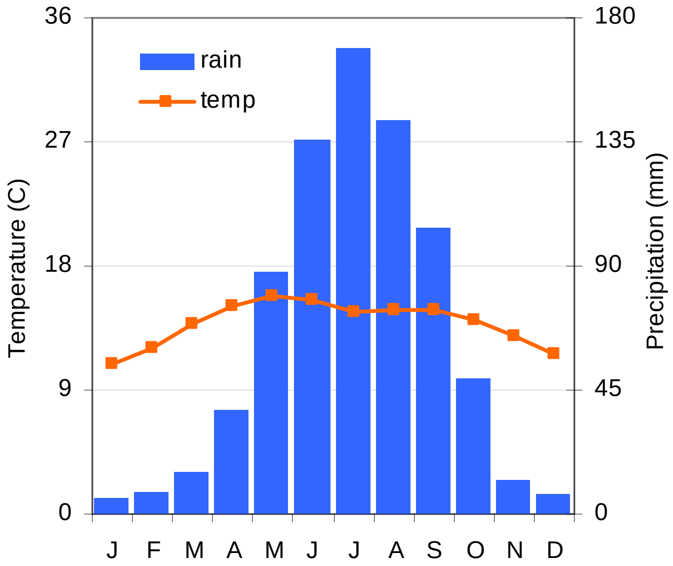

Figure 2: Ombrothermic diagram of Hueyotlipan meteorological station. 1961-1998

Most part of the State is rainfed agriculture, and the climatic regime imposes strong constraint to agriculture in the area:

- The time window suitable for crop cycle is limited between the beginning of the rainfall season and the beginning of frost-risk period. This is a major limitation for maize cropping in the area (*Eakin*, 2000; *Ramirez and Volke Haller*, 1999);
- The establishment of winter crop or cover crop before the beginning of the rainfall season is not possible in rainfed agriculture areas due to severe water deficit during winter months.

2.3. Geology

The geology, as well as the geomorphology of the State of Tlaxcala is strongly influenced by quaternary volcanic activity. The oldest stratigraphic units are tertiary sedimentary rocks formed under lacustrine environment. They form the basis of the Tlaxcala and Huamantla blocks. The basaltic volcanic activity started in the late tertiary but reached its highest intensity during the quaternary (*Erffa et al.*, 1977). La Malinche and Iztaccihuatl are andesitic-dacitic stratovolcanoes that greatly influenced the study area. They were erected during Pleistocene although recent activity has been registered till the Holocene in La Malinche (*Castro-Govea et al.*, 2001). Many smaller quaternary volcanic structures (mainly monogenic cones) had local influence in the area. During this period and till the Holocene several layers of tuffs and volcanic ashes were deposited over the whole area. The most recent arise from Popocatepetl active volcano. Those deposits were identified by *Heine* and *Schönhals* (1973) as “Toba” sediment. They are the main parent material of soils in the State of Tlaxcala and are associated with the presence of *tepetates* (*Werner*, 1988).

2.4. Soils

Soils in the Puebla-Tlaxcala basin have been extensively studied in the 70 and 80’s decades in the framework of the Mexico-project of the German Research Foundation (DGF). The soil map of Tlaxcala at 1:100 000 was published by *Werner* (1988) based on the *FAO-UNESCO* classification (1974). Another soil map is available from INEGI at 1:250 000 based on the FAO-UNESCO classification (1968 with 1970 supplement). Although both maps differ from one another, characteristic soil units can be grouped into three categories according to the type of parent material and the altitude.

i. Soils formed from volcanic ashes over 2800 m.a.s.l. (> 1000 mm annual precipitation)

These conditions are found in the slopes of La Malinche (south), in the Taxco Sierra (Northeast) and in the eastern hillside of the Sierra Nevada (west). In those areas, andosolization (volcanic ash soil formation) process occurs. Depending on the age of the ashes and the degree of andosolization we find Andosol (mostly vitric) or Regosol (mostly tephric) (*Werner*, 1988, , 1976b).

ii. Soils formed from volcanic ashes and Toba sediment between 2250 and 2800 masl (6 months dry season)

These conditions are propitious to the formation of hardened volcanic horizons (*Miehlich*, 1992) and are found in approximately 54 % of the State. They are usually covered by Cambisols with vertic or chromic properties (*Werner*, 1988). In high valleys and plains (northwest), those soils were classified as Phaeozems by INEGI (2006), probably because the hardened volcanic horizon was assimilated to a petrogypsic horizon. In steeper areas, such as the piedmont of Sierra Nevada, Tlaxcala block, Taxco Sierra and the basement of La Malinche, human activities induced severe erosion and denudation of the cambisol overlying the hardened layer, causing the emergence of *tepetates*. Bare *tepetates* cover approximately 15 % of the State surface.

iii. Other soils

Fluvisols and more rarely Gleysols are found in lowlands and alluvial cones on the eastern and western side of la Malinche. Regosols are found in the arid west end of the State in the Huamantla valley.

2.5. Soil use and agriculture

2.5.1. Agriculture

Total arable area represents 60 % of the State surface (*INEGI*, 2006). 89 % of arable area is rainfed agriculture, and only 11 % is irrigated. Irrigated areas are mainly located in the Atoyac and Huamantla valleys. No irrigation is available in the areas most susceptible to erosion (piedmont and sierras).

Three species represents 85 % of the cultivated area: i) Maize (*Zea mays*, 54 % of the cultivated area), the basis of Mexican diet; ii) Oat (*Hordeum vulgare*, 22 %), for brewery industry, grown mainly in Calpulalpan area; iii) Wheat (*Triticum aestivum*, 15 %). Other important crops are beans (*Phaseolus vulgaris*, 3 %), broad bean (*Vicia faba*. 1 %) and alfalfa (*Medicago sativa*, 1 %) in irrigated lowlands.

Livestock production is dominated (in number of animals) by porcine, followed by ovine and caprine (more than 233,000 animals all together). They are traditionally bred by itinerant grazing by small farmers. Cattle overgrazing or uncontrolled goat and sheep grazing is one of the main causes of gully formation.

2.5.2. Forest

Forest areas are mainly located over 2800 masl in La Malinche, Taxco sierra and Sierra Nevada in the Southern, Northern and Western part of the State respectively. They cover 14.5 % of the State area.

2.6. Sociodemographic context

Population in Tlaxcala exceeded one million inhabitants in the last 2005 census (*INEGI*, 2005a). In the last 30 years, population grew by 20,000 inhabitants per year. The increase in population occurred almost exclusively in urban areas, whereas rural population remained constant from the beginning of the century (Figure 2)

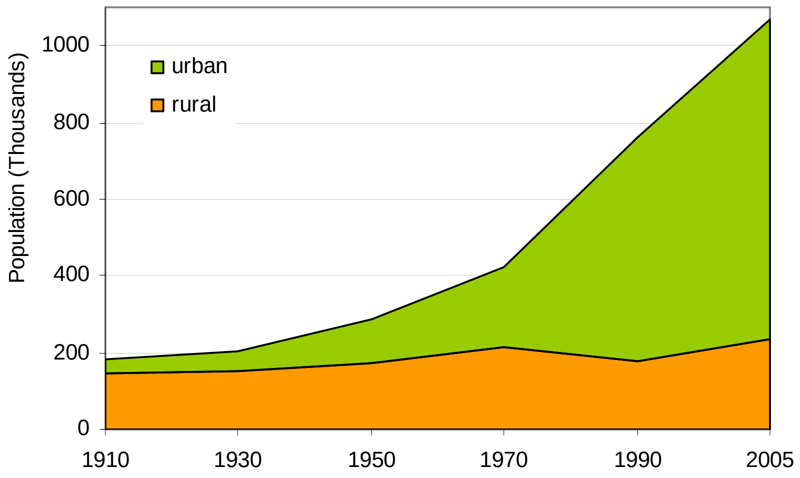

Figure 3: Demographic growth and distribution between rural and urban population in the State of Tlaxcala from 1910 to 2005. Sources: INEGI, censos de población y vivienda 1930 to 2000 and Conteos de Población y Vivienda 1995 and 2005.

Tlaxcala's population represents approximately 1 % of the whole country's population, but with 267 inhabitants per km^2, Tlaxcala is the third most densely populated State (excluding the Federal District) in Mexico (*INEGI*, 2005b, 2005a). Since the beginning of the century, there has been high pressure on natural resources to increase arable lands for food production. This phenomenon led to the deforestation of La Malinche volcano with dramatic consequences on soil erosion (*Werner*, 1976a).

Nowadays, *tepetates* are the only arable land reserve in the State of Tlaxcala. The rehabilitation of all *tepetates* areas could potentially increase the arable land surface by 25 %.

2.6.1. Economy and employment

The contribution of agriculture, forestry and fishery to Tlaxcala's GNP decreased from 8.5 % to 3.8 % between 1993 and 2004 (*INEGI*, 2004). The economy of the State is nowadays mainly supported by tertiary (60.5 %) and secondary (35.6 %) activities.

In rural areas, agriculture is a still a major source of employment. In the district of Hueyotlipan to which belongs Santiago Tlalpan, 41 % of active population is working in agriculture, cattle grazing and forestry (*INEGI*, 2000). Considering the 12 districts were approximately 80 % of *tepetates* areas are located (based on the map by *Werner*, 1988), 27 % of the active population is dedicated to this sector. A significant part of the rural population is, hence, affected by *tepetates*.

2.6.2. Migration

Besides the creation of three industrial parks during the last decade, work expectancy in the state is low and, as a consequence, migration is high. According to official *INEGI* last census (2005a), 3.5 % of the population (persons who were living in the State in 2000) migrated to more active economical poles such as Puebla (26 % of migrants) and Mexico city area (35 %). Migration to the United States officially represents 2.8 % of the migrants, but this value is probably underestimated and does not reflect the magnitude of migration from Hueyotlipan district to the United States (*Charbonnier*, 2004).

2.6.3. Farm unit structure

In Tlalpan area, farms unit are in average 5 ha (*Lepigeon*, 1994). Such surfaces are too small to achieve economical sustain for farmers and their family. In 1994, annual income from agriculture was inferior to the minimum salary for 75 % of the farmers. In Tlalpan, likewise most part of the TMVB (*Prat et al.*, 1997b), all farmers have secondary activities and incomes (construction, plumbing, music, etc. ..) (*Lepigeon*, 1994).

The rehabilitation of unproductive *tepetate* areas is a way to extend arable surface of small farmers, substantially increase their incomes, and could represent a viable alternative to migration.

3. Materials and methods

3.1. Tlalpan experimental site

Santiago Tlalpan is situated at 19º28'N, 98º18'W and at 2600 masl. It is located 25 km north from Tlaxcala city, on the edge of the Tlaxcala block and belongs to Hueyotlipan District.

The site was settled in two stages: in 1986, a large area of bare *tepetate*, adjacent to a deep ravine and with 15 % natural slope, was fragmented and 6 terraces were formed with an average slope of 3 % (A, B, C, D, E, and F); then in 2002, at the beginning of REVOLSO project, two smaller plots were established on the upper part of the ravine (R1 and R2). All plots have the same slope, and were formed from the same tepetate formation (t3). Erosion measurement system was installed in 5 plots (R1, R2, C, D, E).

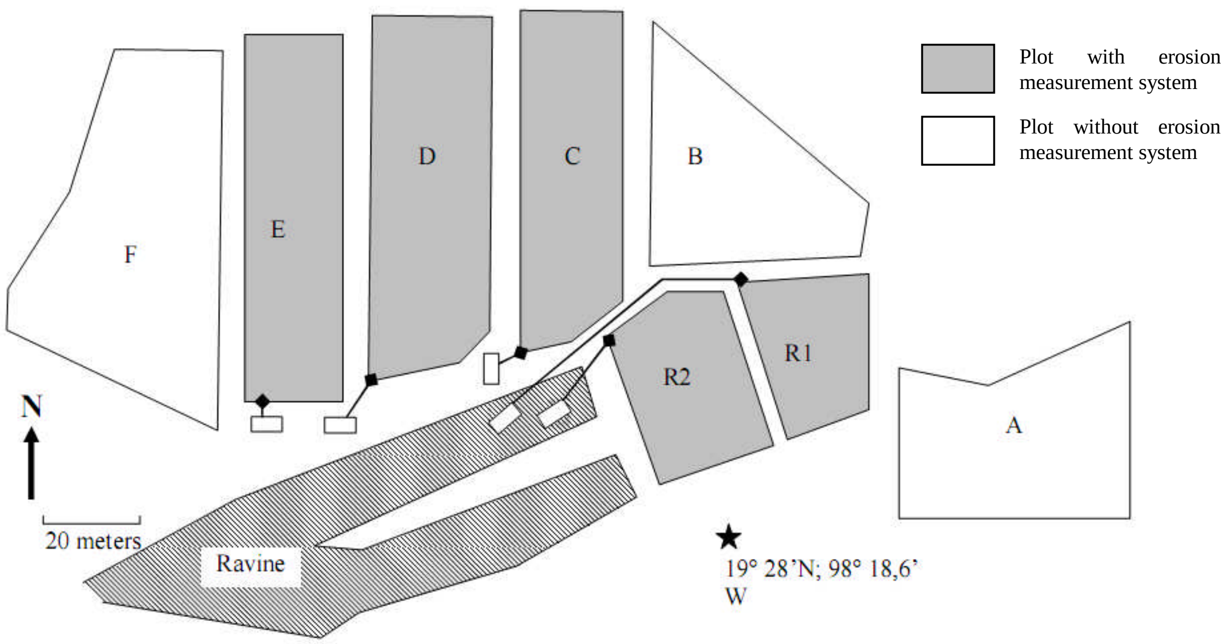

Figure 4: Map of Tlalpan experimental site and main characteristics of the plots.

3.2. Managements

Three managements have been evaluated: 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 mineral fertilizers, and use of phyto-protection products when necessary. The crop residues (straw, stalks) are sold or used for cattle pasture, in spite of its poor nutrimental value. Fertilization inputs are self-moderated because of economic restrictions. The incorporation of organic matter is low and is limited to the decomposition of roots and a small part of the crop residues, since cattle usually graze the land after the harvest.

- *Improved management* is based on conventional management without restrictions of inputs (all inputs required by the crop are applied), and use of associated crop (legumes) when possible. All crop residues are incorporated to the soil, either whole or crushed. 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 minimum time and work requirement.

- *Organic management* involves the same soil cultivation practices than the other management systems, but with use of organic fertilization only (manure or compost) and associated crop when possible. Crop residues are composted with additional farm manure and then reincorporated to the soil. This management requires more time and labour, but provides a higher level of incorporation of organic matter.

The plots fragmented in 1986 (A, B, C, D, E, F) were cultivated until 2002 under conventional management. The main crops were maize and wheat, without any external application of organic matter.

Table 2: Characteristics of Tlalpan experimental plots

Plot	Management	Year of fragmentation	Label	Surface (m^2)	Erosion measurement system
A	Improved	1986		1170	No
B	Conventional	1986		1070	No
C	Improved	1986	86-I	1630	Yes
D	Organic	1986	86-O	2020	Yes
E	Conventional	1986	86-C	1340	Yes
F	Organic	1986		2200	No
R1	Conventional	2002	02-C	580	Yes
R2	Organic	2002	02-O	760	Yes

3.3. Crops and fertilization

Crops and fertilization applied from 2002 to 2005 are presented in table 3 and 4.

Table 3 : Crops cultivated from 2002 to 2005 at Tlalpan experimental site during the investigation.

Management	2002	2003	2004	2005
Improved	Broad bean	Oat + vetch	Maize + bean	Wheat
Conventional	Broad bean	Oat	Maize + bean	Wheat
Organic	Broad bean	Oat + vetch	Maize + bean	Wheat

Broad bean: *Vicia fava*; Vetch: *Vicia sativa*; Maize: *Zea mays*; Oat: *Hordeum vulgare;* Wheat: *Triticum aestivum*; Bean: *Phaseolus vulgaris.*

Table 4: Fertilization applied from 2002 to 2005 at Tlalpan experimental site during the investigation.

		Fertilization ($N-P_2O_5-K_2O$, kg ha^{-1})			
Plot	Management	2002	2003	2004	2005
A	Improved	60-100-34	23-60-00	98-41-00	82-23-00
B	Conventional	23-00-00	23-00-00	81-00-00	62-23-00
C	Improved	60-100-34	23-60-00	98-41-00	82-23-00
D	Organic	6.8 t ha^{-1} (C)	3 t ha^{-1} (FYM)	1.9 t ha^{-1} (C)	3 t ha^{-1} (C)
E	Conventional	23-00-00	23-00-00	81-00-00	62-23-00
F	Organic	6.8 t ha^{-1} (C)	3 t ha^{-1} (FYM)	1.9 t ha^{-1} (C)	3 t ha^{-1} (C)
R1	Conventional	23-46-00	23-00-00	81-00-00	62-23-00
R2	Organic	6.3 t ha^{-1} (FYM) + crop incorporation*	3 t ha^{-1} (FYM)	2.6 t ha^{-1} (C)	4.2 t ha^{-1} (C)

FYM: Farmyard manure (dry matter); C: compost (dry matter); Vetch: *Vicia sativa*.
* the broad bean was not harvested and the whole biomass was incorporated

3.4. Methods

3.4.1. Soil loss and runoff

The study has been performed on large farmers' fields and under natural climatic conditions. The initial erosion measurement system was designed by *Fechter-Escamilla* et al. (1995) and has been described by *Haulon* et al. (2003). It consists of a one-foot H-flume (*Hudson*, 1993) placed at the outlet of the field, and equipped with a water level recorder (OTT Thalimedes® shaft encoder) set up at one minute time-step interval. Water level (mm) was converted into flow discharge (m^3 min^{-1}) based on conversion table given in the Field Manual for Research in Agricultural Hydrology (*Brakensiek et al.*, 1979). After passing through the flume, runoff discharge is channelled to a high capacity rotating tank (2 to 4.5 m^3) set on 4 electronic weight cells. In case the volume of runoff exceeds the capacity of the tanks, a hose connected to a plastic reservoir collects an aliquot of the overflow. The original system (*Fechter-Escamilla et al.*, 1995) was developed to calculate soil loss according to the following formula:

$$\text{Soil Weight}_{\text{in the tank}} = \frac{(W_{\text{tank}} - V_{\text{tank}})\delta_{\text{soil}}}{\delta_{\text{soil}} - \delta_{\text{water}}} \qquad (1)$$

With δ: density, W: weight of the slurry in the tank and V: volume of the slurry in the tank

However, in practice, weight and volume measurement are not precise enough to obtain a reliable calculation of soil loss. Indeed, the average soil weight collected in the tanks ranged from 10 to 20 kg. Considering that the precision of the weight cells is approximately 1%, the standard error for a full tank (2 and 4.5 m^3) is 20 to 45 kg, and the calculation is therefore strongly biased. As a consequence, this method was not used. Instead, soil loss was calculated using a method of sediment concentration calculation as follows:

i. The heaviest fraction of soil particles tend to settle rapidly in accordance with Stoke's law. By the time samples are collected, the day after the storm event, the heaviest particles have settled at the bottom of the tank, and it is not possible to homogenize the whole slurry and maintain the heaviest particles in suspension to take representative samples. Therefore, the "suspended" and "settled" sediments were treated separately.

ii. The "suspended" sediment fraction was homogenized by manual agitation during one minute without disturbing the "settled" sediment fraction, and 1 dm^3 sample was taken immediately at 30 to 50 cm depth. The suspended fraction was then emptied by rotation of the tank. The settled fraction was then collected, its volume was measured and 1 dm^3 sample was taken. The sampling method was tested to evaluate the reproducibility of the protocol. Results showed no significant differences in sediment concentration between position and depth of sampling.

iii. In case the volume of runoff exceeded the capacity of the tank, a sample was collected from the plastic reservoir.

iv. The water level in the flume was recorded by OTT Thalimedes® shaft encoder set up at one minute time step interval. Water level (mm) was converted into flow discharge (m^3 min^{-1}) based on conversion table given in the Field Manual for Research in Agricultural Hydrology (*Brakensiek et al.*, 1979).

v. Samples were oven-dried in the laboratory and their sediment concentration was determined.

vi. Total soil loss was calculated as follow:

$$W_{total} = W_{suspended} + W_{setted} + W_{out\ tank} \tag{2}$$

Soil weight (W) in each fraction equals the volume (V) of that fraction multiply by its sediment concentration, with:

$$V_{suspended} = V_{in\ tank} - V_{settled} \tag{3}$$

$$V_{out\ tank} = V_{total\ at\ field\ outlet} - V_{in\ tank} \tag{4}$$

Statistical analysis

Two issues must be considered:

i. The plots reclaimed in 1986 are larger than the plots reclaimed in 2002. On one hand, plot length could increase flow velocity and particle detachments and as a result increase soil erosion. On the other hand, larger plots may present more depositional areas and, hence, reduce net erosion. Given our experimental design it is not possible to statistically control possible size effect, and we will assume the effect of plot size is negligible.

ii. Given the cost of the erosion measurement system and the lack of *tepetates* available for rehabilitation on the same experimental site (comparison between treatment should be done only under same climatic conditions), no replicates are available. Each combination of age of rehabilitation and management is only represented once.

To compare soil loss and water losses between plots, analysis of variance was performed considering all erosive events[1] within a year. Since soil losses are not normally distributed, the base-10 logarithm of individual event soil loss value (E) was used. Since some events did not produce soil loss (E) in all plots, the ANOVA was performed on $LOG_{10}(E+1)$.

3.4.2. Rain erosivity

Rainfall was recorded by mechanical daily recording rain gauge (pluviograph) during the rainfall season from 2002 to 2005. In addition, a meteorological station was installed in 2003, and precipitations were recorded with a tipping bucket rain gauge at a constant time step of 1 minute. However, the precision of the device failed, and in 2004 a Hobo® event recorder connected to a tipping-bucket rain gauge was installed, allowing a precise calculation of rainfall intensity and kinetic energy. The combination of recording devices ensures continuity of records in case of failure.

Rain kinetic energy was calculated using the equation proposed by *van Dijk* et al.(2002):

$$Ek=28.3[1-0.52^{(-0.042I)}] \qquad (5)$$

Where Ek is the kinetic energy in J m^{-2} mm^{-1} for a time lap of constant intensity.

The total rainfall or storm kinetic energy is the sum of the product of each time lap kinetic energy and the rain depth during this time lap:

[1] We took into account all events that produced soil loss in at least one plot.

$$E = \sum_{1}^{n} Ek_t \cdot R_t \qquad (6)$$

E is the total rainfall energy

Ek_t is the kinetic energy of a constant intensity time lap *t*

R_t is the rain depth during a constant intensity time lap *t*

n is the number of constant intensity time laps during the rainfall

The annual kinetic energy is the sum of all rainfall event's kinetic energy.

The *van Dijk* formula was compared to the equation proposed by *Renard* et al. (1997) for the RUSLE which is adapted from earlier formulation by *Wischmeier* and *Smith* (1958):

$$Ek = 11.9 + 8.73 \log_{10} I \qquad \text{if } I \leq 76 \text{ mm h}^{-1} \qquad (7)$$

$$Ek = 28.3 \qquad \text{if } I > 76 \text{ mm h}^{-1} \qquad (8)$$

3.4.3. Vegetation cover

In 2002 and 2003, vegetation cover was measured by a simple version of quadrat sighting frame (*Stocking*, 1994), consisting of a board perforated with fifty 2 mm-diameter holes at 2 cm interval. The amount of bare ground visible through the hole was quantified from 0 (bare soil) to 5 (totally covered by vegetation). The nature of the cover was also qualified (main crop, associated crop, residues, weeds). However, difficulties with crop height, representativity in case of raw crops and observers variability, also reported by *Stocking* (1994), led to reduced reliability of the measurements. Consequently, in 2005, a new method based on digital photograph taken at 7 meters height and analyzed by image processing software was developed and used. This method discriminates plant area from soil area by binarization processing. 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 treatments.

3.4.4. Aggregate stability

3.4.4.1.Percolation stability

After the works of *Sekera* and *Brunner* (1943) and *Becher* and *Kainz* (1983), *Kainz* and *Weiss* (1988) developed a method to assess aggregate stability based on the percolation of water through a column of calibrated aggregates. The aggregates are placed in a 100 mm-long tube with an inside diameter of 15 mm. Deionised water is then percolated during 10 minutes under a hydrostatic head pressure of 20 hPa. The amount of water percolated is regarded as the percolation stability (PS) index.

The principle driving the percolation stability (PS) test is the obstruction of the pores by displacement and re-organisation of the microaggregates and particles resulting from the aggregates breakdown, thereby reducing the amount of water that passes through the column. In this method, since the aggregates are previously air dried and rapidly wetted, *Auerswald* (1995) stated that the aggregate breakdown occurs mainly by compression of trapped air during wetting (slaking). The magnitude of the breakdown depends on the strength of the cohesive forces holding the aggregate. High values indicate high aggregate stability.

The original test is performed on 1-2 mm diameter air-dried aggregates. In this study, the method was widened and the test was performed on three aggregate sizes: 0.59-1 mm, 1-2 mm, and 2-3.15 mm. The interest was to evaluate the stability of a wider range of aggregate size so that the sample tested is more representative to the whole soil behaviour (*Loch*, 1994). Based on this consideration, the weighted PS (PS*w*) was calculated to take into account the relative proportion of each aggregate size class.

$$PSw = \sum PSx \cdot Wx \tag{9}$$

With PS*x* = Percolation stability index for aggregate size *x*

W*x* = Fraction of aggregate size *x* in relation to the other aggregate sizes tested.

3.4.4.2.Aggregate size distribution

Large samples were taken in field and air dried at room temperature in laboratory. Samples were then sieved through a column of 7 meshes at 10, 8, 5, 3.15, 2, 1 and 0.59 mm in a rotary sieve device during 4 minutes. The aggregates caught on each sieve were weighted and the fraction of each size was calculated. The fraction >10 mm was not considered in the calculation as this size of aggregate is very variable and can affect artificially the final aggregate size distribution. The mean weight diameter (MWD) (*Nimmo and Perkins*, 2002), was then calculated. Greater MWD implies greater stability.

In dry-sieving procedure, the disruptive agent responsible for the aggregate breakdown is the mechanical energy produced by the collision between the aggregates and the sieve or between aggregates themselves. One measure was performed for each sample. Over the 3 years, the sample (< 10 mm) mean weight was 1048 g (standard deviation=318, n=130).

3.4.4.3.Sampling

The sampling and processing differ from one year to another (Table 5). Therefore, the results are not compared between years, but only within a year.

Table 5: Method and sampling details for soil aggregation assessment in Tlalpan.

	2003	2004	2005
Date of sampling	November 2003	November 2004	13/07/2005 22/09/2005 17/11/2005
Date of testing	February 2004	March 2006	August 2005 October 2005 December 2005
Plots	all	all	Erosion plots (C, D, E, R1, R2)
Field sampling	2 samples at 3 positions (top, medium and low part of the plot)	1 compound samples (4 sub-samples) at 2 positions: ridge + furrow	1 compound sample (6 sub-samples)
Depth	0 – 10 cm	0 – 10 cm	0 – 10 cm
Aggregate size tested	1 – 2 mm 3.15 – 5 mm	0.59 – 1 mm 1 – 2 mm 2 – 3.15 mm	0.59 – 1 mm 1 – 2 mm 2 – 3.15 mm
Replicate	3	3	3
N total	288	144	135

3.4.4.4.Statistical analysis

Between groups analysis of variance (ANOVA) was performed using SPSS (SPSS Inc.). Tukey (Honestly Significant Difference) test at 95 % confidence was used for multiple comparisons.

3.4.5. Particle size distribution

Particle size distribution was determined by Laser diffraction (LD) technique on a Beckman-Coulter LS 230 at the School of Geography of the University of Nottingham. Laser diffraction technology have been used in several studies for soil particle size distribution (PSD) in the last 10 years (*Buurman et al.*, 1997; *Muggler et al.*, 1997; *Konert and Vandenberghe*, 1997; *Beuselinck et al.*, 1998; *Chappell*, 1998; *Westerhof et al.*, 1999; *Eshel et al.*, 2004). The theory behind laser diffraction (or light scattering) technique have been extensively described by these authors and is provided by the manufacturer (*Coulter*, 1994).

Apart from the short time analysis required for LD, the main advantage of this technique is that it provides continuous PSD over a wide range of size fraction.

The Fraunhofer optical model was used for calculation and the PIDS (polarization intensity differential of scattered light) module was not used. PSD was measured over the range of 0.375 µm to 2000 µm. The protocol to prepare samples previous to their analysis in the fluid module was as follow:

0.15 to 0.2 g of soil was put in 10 ml hydrogen peroxide (10 % H_2O_2) for 1 hour and was then heated progressively for 2 hours to destroy all organic compounds. The sample was allowed to cool and 25 ml distilled water was added. The sample was then centrifuged at 3500 rpm for 5 minutes and the liquid in excess was poured out gently. Another 25 ml distilled water was added and the sample was centrifuged again to rinse all the remaining peroxide. The liquid was poured and 25 ml Calgon was added. The sample was shaken manually for 1 minute and then placed in an ultrasonic bath for at least 30 minutes before being analyzed in the fluid module containing tap water. Three replicates of each soil were analyzed. Given the high reproducibility between runs (+- 2 %), only one run of 1 minute was performed for each replicate.

PSD by the hydrometer method was also performed in the laboratory of soils of the Autonomous University of Tlaxcala following the protocol proposed by *Gee* and *Or* (2002).

LD particle size distribution between plots were compared by ANOVA repeated measures.

3.4.6. Porosity and pore size distribution

Total porosity was determined by gravimetric method with water saturation (*Flint and Flint*, 2002) and pore size distribution by water desorption method (*Flint and Flint*, 2002), at 2.45, 5.88, 9.8, 33, 100 and 1500 kPa. Total porosity means were compared by ANOVA (Tukey at 0.05), and water retention curve (pore size distribution) were compared by repeated measures ANOVA.

3.4.7. Soil Organic Carbon

In each plots, two composite samples from 10 sub-samples were taken at 0-10 cm depth at the end of the rainy season. Soil organic carbon was measured by dry combustion in a Carmograph 8 Wösthoff at the laboratory of soil science of the Colegio de Postgraduados. Samples were measured once. The precision of the measures was verified by running standard control samples regularly.

4. Results

4.1. Erosivity and soil erosion

4.1.1. Rainfall erosivity

Results presented in this part are based on records from 2002-2005 taken during REVOLSO project, and unpublished records from 1991 to 1997 recorded during previous projects by Jürgen Baumann and Ulrich Fechter-Escamilla and colleagues from the University of Tlaxcala.

4.1.1.1.Annual precipitation

Mean annual precipitation over the period 1991-2005 in Tlalpan was 670 mm. Values ranged from 530 mm (2002) to 805 mm (2003), with a standard deviation of 108 mm. Data recorded over the 2002-2005 period are consistent with those recorded previously over the 1991-1997 period. There is no significant difference ($p<0.05$) between the mean annual precipitation for the two periods (660 and 675 mm respectively)

Table 6: Annual precipitation and R factor in Tlalpan, Tlaxcala.

year	Precipitation (mm)	R (EI30) ($N\ h^{-1}$)
1991	804	358
1992	803	272
1993	663	211
1994	719	435
1995	603	197
1996	607	218
1997	553	N/A
2002	530	184
2003	805	345
2004	756	377
2005	577	195
Mean	675	127

Beside their proximity (3 geographic minutes), Tlalpan appears to be drier than Hueyotlipan, with 105 mm less precipitation in average. Part of this difference is attributed to the fact that winter precipitations were not recorded consistently in Tlalpan. However, the trend confirms the great spatial climatic variability in Tlaxcala (*Conde et al.*, 2006; *Eakin*, 2000).

4.1.1.2.Monthly precipitation

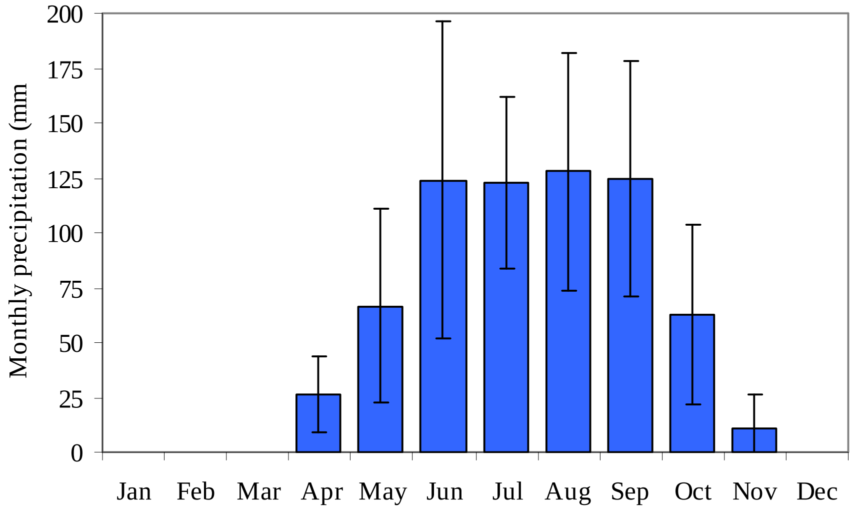

Figure 5: Average monthly precipitation and standard deviation at Tlalpan based on records from 1991 to 1997 and from 2002 to 2005.

Average rainfalls from December to March are not presented because winter precipitations were not recorded every year. However, winter precipitations are minimal and account for less than 5 % of the annual rainfall in the area (*INEGI*, 2006).

At Tlalpan, 75 % of the annual precipitation is distributed from June to September with an average monthly precipitation of 125 mm. Monthly standard deviations reflect great variability between years, and uneven rainfall distribution within a year. Dry periods ("canicula") during the rainfall season are frequent in the area and can cause disastrous damage to crops.

The precipitations in May are crucial as they determine the beginning of the rainfall season and the possible length of the crop cycle before the beginning of the frost-risk period (October). Sowing date and rain depth in the month after sowing have been included in models to predict maize production in the State of Tlaxcala (*Ramirez and Volke Haller*, 1999). According to climatic data recorded at Tlalpan during 11 years, the probability of monthly rain depth superior to 70 mm in May is only 45 %.

Due to winter drought, cover cropping to protect the soil at the beginning of the rainfall season is not possible in this rainfed agriculture area and first storms always occurred on bare and recently worked soils. This is a major limitation for soil conservation strategies.

4.1.1.3.Rainfall patterns in Tlalpan

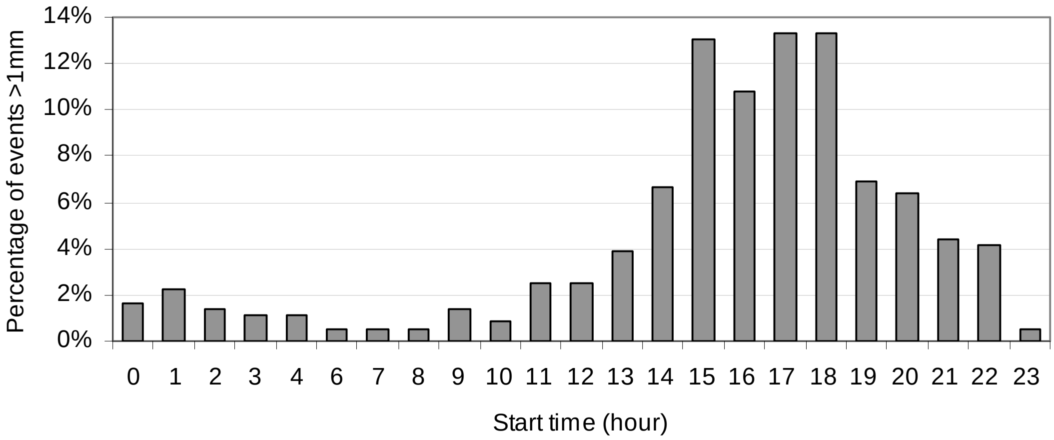

Figure 6: Start time of rainfall events (> 1mm) between 2002 and 2005 in Tlalpan

Over the 2002-2005 period, 360 events separated by at least 60 minutes and with a minimum precipitation of 1 mm were recorded. 71 % of the events started in the afternoon and evening between 14:00 and 20:00, with 51 % of the events concentrated between 15:00 and 18:00. This pattern reflects the dominance of convective rainfalls which are characteristic in Mexican highlands (*Prat*, 1997) and more generally in continental highlands (*Nyssen et al.*, 2005).

Table 7: Mean selected characteristic of rainfall events in Tlalpan over the 1991-2005 period (2003-2005 for soil loss). See Table A- 1 for annual details.

		Events		Depth		EI30		Max I30	Soil loss
		count	%	mm	%	$N\ h^{-1}$	%	$mm\ h^{-1}$	%
Mean	< 1mm	57.6	40.1%	20.5	3.0%	0.4	0.1%	0.8	
	1-4.99 mm	43.8	30.5%	108.0	16.0%	8.3	3.0%	3.5	0.3%
	5-9.99 mm	19.6	13.7%	142.0	21.0%	25.6	9.2%	8.7	4.3%
	10-19.9 mm	16.8	11.7%	236.2	35.0%	87.7	31.4%	16.1	36.1%
	20-29.9 mm	3.9	2.7%	92.9	13.8%	58.9	21.1%	26.1	15.9%
	> 30 mm	1.8	1.3%	75.1	11.1%	98.3	35.2%	50.0	43.4%
	Max rainfall			45.6	6.8%	63.0	22.5%	40.6	13.9%
	Total	143.6		674.6		279.2			

Rain events < 1mm represented on average 40 % of the events, but only accounted for 3 % of the annual precipitation. There were more numerous over the 2002-2005 period than over the 1991-1997 period because of the precision of the recording device (tipping bucket and event recorder) which allowed to record numerous isolated pseudo-events that were not perceptible on the daily pluviograph used between 1991 and 1997.

The number of events is inversely proportional to the size of the event. Events up to 10 mm represented 84 % of the events, 40 % of the annual precipitation, but only contributed to 12 % of the annual erosivity (EI30) and produce 4.3 % of soil loss. Rainfall events of 10-20 mm contributed to 35 % of the annual precipitation. Such events were on average less intense (16.1 mm h^{-1} in 30 minutes) than those of 20-30 mm (26 mm h^{-1}) but they are more numerous and all together accounted for 36.1 % of the annual erosivity against only 15.9 % for events 20-30 mm. Events >30 mm only occur on average 1.8 time per year and account for 11 % of the precipitation. However, they were the most intense (50 mm h^{-1} maximum I30 on average), they produced 35 % of the erosivity and 43.4 % of the annual soil loss. Maximum rainstorm depth ranged from 31 to 67.1 mm over the 1991-1997 period and from 32.7 to 63.8 mm over the 2002-2005 period. The biggest rainstorm is not always the most erosive event, as erosion also depends on the soil condition (protection, roughness, water saturation, etc.) at the moment on the storm.

4.1.2. Runoff and soil loss

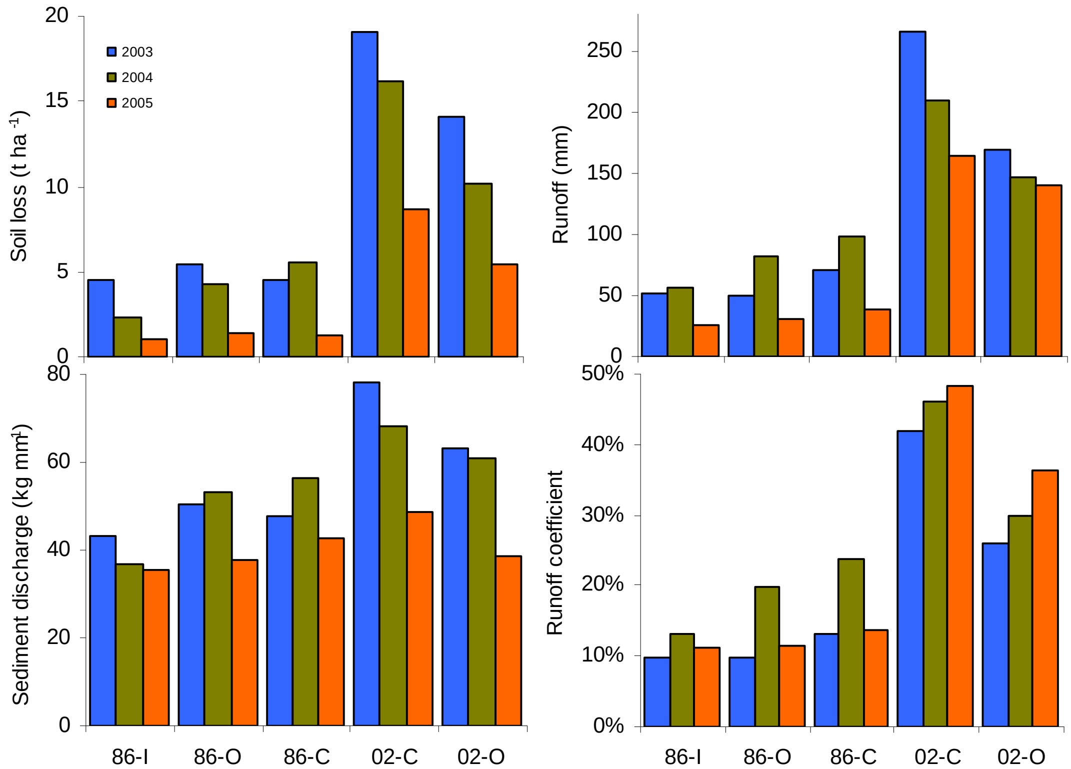

Figure 7: Annual soil loss, runoff, runoff coefficient and sediment discharge in Tlalpan from 2003 to 2005. See Table A- 2 for details.

In recently reclaimed *tepetates* erosion rates ranged from 5.5 to 14.1 t ha^{-1} yr^{-1} in organic management (02-O) and from 8.6 to 19.1 t ha^{-1} yr^{-1} in conventional management (02-C). Over the period, soil loss in conventional management was significantly ($p<0.05$) greater than in organic management, with a difference of 3.1 to 5 ton ha^{-1} yr^{-1} (Table A- 2).

In *tepetates* reclaimed in 1986, erosion rates ranged from 1.1 to 5.5 t ha^{-1} yr^{-1}, with a mean value of 3.4 t ha^{-1} yr^{-1} and no significant difference between managements.

The same trend is observed in runoff, with annual values ranging from 146 to 265 mm in 2002-plots, and from 27 to 99 mm in 1986-plots.

Greater soil loss of 2002-plots was due to greater runoff and to greater sediment discharge. In turn, greater runoff was due to:

1. Greater number of events that caused erosion: on average per year, 25 events generated runoff in recently reclaimed *tepetates*, against 18 events in 1986 *tepetates*. The events responsible for that difference are the one below 20 mm. All events of more than 20 mm produced runoff in all plots (Table A- 4).
2. Higher runoff coefficient: the latter are rather constant between years. In plots reclaimed in 1986, mean runoff coefficient ranged from 11 % to 17 % in improved and conventional management respectively. In 2002-plots, mean runoff coefficient reached 45 % in conventional management and 31 % in the organic one (Table A- 2)

On average, 43 % of the annual soil loss was produced by 3 events >30 mm, including the most erosive event which accounted alone for 33 % of the annual soil loss. Individually, events between 10 and 20 mm only generated on average 80 kg ha^{-1} in 1986-plots and 386 kg ha^{-1} in 2002-plots. However, all together (12.3 events of that size on average), they caused 36 % of the annual soil loss (Table A-3). Although it might be difficult to prevent soil loss from extreme events, conservation techniques could be more efficient to prevent erosion from moderate rainstorm (10-20 mm).

In 2005, the event that produced most soil loss was only 17.5 mm, but occurred 2 days after a rainstorm of 32.3 mm. The biggest rainstorm (43.6 mm) occurred later in the season on 31/08/05 when vegetation cover was higher, and generated the highest runoff rates of the season (Table A- 4), but not as much erosion. This might have generated an over-estimation of the overall contribution of 10-20 mm rainfall size class to annual soil loss, but also highlight the importance of soil conditions and vegetation cover at the beginning of the rainstorm.

4.1.3. Vegetation cover

The efficiency of a crop to protect the soil from raindrop impact can be evaluated according to the amount of vegetation cover the crop is able to provide, and the time elapsed before the cover is developed. The amount of vegetation cover depends on i) the type of crop, mainly responsible for mean differences between years, and ii) crop development, which depends on the management applied and which is mainly responsible for differences between plots within a year. Crop development depends on plant nutrition and water supply.

Results are presented in Table A- 5.

4.1.3.1. 2002

Among the crop rotation applied between 2002 and 2005, broad bean is the crop that provided less vegetation cover to the soil. Maximum cover was reached after approximately 130 days after sowing, with soil covered up to 71 % (86-O) and 79 % (86-C) in 1986-plots, and 44 % (02-O) to 41 % (02-C) in 2002-plots.

4.1.3.2. 2003

In 2003, the association between oat and vetch significantly increased vegetation cover to 84 % (86-I) compared to 61 % (86-C) with oat single cropping in 1986-plots, to 70 % (02-O) compared 39 % (02-C) in plots reclaimed in 2002.

The analysis of the composition of the vegetation cover (Figure 7) clearly shows that:

i. On average over the season, vegetation cover by oat was similar between management, ranging from 38 to 45 %.

ii. The vetch provided another 29 % vegetation cover in 02-O, and 21 % on average in 86-I and 86-O. There were not significant differences in vetch cover between plots where this species was associated with oat (organic and improved).

iii. Vegetation cover was higher in plots reclaimed in 1986 because of adventives weeds (18% of additional cover on average). In plots reclaimed in 2002, the amount of soil covered by weeds is negligible since the material was still free of adventives seeds.

The maximum vegetation cover by oat occurred 54 days after sowing and decayed gradually afterwards. Vetch development and cover was slower, but constant throughout the rainfall season and until harvesting, approximately 100 days after sowing.

The association oat-vetch provided greater vegetation cover and over a larger period. This is a substantial benefit in the study area where hurricane season usually generate strong erosive events at the end of the growing season in September-October (See part 4.1.1).

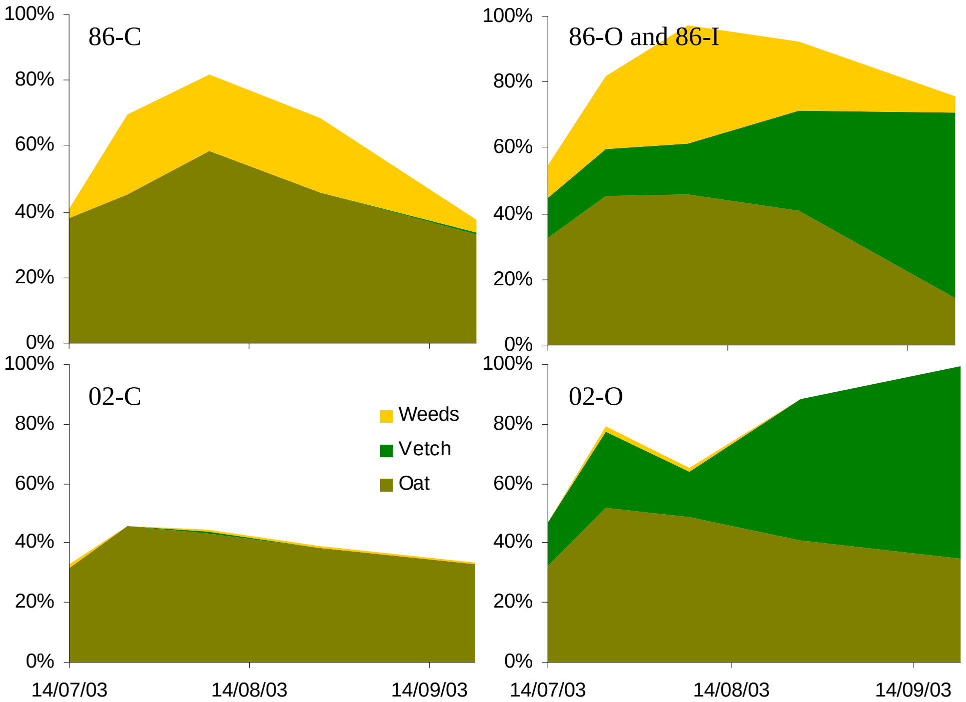

Figure 8: Composition of vegetation cover in 2003 in Tlalpan

Although vegetation cover was established rapidly after sowing, the biggest rainstorms occurred at the beginning of the season when only 10 % of the soil (on average) was covered and caused major soil loss (Figure 9).

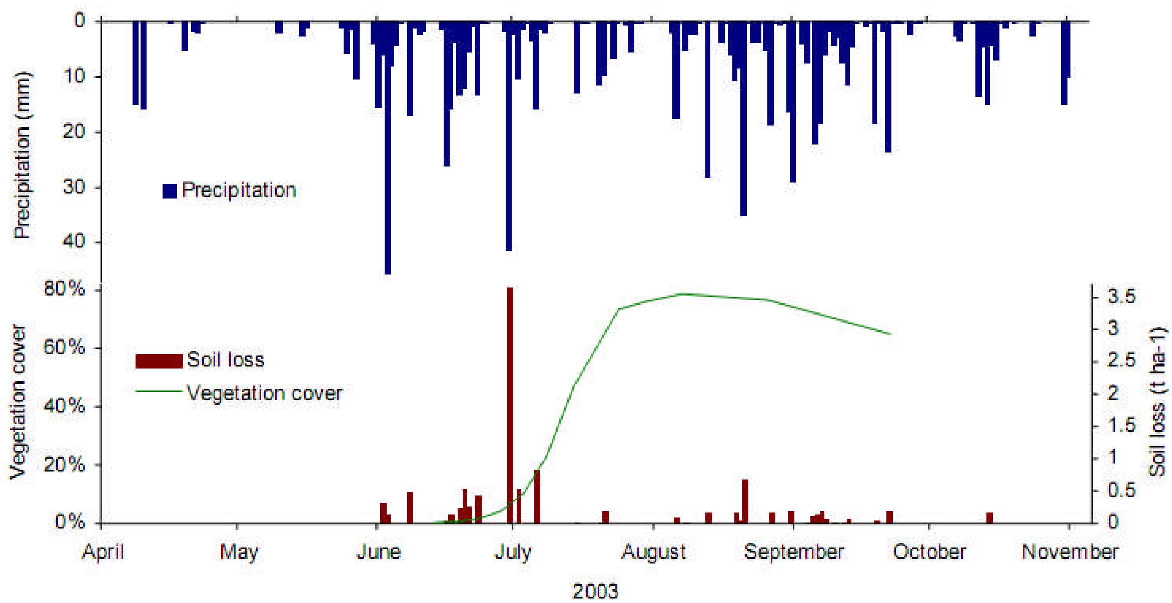

Figure 9: Distribution of vegetation cover (average value from all plots), precipitation and soil loss (average value from all plots) during 2003 in Tlalpan.

4.1.3.3.2004

The evaluation of the vegetation cover was done at grain filling stage, approximately 100 days after sowing. Based on this observation, vegetation cover was higher in 86-I (87 %) than in 86-O and 86-C (78 %). In recently reclaimed *tepetates*, 02-O reached 70 % cover, against only 35 % in 02-C.

This observation confirmed the fertility limitations of recently reclaimed *tepetates* for maize cropping under conventional management (*Baumann and Werner*, 1997b). However, it also proved that from the third year after fragmentation, maize cropping can produce similar yields (Table A- 7) and vegetation cover than reclaimed tepetates with several years of rehabilitation, providing adequate plant nutrition is applied.

In 2004, the biggest rainstorm occurred in September during the hurricane season and caused major soil loss although vegetation cover was already well established (Figure 10). It is a clear illustration that vegetation cover can mitigate the effect of erosive event by protecting the soil against raindrop impact, but has limited effect in case of extreme event when particle detachment by overland flow is the dominant detachment mechanism.

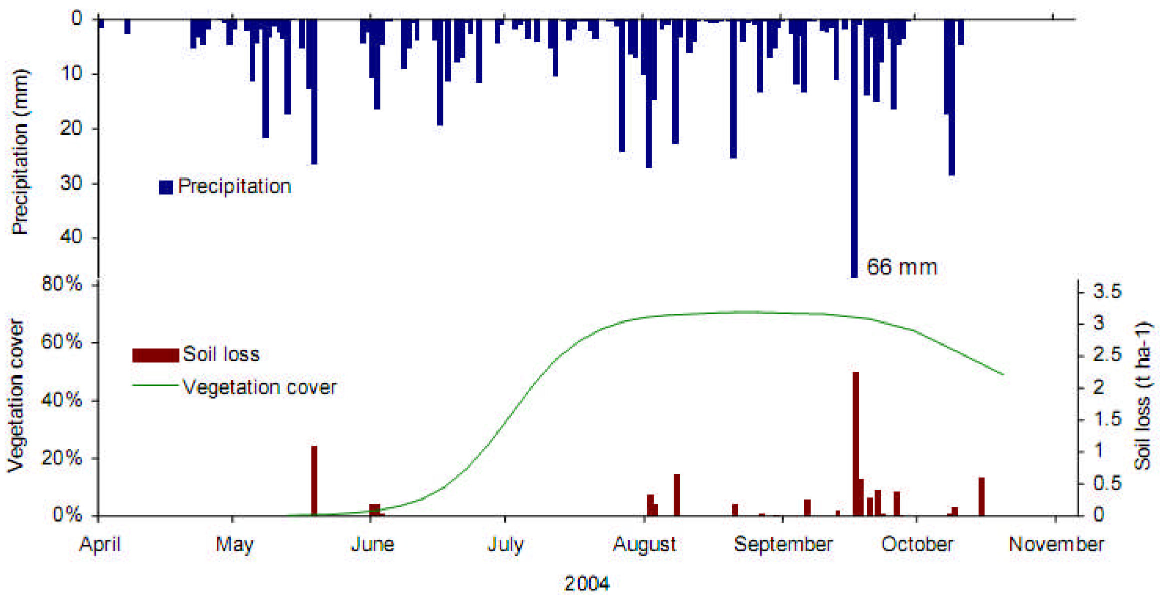

Figure 10: Distribution of vegetation cover (predicted average value of all plots), precipitation and soil loss (average value of all plots) during 2004 in Tlalpan.

4.1.3.4. 2005

Thanks to the aerial photography method, we were able to monitor the vegetation cover during the whole crop cycle. Over this period, 86-O and 86-I provided up to 90 % of soil cover 100 days after sowing. 86-C was significantly lower with a maximum of 81 %. The plots reclaimed in 2002 suffered nutrition limitations and vegetation cover did not reach more than 63 %. Over the period the difference between the two managements was not significant.

On average in plots reclaimed in 1986, wheat was able to provide more than 80 % soil cover 60 days after sowing and maintained this level during approximately 60 days, representing 46 % of the vegetative period (Figure 11). This level of vegetation cover was particularly effective in mitigating soil loss for the two extreme rainstorms (over 40 mm) which occurred in August (31st) and October (11th).

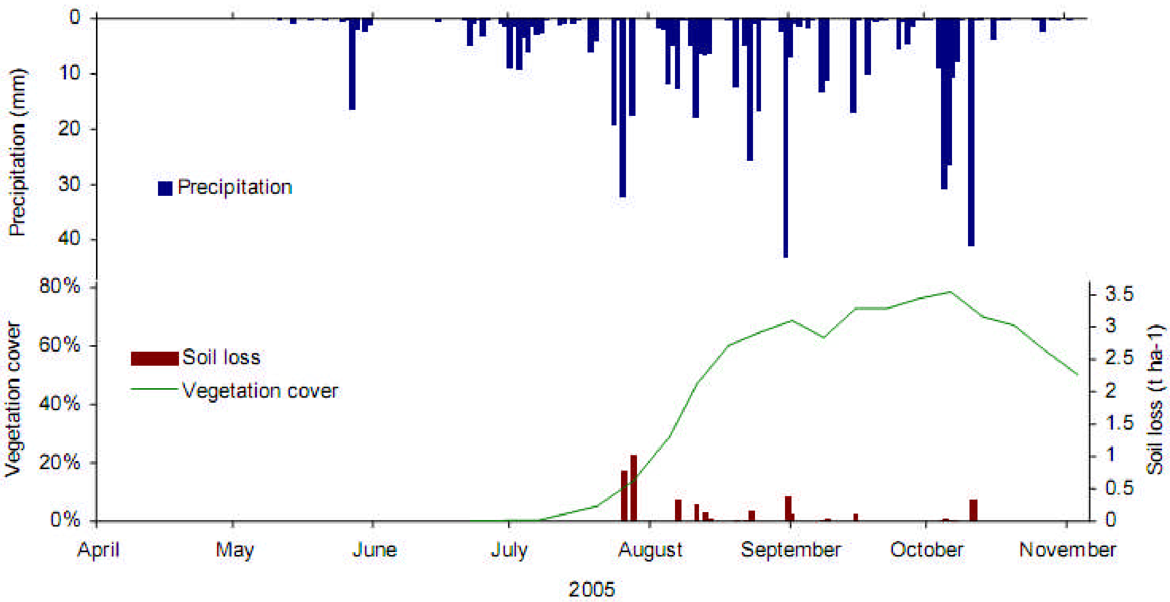

Figure 11: Distribution of vegetation cover (average value of all plots), precipitation and soil loss (average value of all plots) during 2005 in Tlalpan

4.2. Soil properties and crop production

4.2.1. Soil Organic Carbon

The main difference between Conventional, Improved and Organic management is the incorporation of organic matter (Cf chapter 3.3). The evolution of SOC content is an indicator of the effect of management on carbon dynamic in *tepetates*.

In total, 5.6 Mg OM (biomass) ha^{-1} yr^{-1} and 6.8 Mg OM ha^{-1} yr^{-1} were incorporated over the period in 86-O and 02-O respectively. Organic fertilization represented on average 63 % of the annual incorporation rate, whereas crop residues accounted for 24% and roots for another 13 % of the amount of C incorporated each year in average (Table 8). In 86-I, the incorporation of organic material amounted 4.4 Mg OM ha^{-1} yr^{-1}, of which 89 % was provided by crop residues and 11% by roots. In 86-C, average incorporation rate was 2.5 Mg OM ha^{-1} yr^{-1}, with crop residues accounting for 67% of the total accumulation and roots for 33 %. In 02-O, only 1.1 Mg OM ha^{-1} yr^{-1} was incorporated, of which the major part (60 %) came from roots (Table 8).

Table 8: Organic material (biomass) inputs and C accumulation rates in Tlalpan from 2002 to 2005 at 0-20 cm depth. OM inputs from roots were estimated from the work of Fechter-Escamilla et al. (1997b).

		86-C	86-I	86-O	02-C	02-O
2002	organic fertilziation	-	-	6.8	-	6.3
	residues	-	-	-	-	-
	roots	-	-	-	-	-
2003	organic fertilziation	-	-	3.0	-	3.0
	residues n-1 (broad bean)	-	3.2	-	-	2.3a
	roots n-1 (broad bean)	1.1	1.1	1.1	1.1	1.1
2004	organic fertilziation	-	-	1.9	-	2.6
	residues n-1 (oat or oat + vetch)	3.8	3.3	2.9	1.2	3.9
	roots n-1 (oat or oat + vetch)	0.8	1.4	1.4	0.8	1.4
2005	organic fertilziation	-	-	3.0	-	4.3
	residues n-1 (maize)	1.5	5.5	1.5	0.5	1.4
	roots n-1 (maize)	0.8	0.8	0.8	0.8	0.8
Total	organic fertilziation	-	-	14.7	-	16.2
	residues	5.2	12.0	4.4	1.7	7.7
	roots	2.6	3.2	3.2	2.6	3.2
	Total (Mg OM ha^{-1})	**7.8**	**15.2**	**22.3**	**4.3**	**27.1**
	Incorporation rate (Mg OM ha^{-1} yr^{-1})	**2.0**	**3.8**	**5.6**	**1.1**	**6.8**
	Incorporation rate (Mg C ha^{-1} yr^{-1})[b]	**1.0**	**1.9**	**2.8**	**0.5**	**3.4**
	Accumulation rate (Mg C ha^{-1} yr^{-1})[c]	**0.21**	**0.37**	**0.61**	**0.22**	**0.80**
	Ratio accumulated/incorporated	**21%**	**19%**	**22%**	**40%**	**24%**

[a] incorporated as green manure

[b] with C = 1/2 OM

[c] Cf table 12

In 86-C, where crop residues were exported and no organic material was incorporated, SOC content (0-20 cm depth) increased by 0.36 mg g^{-1} over the period (Table 9), indicating that after more than 15 years of cultivation after fragmentation and with reduced inputs of O.M, SOC keeps increasing under conventional management. In 86-I, where residues were incorporated, SOC increased by 0.61 mg g^{-1} over the period. In 86-O, where residues were composted and organic fertilization was applied, SOC increased by 1.01 mg g^{-1}. In 02-O, the incorporation of manure after fragmentation and the incorporation of the green manure (broad bean) produced an increase of 0.77 mg g^{-1} within the first year after fragmentation. Over the 4 years period with regular but reasonable organic matter inputs (Table 8) SOC increased by 1.34 mg g^{-1}. In 02-C with no organic matter incorporation apart from roots and residues, SOC increased by 0.36 mg g^{-1} (Table 9).

Organic farming after fragmentation increased carbon sequestration rates to equivalent 0.80 Mg C ha^{-1} yr^{-1} compared to 0.22 Mg C ha^{-1} yr^{-1} in conventional farming.

Table 9: Soil Organic Carbon (mg g^{-1}) and accumulation rate at 0-20 cm depth in Tlalpan from 2002 to 2005. Data at 0-10 and 10-20 cm depth are presented in Table A- 6 in Appendix 7.

Management	SOC (mg g^{-1})					Accumulation rates	
	2002	2003	2004	2005	Δ 02-05	mg C g^{-1} yr^{-1}	Mg C ha^{-1} yr^{-1}
86-C	2.99	3.70	3.40	3.34	0.35	0.09	0.21
86-I	3.21	3.50	3.83	3.83	0.61	0.15	0.37
86-O	3.09	4.42	4.78	4.10	1.01	0.25	0.61
02-C	1.08	0.81	1.45	1.43	0.36	0.09	0.22
02-O	1.08	1.84	2.20	2.41	1.34	0.33	0.80

4.2.2. Soil water content

In 2004 soil moisture was assessed by TDR from sowing to mid-September. Measurements were not continued due to failure of the device. In 2004, no significant differences were observed between treatments (Figure 12).

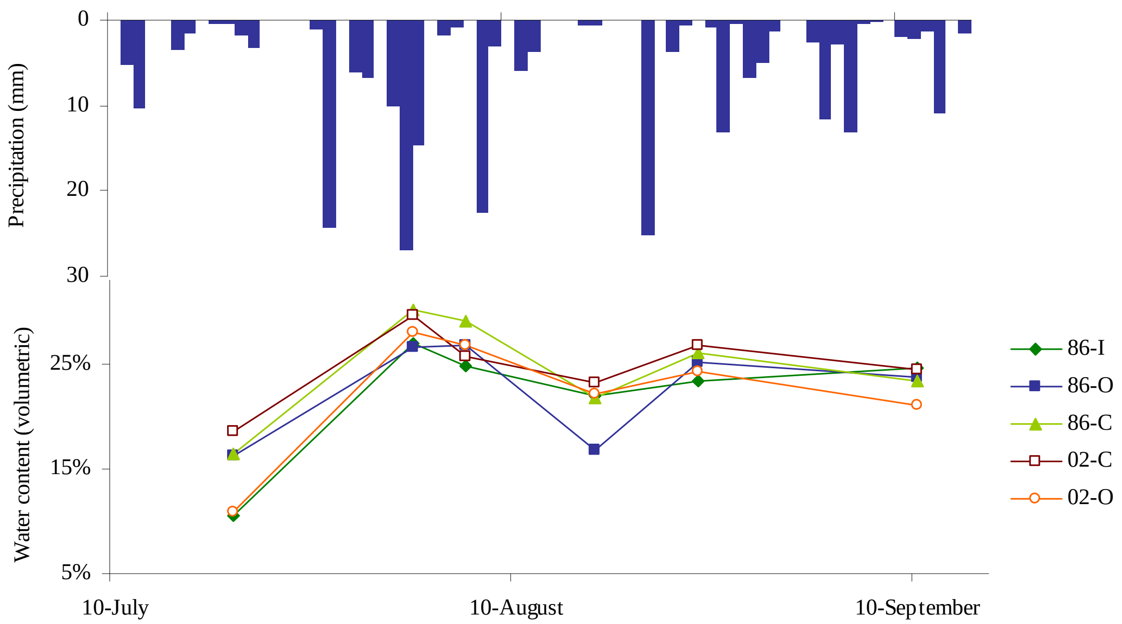

Figure 12: Monitoring of soil water content (volumetric) at 10 cm depth by TDR during 2004 cropping season. Cf Table A- 8.

In 2005, soil moisture was assessed by tensiometers on a regular basis (32 measurements). Over the period, soil water content was significantly lower in 02-plots (mean value of 23 %) than in 86-I and 86-C (Mean value of 33 %) (Figure 13 and Table A- 9)

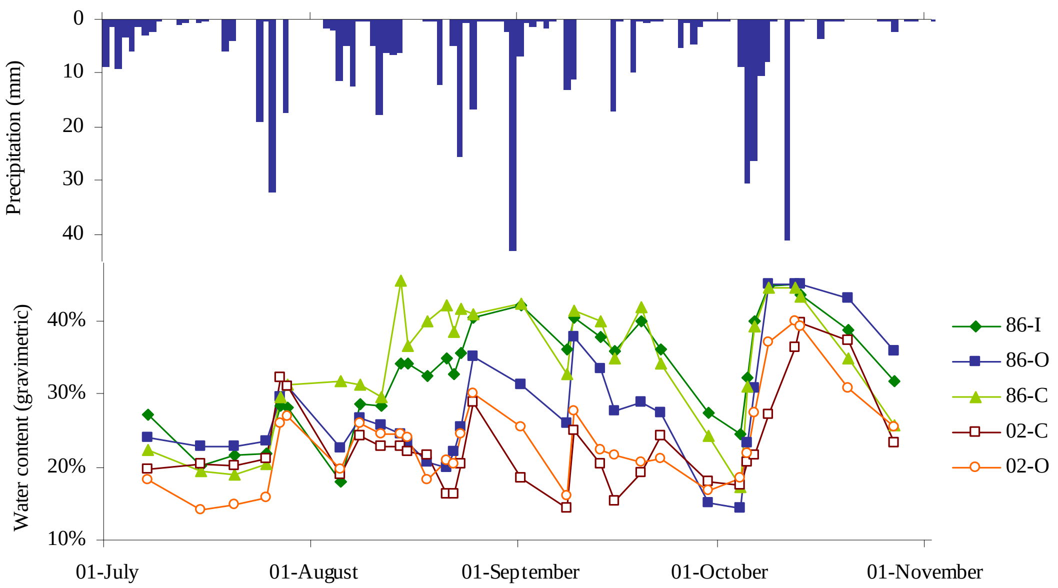

Figure 13: Monitoring of soil water content (gravimetric) by tensiometers during 2005 cropping season (weighted average from measures done at 5, 10, 15, 25 and 40 cm depth). Cf Table A- 9.

4.2.3. Crop production

Crop production and vegetation cover are strongly related, since both parameter depends on crop development. Crop yields are presented in Table A- 7, to support the discussion on the effect of management on vegetation cover.

4.3. Soil structure

4.3.1. Particle size distribution

Table 10: Particle size distribution in Tlalpan experimental site's plots.

	Clay	Silt			Sands			
	< 2 µm	2 - 20 µm	20 - 50 µm	**2 - 50 µm**	50 - 250 µm	250 - 500 µm	500 - 2000 µm	**50 - 2000 µm**
A	**6.3**	31.3	13.1	**44.4**	35.5	10.0	3.9	**49.3**
B	**7.7**	34.5	14.0	**48.5**	31.1	9.0	3.7	**43.9**
C	**7.6**	35.8	14.3	**50.1**	29.7	9.2	3.4	**42.3**
D	**8.2**	34.0	13.4	**47.3**	30.7	9.6	4.2	**44.5**
E	**9.1**	38.7	11.8	**50.6**	27.6	9.2	3.6	**40.4**
F	**9.9**	35.0	11.5	**46.5**	29.1	10.3	4.3	**43.7**
R1	**10.7**	37.7	10.8	**48.5**	26.7	9.8	4.4	**40.9**
R2	**9.5**	37.3	13.1	**50.4**	28.7	8.7	2.8	**40.1**
Mean	**8.6**	35.5	12.7	**48.3**	29.9	9.5	3.8	**43.1**

The average texture is 8.6 % clay (<2 µm), 48.3 % silt (2 - 50 µm) and 43.1 % sand (50 – 2000 µm). The most represented fraction is fine silt-size (2 – 20 µm) particles, accounting for 35.5 % of the soil volume on average. Very fine and fine sands accounted for 29.9 % of the soil volume, whereas coarse and very coarse sands (<500 µm) only accounted for 3.8 % of the soil. There were no significant differences in particle size distribution between plots (ANOVA repeated measures).

LD PSA revealed the bimodal particle distribution with a peak at 5 µm and another one at 100 µm (Figure 14)

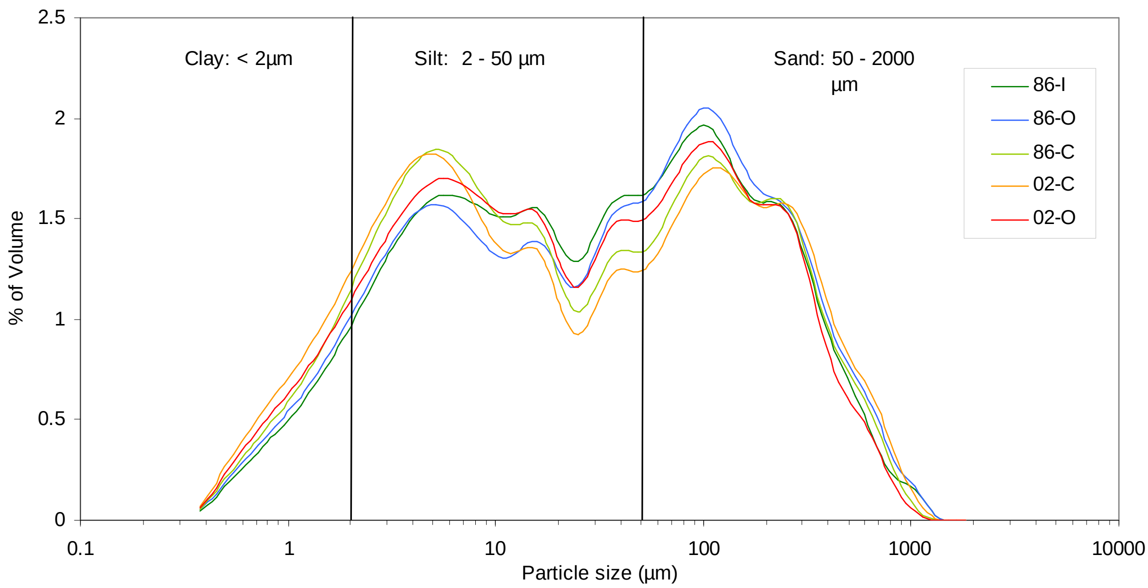

Figure 14: Particle size distribution measured by Laser Diffraction in Tlalpan in plots where erosion was measured.

Soil texture classification systems were developed for PSD obtained by sieving-sedimentation methods. No classification systems exist yet for PSD obtained by LD and it is therefore necessary to convert LD PSD to pipette or hydrometer PSD in order to define the soil texture class. According to LD PSD, reclaimed *tepetates* in Tlalpan would be clay loams (USDA classification).

Laser diffraction grain analysis tends to underestimate clay content in comparison to the sieve-pipette method more conventionally used (*Beuselinck et al.*, 1998; *Konert and Vandenberghe*, 1997; *Eshel et al.*, 2004). This distortion is due to the fact that both methods do not measure the same property of the same material. The laser diffraction analysis determines the diameter of a particle whose diffraction is equivalent to the one of a sphere (optical-equivalent diameter). Gravitational sedimentary pipette method determines the diameter of a particle whose settling velocity is equivalent to the one of a quartz sphere (spherical-equivalent diameter).

Because clays are platy particles, their average optical diameter is much greater than their equivalent spherical diameter. *Konert* and *Vandenberghe* (1997) showed that some particles with a clay spherical-equivalent diameter of 2 µm (from pipette method) have a optical-equivalent diameter of 3.9 µm. Much of the material measured as clay by the pipette method is therefore measured as silt on the diffraction method. Since coarse silt and sand spherical and optical diameters are similar, there is a good relationship between pipette and laser diffraction method for sands content (*Beuselinck et al.*, 1998; *Konert and Vandenberghe*, 1997; *Eshel et al.*, 2004). However, because of the underestimation of clays, silt fraction tends to be largely overestimated. To convert particle size distribution obtained by LD to values obtained by sieve-pipette, two methods have been proposed:

i. *Konert* and *Vandenberghe* (1997) proposed that clay (<2 µm) content by sieve-pipette method be equivalent to particles size <8 µm measured by laser diffraction.

ii. *Beuselinck* et al. (1998) proposed to estimate clay and sand content using RMA regression equations:

For clay (< 2 µm): $y = 2.744x - 7.773$

For sand (> 63 µm): $y = 1.155x - 6.105$

And then calculate silt content as 100 – (% estimated clay + % estimated sand).

Table 11: Measured and corrected texture obtained by LD and pipette methods in Tlalpan.

Method	% Clay < 2 µm	% Silt 2 - 50 µm	% Sands 50 - 2000 µm
LD (Coulter LS 230)	8.6	48.3	43.1
Hydrometer	32.5	25.8	41.8
LD Corrected (Beuselinck)	15.9	40.4	43.7
LD Corrected (Konert)	30.5	26.4	43.1
Sieve-pipette (Covaleda, 2007)	33.7	30.0	36.4
Sieve-pipette (Baumann, 1996)	26.9	35.0	38.1

[a] Baumann used sands > 63 µm. Silt fraction is therefore overestimated compared to the USDA classification, and sand fraction underestimated.
[b] RMA relationship for sands was calculated by Beuselinck for sands > 63 µm.

Hydrometer PSD is in the range of the pipette PSD reported by Covaleda et al (2007), with a difference of 1.2 % in clay content and 4.4% in sand content. However, it differs from pipette PSD reported by *Baumann* (1996) (Δ clay: 5.6 % and Δ sands: 3.7 %). Part of this difference is due to the fact that the upper limit for silt fraction was 63 µm and induced an overestimation of silt fraction (Δ = 9.2 %).

The correction proposed by *Konert* and *Vandenberghe* (1997) (increasing the limit of clay fraction to 8 µm) gave a good approximation of the equivalent pipette PSD, with differences of less than 2 % in each size fraction compared to hydrometer PSD.

The correction proposed by *Beuselinck* et al. (1998) did not predict satisfactorily the clay content measured by the hydrometer method, with a difference of 16.6 %. The RMA relationships defined by *Beuselinck* et al. (1998) were based on 83 samples derived from natural silt and modified to obtain a wide range of texture. However, the clay fraction used in their experiment consists mainly of illite and smectite, whereas clays minerals in *tepetates* are mainly halloysite and cristobalite (*Peña and Zebrowski*, 1992a). This may have created a bias since relationships between LS and pipette methods are affected by clay mineralogy and morphology (*Beuselinck et al.*, 1998).

It is important to highlight that all methods suffer from inherent flaws (*Eshel et al.*, 2004) and none can be considered as absolutely correct.

4.3.2. Aggregation

4.3.2.1.Dry aggregate size distribution

The smallest aggregate fraction (<0.59 mm) is the predominant fraction and represented on average 31% of the soil sample (> 10 mm). There is a significant difference ($p<0.001$) in the fraction of aggregates size >1 mm between 1986-plots (34.8 %) and 2002-plots (42.3 %) (Table A- 15). This feature reflects a lower aggregation of the finer particles in the recently rehabilitated *tepetates*, which is also expressed by smaller MWD over the period. All other aggregate-size fraction ranged between 10 % and 15 % of the soil (< 10 mm).

In 2003, MWD are higher because the smallest mesh size was 1 mm, whereas in 2004 and 2005, samples were sieved down to 0.59 mm. Since MWD is an integration of the cumulative size fraction, and since the smallest size class is the most important fraction, the MWD calculation was affected.

In 2002-plots, there was no significant effect of management on ASD, with a mean MWD of 2.67 mm. In 1986-plots however, 86-O obtained higher MWD value (3.23 mm) than 86-C (3.14 mm) and 86-I (2.99 mm), although the difference was only significant between 86-I and 86-0.

Evolution of ASD during crop season

In 2005, samples were taken at the beginning, middle and end of the season. In recently reclaimed plots, ASD remained constant throughout the season, with fraction <0.59 accounting for approximately 30 % of the soil and fractions > 1mm accounting for 10 to 15 % each (Table A- 16). On September 22nd, we observed a significant difference ($p<0.05$) in MWD between 1986-plots (3.93 mm) and 2002-plots (2.39 mm). This difference is due to a decrease in aggregate fraction < 1mm and an increase in aggregate fraction > 2mm compared to July and November (Figure 15).

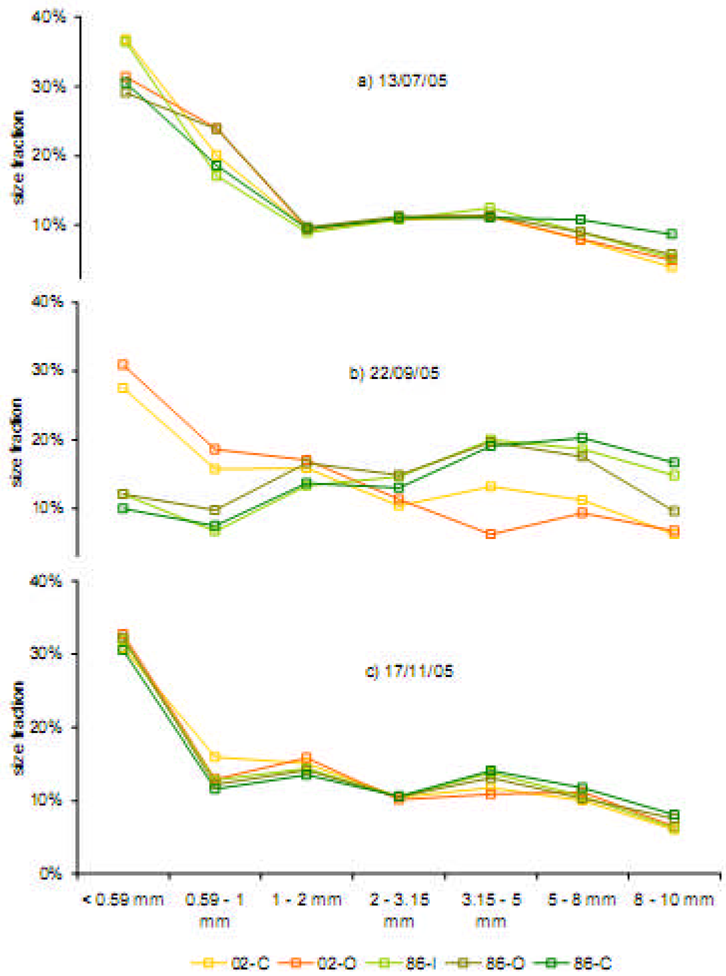

Figure 15: Dry aggregate size distribution during the rainfall season in 2005 in Tlalpan.

Soil water content was also monitored during the cropping season and the results showed that there is a good correlation (r^2 adjusted =0.83, N=15, $p<0.001$) between MWD and soil water content at sampling. This result is consistent with the conclusions of several authors that reported significant effect of soil moisture at the time of sampling on aggregate stability and size distribution (*Kemper and Rosenau*, 1984; *Caron and Kay*, 1992). Further monitoring of soil moisture and aggregate size distribution is required to draw more consistent conclusions on how soil moisture content affects aggregate size distribution.

Relationship between MWD and aggregate size distribution

The MWD is computed from integrating the cumulative abundance of aggregates as a function of diameter (*Nimmo and Perkins*, 2002). In our study, the MWD was obtained by integrating 7 sizes classes (6 in 2003) obtained by sieving. Since the aggregate size <0.59 mm accounts in average for 30 % of the aggregates <10 mm, we found a strong negative linear relationship between MWD and the fraction of aggregate <0.59 mm (r^2=0.85, N=64, p<0.001) (Figure 16)

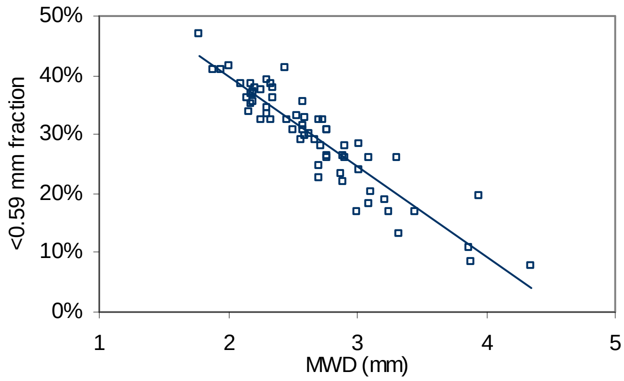

Figure 16: Linear regression between MWD and <0.59 mm fraction in 2004.

The fraction of aggregates size <0.59 mm is therefore a good indicator of the level of aggregation in reclaimed *tepetates* and could be an alternative to the MWD to assess aggregation.

4.3.2.2.Aggregate stability

Note on annual variability

Within a year, all samples received the same preparation, but samples treatment differs between years (Table 5). The main difference is the time elapsed between the date of sampling and the date of testing. In 2005, samples were analyzed few weeks after they were air dried whereas samples from 2004 cycle were stored for more than a year before being analyzed. This may have increased aggregate cohesion (*Diaz-Zorita et al.*, 2002; *Kemper and Rosenau*, 1986) and may explain the variability observed between years. Moreover, 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.*, 1990b). Therefore, the analysis of results will only focus on differences between plots within years.

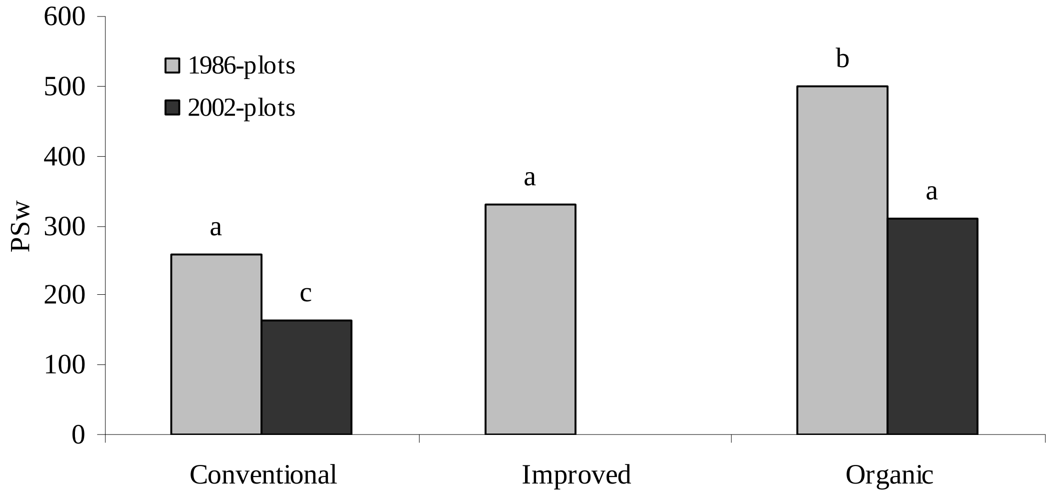

Figure 17: Effect of management and age of rehabilitation on mean PSw over the period 2003-2005. Different letter indicate significant difference (p<0.05).

On average over the period, there is a significant effect (p<0.001) of the age of rehabilitation on PSw. 1986-plots were more stable to percolation (361.1 ml 10 min^{-1}) than 2002-plots (236.9 ml 10 min^{-1}) (Table A- 17). Management also had a significant effect on PSw (p<0.001), and this effect is not dependant from the year of rehabilitation (interaction not significant). The effect of age of rehabilitation is clearly visible within a given management (02-O significantly less stable than 86-O, and 02-C significantly less stable than 86-C) (Figure 17). 02-O obtained similar PSw value (308.7 ml 10 min^{-1}) than 86-C (259.3 ml 10 min^{-1}) and 86-I (329.5 ml 10 min^{-1}) (Table A- 17).

In 2005, aggregate stability was measured at three different dates during the rainfall season. The results obtained illustrate the dynamic of aggregate stability in reclaimed *tepetates* (Figure 18 and Table A- 17). The first sampling was done 2 months after compost was applied in organic management (86-O and 02-O). We observed a peak of stability at the beginning of the crop cycle with PSw values significantly greater in organic management than in conventional and improved managements, regardless of the age of rehabilitation (Table A- 17). PSw decreased in all plots at the end of the cropping season, and was significantly lower in 2002-plots than in 1986-plots, both in conventional and organic management.

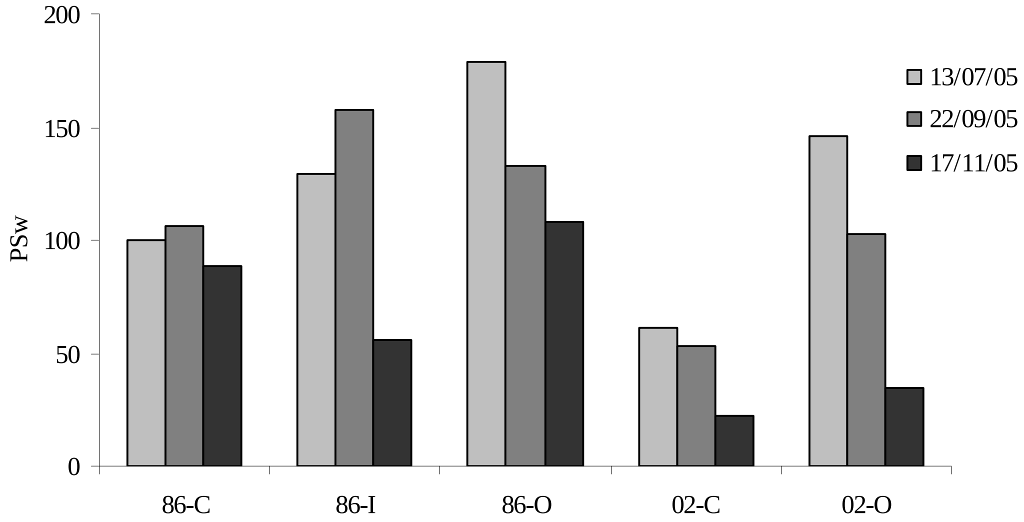

Figure 18: Aggregate stability (PSw) in 2005 and its evolution during the crop cycle.

Detailed PS values for each aggregate size helps us analyze a step further the dynamic of aggregate stability in reclaimed *tepetates*. For illustration sake, Figure 19 only show PS values in 2002 plots for the 3 aggregate sizes tested. The results of all plots are presented in Table A- 18.

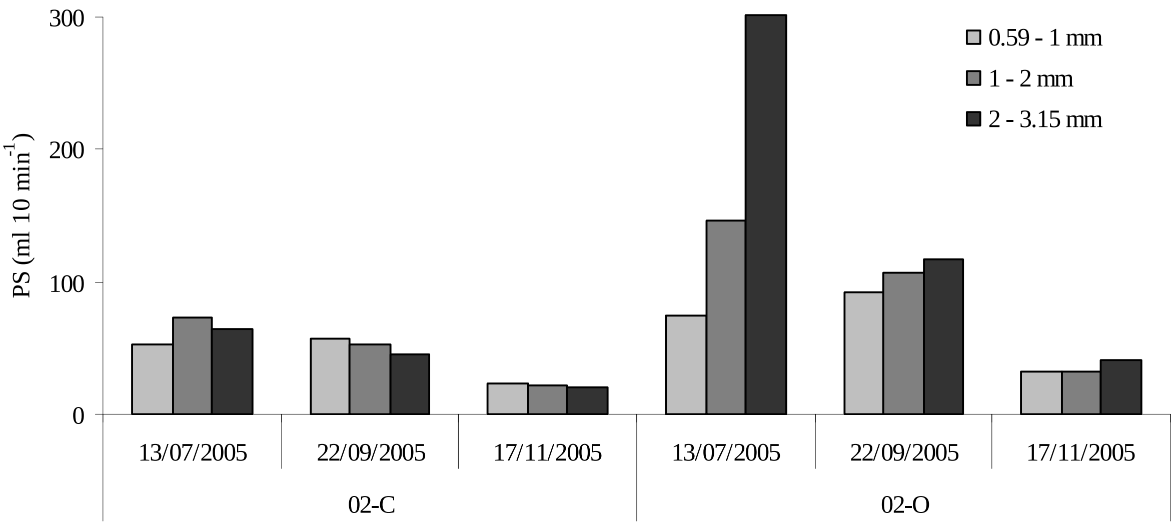

Figure 19: PS (ml 10 min^{-1}) values in 02-C and 02-O during the cropping season in 2005 in relation to aggregate size.

Since the PS index is the amount of water percolated through a column of calibrated aggregates, we expect the PS index to be positively correlated to the aggregate size. Indeed, in the hypothetical case of aggregates being uniform stable spheres, and assuming aggregates are packed under the same model (*Hillel*, 2004), the smaller the aggregate diameter, the smaller the resulting pores diameter, and in turn, the smaller the discharge.

Figure 14 shows three mains features:

1. In recently reclaimed *tepetate* under conventional management (02-C) all aggregates sizes had similar PS index (non significant differences).
2. In organic management (02-O), PS index for 2-3.15 mm aggregates was significantly ($p<0.01$) higher than the other aggregate sizes on 13/07/05, but decreased and became no longer significantly different after this date.
3. The stability of aggregates decreased during the growing season in all aggregate sizes. At the end of the season, there were no differences in PS between managements.

In plots reclaimed in 1986, the same “stability peak” is observed in aggregates 2-3.15 mm at the beginning of the cropping season in 86-O (332 ml 10 min^{-1}) and, to a lesser extent, in 86-I (208 ml 10 min^{-1}) and 86-C (158 ml 10 min^{-1}) (Table A- 18). PS values for aggregates 2 - 3.15 mm decreased during the season, but remained higher than smaller aggregates fractions in all 86-plots.

Effect of ridge and furrow on aggregate stability

Traditionally in Mexico, maize is cultivated in a ridge and furrow system. In 2004, samples were taken in ridge and furrow areas to evaluate the impact of such system on soil erodibility (Table A- 17).

The furrow areas provided significantly higher PSw values (232 ml percolated in 10 min) than the ridge area (139 ml 10 min^{-1}). This is due to higher PS values for all 3 sizes of aggregates, and not to a different aggregate size distribution (Table A- 18). This observation suggests that a furrow-ridge system improves the overall aggregate stability thanks to the area occupied by furrows. We assume that as runoff occurs in furrows, the particles are transported according to their size and to the flow velocity, as shown in the Hjulström diagram. When flow rate decreases, bigger particles settle whereas smaller particles are transported downstream. This sedimentation process occurs in furrows and may result in a coarser texture in these areas. As the sand fraction increases, the PS values obtained increase too, since the PS is much positively correlated to the amount of sand in soils (*Mbagwu and Auerswald*, 1999). In this case, higher PS values do not necessarily reflect higher cohesive strength within the aggregate, but a higher porosity due to the amount a sands.

This hypothesis must be confirmed by PSD analysis in furrows and ridges areas.

4.3.3. Porosity and pore size distribution

4.3.3.1.Total porosity and bulk density

Some definitions:

- In our study, “fine pores” are the pores with equivalent diameter of less than 0.2 µm. The volume of fine pores corresponds to the volume of water in the soil at 15 bars, which is considered to be the physical definition of the permanent wilting point (θ_{pwp})
- “Large pores” are the pores with equivalent diameter of more than 10 µm. The volume of large pores equals the volume of water in soil between field saturation and field capacity (θ_{fc}) at -0.33 bar.
- “Medium pores” are the pores whose equivalent diameter range from 0.2 to 10 µm. The volume of medium pores corresponds to the available water content, and is equivalent to the volume of water retained in soil between θ_{fc} and θ_{pwp}.

Table 12: Mean porosity (0 – 40 cm) in reclaimed *tepetates* from 2003 to 2005 in Tlalpan. Different letter indicates significant difference (p<0.01)

Year	Parameter	1986				2002		
		Conventional	Improved	Organic	Mean	Conventional	Organic	Mean
2003	Pores >10 µm	11.3 a	11.8 a	12.8 a	12.0	12.7 a	10.2 a	11.4
	Pores 0.2 -10 µm	12.3 a	12.7 a	13.4 a	12.8	12.5 a	12.8 a	12.7
	Pores <0.2 µm	20.1 ab	20.3 ab	19.4 a	19.9	20.8 bc	21.7 c	21.3
	PT sat	43.6 a	44.8 ab	45.5 b	44.6	46.1 b	44.6 ab	45.3
	Bulk density	1.27 a	1.26 ab	1.23 ab	1.25	1.21 b	1.24 ab	1.22
2004	Pores >10 µm	16.5 a	17.1 a	16.0 a	16.5	14.8 a	17.1 a	15.9
	Pores 0.2 -10 µm	15.6 a	15.2 ab	14.9 ab	15.2	15.2 ab	13.8 b	14.5
	Pores <0.2 µm	16.0 a	15.2 b	15.3 b	**15.5**	17.6 c	18.6 d	**18.1**
	PT sat	48.0 bc	47.5 ab	46.1 a	47.2	47.5 ab	49.6 c	48.5
	Bulk density	1.22 a	1.19 ab	1.23 a	1.21	1.19 ab	1.16 b	1.18
2005	Pores >10 µm	20.1 ab	22.5 a	18.2 b	20.3	18.9 ab	20.1 ab	19.5
	Pores 0.2 -10 µm	13.9 a	13.2 a	15.8 b	14.3	14.3 ab	13.6 a	14.0
	Pores <0.2 µm	15.8 a	15.5 ab	15.0 b	**15.4**	17.6 c	18.6 d	**18.1**
	PT sat	49.8 ab	51.2 ab	49.0 a	50.0	50.8 ab	52.4 b	51.6
	Bulk density	1.16 ab	1.15 ab	1.19 a	1.16	1.15 ab	1.13 b	1.14

In 2003 the bulk density ranged from 1.21 (02-C) to 1.27 g cm^{-3} (86-C), with an average of 1.24 g cm^{-3}. Total porosity ranged accordingly from 43.6 to 46.1 % with an average of 44.9 %. Fine pores (<0.2 µm) represented in average 20.4 % of the soil volume and 45 % of the total porosity. Large pores only accounted in average for 11.7 % of the soil volume.

In 2004, the average total porosity increased to 47.8 %, thanks to an increase in medium (14.9 %) and large pores (16.3 %). Fine pores decreased to 16.5 %. The difference between 2003 and 2004 is observed in all treatment, regardless of age or management. However, although large pores volume is not significantly different ($p<0.05$) between plots, fine pores volume is significantly greater in recently reclaimed *tepetates*, both in 2004 and 2005.

In 2005, the average porosity increased to 50.6 % thanks to an increase in large pores (20 %). The volume of medium and fine pores remained constant compared to 2004, at 14.1% and 16.5 % respectively. The same way as in 2004, the increase in porosity is observed in all treatment regardless of age or management.

The increase in porosity between years is probably due to different soil conditions during sampling rather than evolution of physical parameter over the years.

4.3.3.2.Pore size distribution

Detailed pore size distribution results are presented in Table A- 19, Table A- 20, and Table A- 21.

In agreement with total porosity results, there is no significant difference in pore size distribution between plots within a year (repeated measures ANOVA).

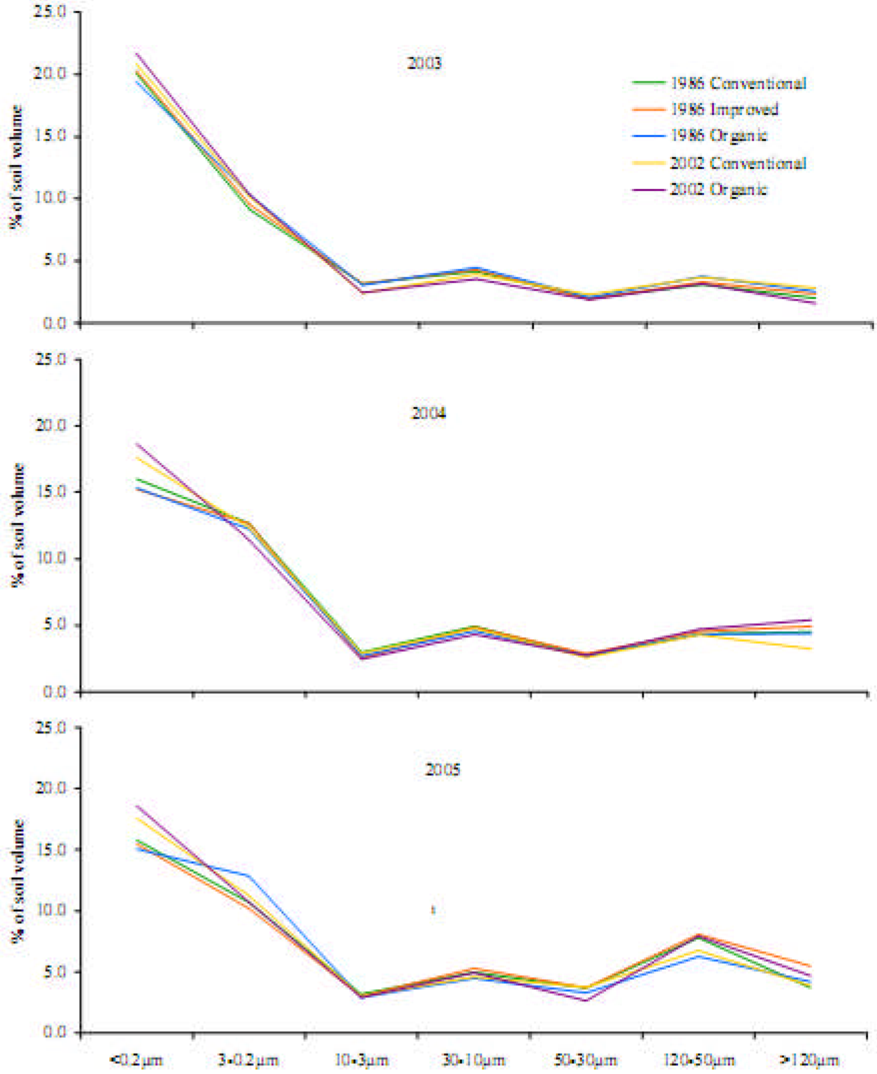

Figure 20: Pore size distribution in 2003, 2004 and 2005 (Table A-19, A-20 and A-21)

4.3.3.3.Effect of depth on porosity

In 2003, total porosity ranged on average from 44.1 % at 10 cm depth to 45.2 % at 40 cm, with no significant difference (P>0.05) between depth, regardless of the plot (Table A- 19 and Table A- 21)

In 2004, in ridge areas, the porosity varied on average between 48.6 % at 5 cm and 46.8 % at 40 cm, but this difference was not significant (Table A- 20).

In 2005, total porosity significantly decreased with depth, with values of 51.2 % in the first 20 cm depth, 49.5 % at 30 cm depth and 46.4 % at 40 cm. Porosity decreased with depth in all plots (table A-17 appendix 6). The decrease in total porosity in linked to a decrease of the volume of pores >10 µm, from 22.8 % at 10 cm depth to 14.4 % at 40 cm depth. The volume of pores <10 µm remained constant in the profile with values ranging from 15.4 % at 5 cm and 15.2 % at 40 cm for medium pores and from 15.7 % at 5 cm to 16.8 % at 40 cm depth for fine pores (Figure 21). The presence of structural crust and compaction of the upper horizon is also clearly visible, with a decrease of larger pores (>120 µm) at 5 cm (3.3 %) compared to 10 cm (5.5 %) (Table A- 20).

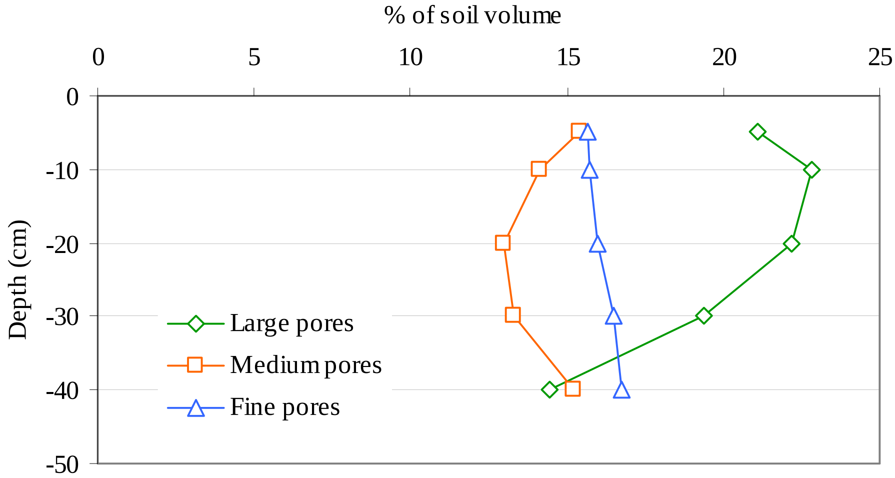

Figure 21: Effect of depth on pore size distribution in 2005 in Tlalpan (Table A-21)

4.3.3.4. Effect of ridge and furrow systems on porosity

In 2004, maize was cultivated on a traditional ridge and furrow system. Samples were taken both on furrow and ridge areas to assess the possible effect of such system on porosity.

Analysis of variance showed that in the first 5 cm depth, porosity in ridge area (48.6 %) is significantly higher ($p<0.001$) than in furrow area (45.6 %), regardless of the plot (Figure 22).

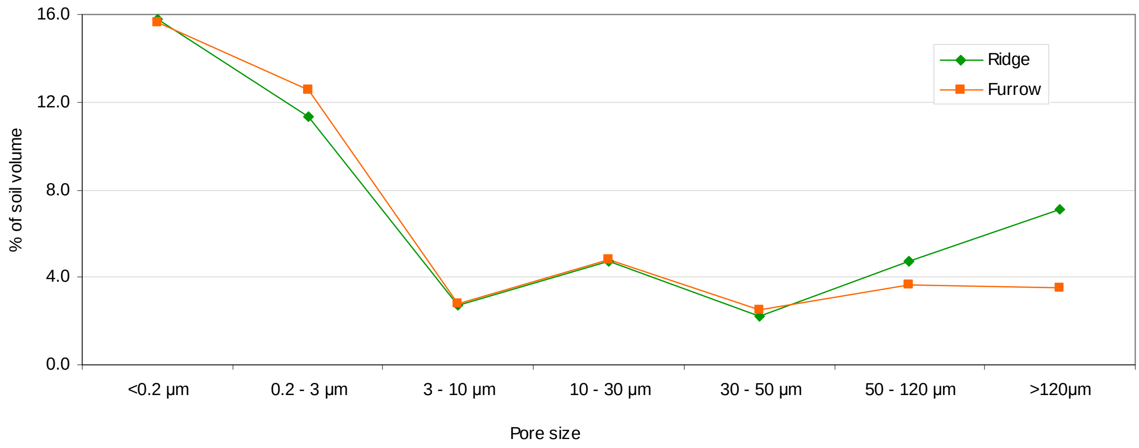

Figure 22: Pore size distribution at 5 cm depth in ridge and furrow maize cropping in reclaimed *tepetate* (Table A- 22).

The reduced porosity in furrows is due to a reduction of pores 50 -120 µm and > 120 µm. The latter (> 120 µm) occupy 7.1 % in ridge area against only 3.5 % in furrows. Volume of pores <50 µm is not significantly different between the two areas.

In furrows, runoff crusts are formed by successive organized deposits of sand and silt particles settling down according to the flow velocity (*Casenave and Valentin*, 1989; *Janeau et al.*, 1992). The organization of particles and the absence of roots in this area reduced macroporosity (> 50 µm).

4.4. Statistical analysis

4.4.1. Relationship between SOC, aggregate stability and erodibility

Table 13: Bivariate covariance table between SOC, PS 1-2 mm (Percolation stability index measured on aggregates 1-2mm), PSw (weighted percolation stability index), MWD, runoff and soil loss (annual values) in reclaimed terraced *tepetates*.

		SOC	PS (1-2 mm)	MWD	PSw	Runoff
2003	PS (1-2 mm)	0.62	-			
	MWD	0.74*	0.29	-		
	PSw	0.72*	0.85**	0.44	-	
	Runoff	-0.96*	-0.51	-0.57	-0.74	-
	Soil loss	-0.95*	-0.47	-0.57	-0.69	0.98**
2004	PS (1-2 mm)	0.46	-			
	MWD	0.45	0.09	-		
	PSw	0.49	0.99**	0.19	-	
	Runoff	-0.88*	-0.34	0.14	-0.34	-
	Soil loss	-0.89*	-0.36	0.12	-0.35	0.99**
2005	PS (1-2 mm)	0.78	-			
	MWD	0.50	-0.02	-		
	PSw	0.92*	0.97**	0.17	-	
	Runoff	-0.95*	-0.67	-0.42	-0.83	-
	Soil loss	-0.96**	-0.73	-0.44	-0.87	0.98**
all years	PS (1-2 mm)	0.39	-			
	MWD	0.33	-0.24	-		
	PSw	0.46*	0.98**	-0.17	-	
	Runoff	-0.89**	-0.03	-0.22	-0.05	-
	Soil loss	-0.82**	0.01	-0.04	-0.01	0.93**

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

4.4.1.1.Relationship between aggregation and SOC content

Overall, the relationship between aggregation (PS, PSw, MWD) and SOC is very poor or inexistent: there is no significant relationship between SOC and PS (1-2 mm), neither between SOC and MWD (r= 0.33), and a weak, although significant (r=0.46), relationship between SOC and PSw.

The samples used for SOC analysis and the samples used for aggregation analysis (MWD, PS, PSw) are different and were not taken at the same date. Therefore, SOC and aggregation are related to the same plot, but not to the same sample. The lack of correlation is therefore partly due a methodological problem and does not necessarily imply they are not related. This result is discussed further in part 5.

4.4.1.2.Relationship between aggregation and erodibility

There is no significant relationship between the aggregation parameters (PSw, PS, MWD) and erodibility (soil loss and runoff). Part of it can be attributed to methodological issues already mentioned in part 4.3.2.

4.4.1.3.Relationship between SOC and erodibility

There is a strong relationship between SOC and soil erosion, for both soil loss ($r = 0.82$) and runoff ($r = 0.89$). This relationship is analyzed further in the following chapter (4.4.2)

4.4.2. Soil loss and runoff prediction

The objective of this chapter is to:

1. Assess the relationship between erosivity, SOC and vegetation cover on soil loss and runoff.
2. Predict soil loss and runoff in terraced reclaimed *tepetates* for individual event and annual value

4.4.2.1. Data set

In total over the 3 years, 310 erosive events were recorded in the 5 experimental plots. Some events were discarded according to the following criteria:

- When detailed rainstorm data was not available
- When runoff volume was below a threshold value of 1 mm in plots reclaimed in 1986, or 5 mm in plots reclaimed in 2002. In cases where runoff was >1 mm in at least 2 plots (1986-plots), the event was included for all plots. This criteria was set to avoid over representation of small events.

In total 141 events (or cases) were selected (Table A- 10). According to *Tabachnick* and *Fidell* (2001), the minimum size recommended in a multiple regression is $N > 50 + 8m$ where m is the number of independent variables. In our study 3 independent variables are used. The number of cases selected if therefore approximately twice the minimum size recommended (74). The model includes 45 % of the erosive events, and covers 77 % of the total soil loss recorded. Descriptive statistics of the variables (Table A- 11) showed that soil loss, runoff, and all the rain parameters are positively skewed. To comply with multivariate analysis assumption of normality, skewed variables were logarithmically transformed.

4.4.2.2.Variables

SOC content

Since SOC content was not monitored throughout the cropping season but only at the end of the season, annual values are used.

Vegetation cover prediction

Since vegetation cover was not monitored on a daily basis, we used predicted values of vegetation cover for each erosive event in the analysis.

When the maximum value is known, vegetative growth pattern are well described by symmetrical logistic equations (*Landsberg*, 1977), such as:

$$Cv = \frac{C\max}{1 + b\exp(-kT)} \qquad \textbf{(10)}$$

Where: C*v* is the vegetation cover,

*C*max is the asymptote (maximum vegetation cover)

b and *k* are curvature parameters

T is time in days after planting.

In 2003 and 2005, *b* and *k* were determined to best-fit the measured data. In 2004, they were set so that maximum vegetation cover was reached approximately 90 days after sowing.

After maximum crop development, leaf senescence causes vegetation cover to decrease. The decay in vegetation cover was predicted by linear interpolation in 2003 and 2005. In 2004, the decrease was considered to follow the same logistic curve after maximum value was reached (90 days), with a loss of vegetation cover of 40% of the maximum value (*Lizaso et al.*, 2003).

Table 14: Curvature parameters for the modelling of vegetation cover . [(a)] Observed vs predicted.

Year	b	k	$r^{2\,(a)}$	N	Sig.
2003	6	0.2	0.85	15	p<0.001
2004	6	0.12			
2005	9	0.2	0.94	58	p<0.001

4.4.2.3.Relationship between erosivity and erosion

EI30 is the rain erosivity parameter (R factor) used in the USLE (*Wischmeier and Smith*, 1978). It is the product of the kinetic energy of the storm with the maximum intensity in 30 minutes. Some authors (*Prat*, 1997) suggested that due to the rainstorm intensity patterns in Mexican central highlands, EI10 should be better correlated to soil loss. Our results showed that, in cultivated conditions, and for single events, EI10 is more strongly correlated with soil loss than EI30, with average correlation coefficient of 0.55 and 0.52 respectively (Table A- 12). EI30 is however more strongly correlated to runoff than EI10, with r = 0.77 and 0.75 respectively. Rain precipitation and kinetic energy are also strongly related to runoff, with r = 0.77 and 0.78 respectively (Table A- 12). When detailed rainfall recording is not available, rain depth can be used satisfactorily to predict runoff.

4.4.2.4.Soil loss and runoff prediction

For single event

Erosivity, Vegetation cover and SOC made a significant unique contribution to predict soil loss and runoff. EI10 or EI30 are the best erosivity parameters to predict soil loss, explaining together with vegetation cover and SOC 62 % of the variance (Table A- 13). Although not as accurate as EI30 or EI10, rain depth is significantly correlated to soil erosion and can also be used to predict soil loss instead of EI30 when detailed rainfall records are not available (pluviometers).

The erosivity factor (EI30) made the greatest contribution to predict soil loss, accounting for 27 % (EI30) of the variance, whereas vegetation cover accounted for 26 % and SOC for another 9 % (EI30) (Table A- 13).

Runoff was better predicted than soil loss thanks to a greater contribution of the erosivity parameter. Both EI30 and rain depth, together with soil cover and SOC predicted significantly (R^2=0.68) the volume of runoff. EI30 alone accounted for 41 % of the total variance, with soil cover contributing another 23 % and SOC only 4 %. Whereas EI10 is a good indicator to predict soil loss, it is not so efficient to predict runoff (R^2 = 0.64). EI30 is the best erosivity indicator to predict both soil loss and runoff (Table A- 13).

Finally, if runoff measurement are available, soil loss can be predicted with precision (R^2 = 0.81). In this case runoff accounted for 68% of the variance and soil cover for another 13 %. SOC did not make any significant unique contribution (P > 0.05) and was discarded.

Table 15: Multiple regression equation for single event soil loss and runoff prediction in terraced (slope 3-4%) cultivated *tepetates* in Tlalpan, Tlaxcala. Erosion (soil loss in kg ha^{-1}); Runoff (mm); EI30 (MJ ha^{-1} mm h^{-1}, or 10 N h^{-1}); COVER (m^2 m^{-2} :area of soil covered per unit of area); SOC (mg g^{-1}).

Regression equation	R^2	Sig.
LOGerosion = 1.958 + 0.66(LOGEI30) - 1.09(COVER) - 0.15(SOC)	0.62	p<0.001
LOGrunoff = 0.046 + 0.62(LOGEI30) - 0.3(COVER) - 0.16(SOC)	0.68	p<0.001
LOGerosion = 1.96 + 1.05(LOGrunoff) - 0.76(COVER)	0.81	p<0.001

Soil loss and runoff prediction equations presented in table 9 are valid for individual erosive events included in the range of those considered in the model and for terraced cultivated *tepetates* with slopes of approximately 3 – 4 %, and with SOC content ranginf from 1 to 5 mg g^{-1}. They have not been validated for other conditions and should therefore not been extrapolated.

The multiple regression analysis clearly highlighted that among the parameter that can be influenced by management (vegetation cover and SOC), soil protection by vegetation cover has the greatest impact on soil erosion. SOC also make a significant contribution to soil erosion but to a lesser extent.

In case of a single extreme annual event (on average 45 mm and EI30 = 63 N h^{-1}), and a vegetation cover of 50 %, increasing SOC from 1 to 2 mg g^{-1} can reduce soil loss from 1.26 t ha^{-1} to 0.88 t ha^{-1} (30 % decrease). For the same extreme annual event, and in reclaimed *tepetate* with 1 mg g^{-1} SOC content, increasing vegetation cover from 50 to 80 % can reduce soil loss from 1.26 t ha^{-1} to 0.59 t ha^{-1} (53 % decrease).

For annual values

The prediction models adjusted to annual runoff and soil loss explain a larger proportion of the variances than for individual events (results in Table A- 14).

Annual runoff rates can be predicted by SOC and EI30 and COVER with good accuracy (r^2 = 0.91, n = 15, Table 11). SOC alone is the main contributor and accounted for 79% of the variance. Vegetation cover (COVER) and rain erosivity (EI30) explained another 6 % and 5 % of the variance respectively (Table A- 14).

Erosion rates are well predicted by SOC content and EI30 (r^2 = 0.84, n = 15, Table 11). In that case SOC is the main contributor to soil loss variance (r^2 = 0.64), whereas EI30 explained another 20 %. Vegetation cover did not make any significant contribution to soil loss prediction. When annual runoff data are available, 89 % of the annual soil loss can be predicted. In this case runoff is the main contributor (r^2 = 0.85), with EI30 accounting for another 4 %. SOC and vegetation cover did not improve the model any further in this case (no significant single contribution). Using the sum of EI30 of all erosive events only instead of the annual EI30 (the sum of all events, both erosive and non-erosive) did not improve the model fit.

Table 16: Multiple regression equation for annual soil loss and runoff prediction in terraced (slope 3-4%) cultivated *tepetates*. Soil loss (t ha^{-1}); Runoff (mm); EI30 (N h^{-1}); SOC (mg g^{-1}); COVERmax (m^2 m^{-2}: vegetation cover at crop maximum development).

Regression equation	r^2	n	Sig.
Soil loss = 9.75 - 3.98(SOC) + 0.03(EI30)	0.84	15	p<0.001
Soil loss = 0.07(RUNOFF) + 0.015(EI30) - 4.83	0.89	15	p<0.001
Runoff = 256.23 - 37.50(SOC) + -144.82(COVERmax) + 0.207(EI30)	0.91	15	p<0.001

The significance of the regression analysis greatly depends on the contrast between 86-plots and 02-plots. There is a strong relationship between runoff rates and SOC in recently reclaimed plots, but no relationship in 86-plots (figure 11).

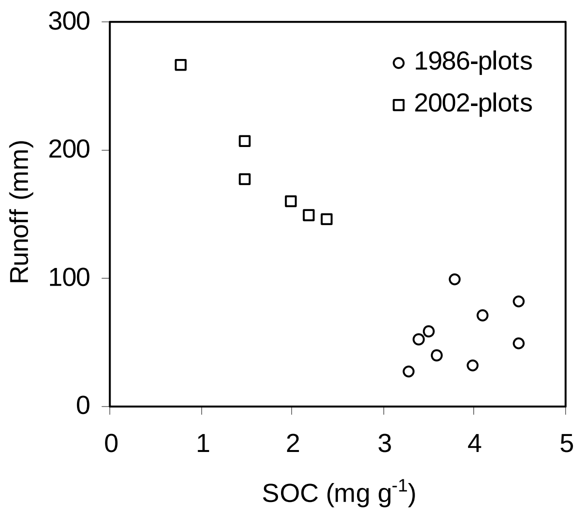

Figure 23: Relationship between SOC and annual runoff rates in plots reclaimed in 1986 and 2002.

It is important to stress that annual sediment and runoff rates prediction are based upon 15 values (5 plots * 3 years), and although the r^2 reported are adjusted to take into account the size of the sample, the latter is under the recommended size. All interpretation based upon the regression equations proposed should be made with the necessary critical judgment.

5. Discussion: Effect of organic farming on soil erosion and soil structure

5.1. Erosivity

Rain erosivity in Tlalpan is moderate, with average annual precipitation of 675 mm and average R of 127 N h^{-1}. It is however, higher than on the western side of the Sierra Nevada (Prat, 1997).

Our results complement the previous studies of *Baumann* (1996) and *Fechter-Escamilla* (1997a) and give a longer term perspective of rainfall patterns in the Bloque de Tlaxcala. Rainfall patterns recorded over the 2002-2005 period and confirmed that in this region soil loss is caused by a reduced number of rainstorms. Such rainfall and erosion distribution pattern have also been observed in many locations in the world and under contrasting rainfall regime (*Edwards and Owens*, 1991; *Langdale et al.*, 1992; *Nyssen et al.*, 2005; *Gonzalez-Hidalgo et al.*, 2007).

Rain erosivity in Tlalpan have been extensively discussed by *Baumann* (1996). Our results confirm trends previously reported but do not give further insights. Hence, this aspect won't be developed further.

5.2. Effect of organic farming on soil erosion

5.2.1. Carbon dynamic in reclaimed *tepetates*

5.2.1.1.Incorporation and accumulation of SOC

In organic management, organic fertilization was applied at an average rate of 3.7 and 4.1 t ha^{-1} yr^{-1} (dry material) in 86-O and 02-O respectively. Such rates are lower than organic fertilization rates applied in other experiments in reclaimed volcanic ash soils:

i. In Eastern side of the Sierra Nevada, *Baez* et al. (1997) applied 40 t ha^{-1} fresh farmyard manure the first year after fragmentation and 20 t ha^{-1} the years onwards.

ii. In Ecuadorian Cangahua, *Podwojewski* and *Germain* (2005) applied 40 t ha^{-1} dry material after fragmentation and 10 t ha^{-1} the following years.

iii. Acebedo et al. (2001) studied *tepetate* aggregation in greenhouse conditions after incorporation of the equivalent of 50 t ha^{-1} dry cattle manure.

iv. In Salvador, *Collinet* and *Mazariego* (1993) used 15 t ha^{-1} yr^{-1} dry poultry manure to reclaim volcanic ash soils.

Manure or compost application of more than 10 t ha^{-1} yr^{-1} are hardly available for the average farm in the area (*Lepigeon,* 1994) and would require external provision of organic material (manure, residues, etc..). It would in turn increase production costs and make the farm more dependant on external inputs. The organic management evaluated in our experiment was designed to be acceptable and adoptable by local small holders, as well as being economically viable and environmentally reproducible. Ideally, organic farming should limit external inputs to reduce costs and tend to be self sufficient in terms of organic fertilization. In this respect, compost should be produced using the amount of residues available from the previous crop and manure produced on the farm. For experimentation sake, it was not possible to follow this principle every year, but attempt has been made to keep external inputs of organic material to reasonable levels and to make the organic management reproducible and adoptable to small farmers in the area.

In plots reclaimed in 1986, 20 % (on average) of the C incorporated between 2002 and 2005 was accumulated in soil (Table 8). In recently reclaimed *tepetates* this ratio was 24 % in organic management and 40 % in traditional management. The higher translocation efficiency in traditional management can be explained by the origin of the C incorporated. Numerous studies have demonstrated that root-derived Carbon was more persistent than shoot-derived C (*Rasse et al.*, 2005). *Puget* and *Drinkwater* (2001) observed an increased retention of root-derived C in soils 6 months following crop incorporation in comparison to shoot-derived C. Experimental results summarized by *Bolinder* et al. (1999) also suggest that the percentage of below ground corn-C incorporated into SOC (range 16 – 30 %) is higher than that from above ground corn biomass (range 7.7 – 20 %). Hence, since the percentage of C inputs from roots is higher in 02-C than in the other plots, a greater proportion of C incorporated was accumulated in the soil in comparison to other systems. Our results are coherent with those reported by Bolinder, although differences exist because our study considered C translocation from different crops (not only maize) without discrimination between above- and below-ground C inputs.

On irrigated intensive cropping Vertisols in Central Mexico, *Follett* et al. (2005) calculated C sequestration efficiency of 22 % for above-ground C and estimated to 11 % the C sequestration efficiency for total C incorporated (above- and below-ground C).

In that respect, more research is needed to study further carbon sequestration mechanism in reclaimed *tepetates* and its impact on soil erosion. Understanding the effects of management on carbon sequestration in soil like *tepetates* with an initial SOC content almost inexistent is critical to developing adequate C conservation strategies.

5.2.1.2.Carbon losses

Carbon accumulation rates can be very slow in reclaimed *tepetates*, even with regular incorporation of OM (*Baez et al.*, 2002). This observation suggests that C loss by mineralization or erosion can be considerable (*Etchevers et al.*, 1997). Part of it can be attributed to intensive traditional tillage which increases aggregate disruption and carbon mineralization.

Carbon losses by erosion ranged from 38 kg ha^{-1} (86-I) to 87 kg ha^{-1} (02-C) in 2004 and from 17 to 68 kg ha^{-1} in 2005 (Table 18). The average organic carbon content in eroded sediments ranged from 5.4 g kg^{-1} (02-C) to 16.6 g kg^{-1} (86-I) in 2004 and from 8.7 (02-C) to 16.8 g kg^{-1} (86-C) in 2005.

It is a fact well established that OC concentration in eroded sediment is greater than in the soil they are originated (e.g. *Rumpel et al.*, 2006; *Bellanger et al.*, 2004). The preferential removal of the soil organic matter fraction by erosion is due to the low density of O.M, its concentration in the vicinity of the surface, and its association with fine particles and micro-aggregates which are more readily transported by runoff (*Lal*, 2003; *Yadav and Malanson,* 2007).

This phenomenon is expressed in terms of enrichment ratio (E_R), such as:

$$\mathbf{E_R = SOC_{sediment}/SOC_{soil\ uneroded}} \qquad \textbf{(11)}$$

Carbon losses primarily depend on soil loss and SOC content and can be predicted according to the following equation (*Starr et al.*, 2000; *Quinton et al.*, 2006):

$$\textbf{SOC loss = (soil loss)(SOC content)}(\mathbf{E_R}) \qquad \textbf{(12)}$$

In Tlalpan, E_R ranged from 4.8 to 3.5 with an average of 3.7 in 2004 and from 3.9 to 5.8 with an average of 4.8 in 2005.

Quinton et al (2006) found in the literature organic matter enrichment ratio ranging from 1.5 to 4.5. In Northern Laos in soils with high erosion rates, Rumpel et al. (2006) obtained E_R ranging from 1.7 to 2.7. However, neither Quinton et al. nor Rumpel et al. indicated the depth of the horizon considered to calculate E_R. Since SOC is preferentially accumulated in the upper layers of the soil, E_R can be greatly influenced by the depth of the horizon considered in the calculation. In the UK, Owens (2002) found E_R of 1.2 to 1.5 in average and concluded that it was easier to apply techniques to reduce erosion rates, and thereby carbon losses than applying techniques to reduce E_R. Even though E_R comparisons with other studies found in the international literature are hazardous because of the lack of information regarding the depth of the horizon that was considered to calculate E_R, it appears that our values of E_R are higher than the one reported in template regions. This is likely to be due to the very low SOC content in reclaimed *tepetates* which increase the contrast between the arable horizon and the upper part of the horizon where SOM is concentrated.

Table 17: Carbon losses by erosion and C concentration in sediment in Tlalpan in 2004 and 2005. Source: (*Báez et al.*, 2006).

		86-I	86-O	86-C	02-C	02-O
C losses by erosion (kg C ha^{-1})	2004	38	65	71	87	85
	2005	17	22	22	75	68
C in sediment (g C kg^{-1})	2004	16.6	15.3	12.7	5.4	8.3
	2005	15.7	15.8	16.8	8.7	12.4
C lost / C accumulated	2004	0.10	0.11	0.34	0.40	0.11
	2005	0.05	0.04	0.11	0.35	0.08
E_R (SOC at 0-10 cm)	2004	4.8	3.4	3.3	3.6	3.5
	2005	4.7	3.9	4.6	5.8	5.2

In 2005, C losses by erosion represented approximately 10% of the average C accumulation rate in Organic and Improved management. However in conventional management, where C inputs are limited, C losses by erosion represented 34 % (86-C) and 40 % (02-C) of the C accumulated per year. Losses of carbon by erosion in reclaimed *tepetates* are significant but are easily balanced by organic matter inputs from roots and crop residues, even in traditional management. Soil erosion is thus a phenomenon which does not cause severe on-site depletion of carbon content as reported in other ecosystems (*Lal*, 2003), but which reduces C accumulation rate in cultivated *tepetates*.

Baez et al. (2006) and *Covaleda* et al. (2007) concluded that carbon losses by erosion in reclaimed *tepetates* were minimal in the carbon balance and that loss of C occurred almost exclusively by mineralization. Nonetheless, although on-site losses of carbon in reclaimed *tepetates* are limited, the mechanisms involved in soil erosion greatly contribute to carbon losses. Aggregate breakdown by slaking, differential swelling, or raindrop impact (*Le Bissonnais*, 1996) releases encapsulated carbon which is then exposed to oxidation and microbial processes (*Six et al.*, 2004). In addition, the C released is preferentially transported by runoff or wind (*Lal*, 2003). Whereas on-site removal of SOM by erosion can be redistributed within the watershed or ecosystem, SOM exposed to mineralization or oxidation by breakdown of aggregate is lost to the atmosphere (*Polyakov and Lal*, 2004). More research is needed to determine the part of carbon mineralization induced by the mechanism involved in soil erosion, and the effect of organic farming on C mineralization.

5.2.2. Vegetation cover

Vegetation cover reduces particle detachment by intercepting and dissipating part of the energy of raindrops before they strike the soil surface (*Hudson*, 1995). As a result, it reduces sealing and crust formation, favours infiltration and, hence, decreases runoff and erosion rates (*Box and Bruce*, 1995; *Stocking*, 1994; *Morgan*, 2005). There are numerous evidences of the positive effect of vegetation cover on soil erosion in international literature. In chapter 4.4.2, the regression analysis showed that vegetation cover explained 26 % of the variance in soil loss for individual rainstorm. This result gives a quantitative indication of the effect of vegetation cover in reclaimed *tepetates*, and the role this factor can play in the first years after fragmentation.

The discussion will not focus on the effect of vegetation cover on soil erosion, which is a fact very well established, but on the way management practices can affect vegetation cover. Two aspects are considered: 1) crop development, which depends on plant nutrition and water supply, and 2) crops association.

5.2.2.1.Crop development and vegetation cover

As presented before (Table A- 7) recently fragmented *tepetates* are almost sterile material due to their lack of N and P, but these deficiencies can be overcome by appropriate fertilization to reach acceptable crop production (*Etchevers et al.*, 1992; *Navaro and Zebrowski*, 1992; *Marquez et al.*, 1992; *Baez et al.*, 1997).

In practice, small-holders in the area tend to adapt the amount of fertilization to their financial capacities at the time the fertilization is required. As a result, fertilization in traditional management is often below crop requirements and can limit crop development and vegetation cover. Our results clearly showed that in recently reclaimed *tepetates*, the amount of fertilization applied under conventional management (02-C) don’t overcome fertility deficiencies and result in poor vegetation cover.

When applied at 15 t ha^{-1} (fresh manure) in recently fragmented *tepetates*, organic fertilization provided vegetation cover similar to *tepetates* cultivated for more than 15 years.

However, in 2005 with wheat cropping, the amount of compost applied in 02-O (4.2 t ha^{-1}) resulted in poor crop development and vegetation cover. This observation suggests that the amount of organic fertilization required to provide an optimum nutrition for the crop is greater than what can be produced by composting the previous crop residues. Two options can be considered to reach optimum crop development and vegetation cover:

1) Increasing the organic fertilization, with additional inputs of manure, produced on the farm or purchased locally, or compost. The latter implies purchasing additional organic material to be composted (straw, maize stalks, etc…). Further research is needed to evaluate the cost-benefit relationship and the cost of opportunity of strict organic farming.

2) Complementing organic fertilization with mineral fertilization, which is an effective way to increase soil fertility (*FAO*, 1999).

In any cases, the fertilization strategy must be adapted to the type of production system found in the area and to the specific conditions of the smallholders.

Water supply

Results of porosity showed no evidence of significant differences in water holding capacity between plots (Chapter 4.3.3). However, surface crusting and sealing enhanced by aggregate breakdown reduce infiltration and, as a consequence, water storage and availability for plants. The frequent monitoring of soil water content done in 2005 indicated that over the period 2002-plots were significantly drier than 1986-plots (Table A- 9). This is consistent with runoff measurements which showed that in 2005, 164 mm and 140 mm water were lost by runoff in 02-C and 02-O respectively, against 33 mm on average in 86-plots (Table A- 2). It clearly highlights that when nutrition deficiencies are not overcome, either by organic or mineral fertilization, it gives rise to a vicious circle that will enhance soil erosion: nutrition deficiencies reduce crop growth and vegetation cover. This will enhance surface crusting and sealing and will increase runoff. In turn, water losses by runoff decrease water supply which will affect plant growth and vegetation cover (Figure 24).

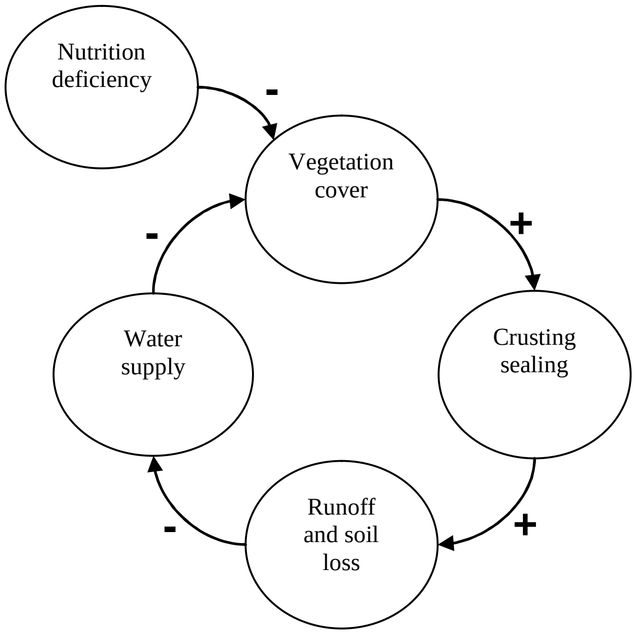

Figure 24: Cause-effect relationship between water supply, vegetation cover and soil erosion. + and – indicate an increasing (+) and decreasing (-) effect.

5.2.2.2.Crop association

Crop association, or multiple cropping, proved very promising to reclaim *tepetates* since it increased forage yields and vegetation cover by 30 % in average over the period in recently reclaimed *tepetates*. *Baez* el al (1997) evaluated various crop association and compared them to monoculture. They did not measure vegetation cover but crop production and concluded that associations between cereals and legumes are much more productive than cereals monoculture. They also reported satisfactory results for the association oat-vetch, but recommended to use *Medicago polimorfa* instead of *Vicia sativa* because of the aggressiveness of the latter which compete for water and can affect oat development in dry years. In agreement with Baez et al, the association oat-vetch in our experiment proved to be a very suitable crop during the first cycle after fragmentation since it provided high vegetation cover and similar yields to those obtained in *tepetates* cultivated for more than 15 years. Oat-vetch association is cultivated in many part of the world and is recognized as an excellent forage (*FAO*, 2003). In Tlalpan, *Fechter-Escamilla* et al (1997b) showed that vegetation cover provided by *Trifolium repens* and *Medicago polimorfa* associated with maize reduced soil loss rates to 1.54 t ha^{-1} compared with 7.31 t ha^{-1} in maize cropping (Table 18).

5.2.2.3.Mulching

In Mexican highlands, like in semi arid areas, the extended dry season prevent the establishment of cover crop before the onset of the rainfall season, leaving the soil exposed to the first erosive rainstorms. Mulching is an alternative whose effectiveness is widely recognized (e.g. *Lal*, 1995; *Morgan*, 2005; *Hobbs*, 2007). The residue cover both protects the soil from raindrop impact and decreases stream power by increasing roughness.

Mulching has not been evaluated in Tlalpan within REVOLSO project, but has been evaluated in Michoacan on reclaimed deteriorated Acrisols by *Bravo* et al. (2006). They showed that 30 % residue cover by at the beginning of the rainfall season reduced erosion rates by 70 % compared to unprotected soil. Similar results were obtained previously in Patzcuaro watershed on andosols by *Tiscareno-Lopez* et al. (1999). More examples of soil loss reduction by mulching in different type of soils and climate are given by *Morgan* (2005) who suggest that an application of 5 t ha^{-1} of straw is sufficient to achieve an optimum soil cover of 70 to 75 %. In Mexico, *Roldan* et al (2003) used approximately 3 t ha^{-1} crop residue to provide 33 % ground cover, and approximately 5 t ha^{-1} to provide 66 % ground cover.

Mulching requires significant amount of residues, which will be incorporated to the soil and mineralized. However in the study area, crop residues are traditionally exported for animal pasture despite their poor nutrimental value. Residue management is, thus, an issue that must be address since soil conservation practices that promote organic matter incorporation and mulching are competing with traditional use of crop residues. To increase probabilities that farmers adopt new technologies, it is therefore necessary to develop simultaneously sustainable alternatives to traditional animal feeding system.

5.2.3. Runoff and erosion rates in reclaimed *tepetates*

After 16 years of cultivation, soil erosion rates in reclaimed terraced *tepetates* in Tlaxcala are below 5 t ha^{-1} yr^{-1}. Soil loss rates below 10 t ha^{-1} yr^{-1} are usually considered tolerable (*Hudson*, 1995; *Morgan*, 2005). Soil erosion is critical after fragmentation, with soil loss rates of more than 15 t ha^{-1} yr^{-1}, but can be kept within acceptable range as long as they are cultivated with dense vegetation cover within the first years of cultivation. The study proved that regular incorporation of OM to the soil after fragmentation reduces significantly erosion rates from the first years after fragmentation.

In Tlalpan, soil erosion has been measured previously at field scale in 1995 and 1996 in *tepetates* cultivated for 9 and 10 years after fragmentation (*Fechter-Escamilla et al.*, 1997b).

The two years were little erosive, with R factor of 196 N h^{-1} and 218 N h^{-1} respectively, and erosion rates ranged from 1.54 ton ha^{-1} to 7.31 ton ha^{-1} depending on the treatment (Table 18). Reduced tillage without soil cover increased significantly runoff rates because of the low infiltration in the upper horizon (*Fechter-Escamilla et al.*, 1997b), increasing in turn erosion rates compared to traditional tillage. However, reduced tillage with additional ground cover provided by the associated crops both reduced runoff and soil loss compared to traditional tillage.

Table 18: Field scale (1200 – 1500 m^2) soil loss and runoff in Tlalpan in 1995 and 1996. Source: Fechter-Escamilla et al. (1997b). LT: Traditional tillage (Maize cropping with soil preparation by disc ploughing and two hoeing during cropping); LRscv: No tillage without vegetation cover (Maize cropping by direct sowing and weed control with herbicides); LRccv: No tillage with associated vegetation cover (Maize cropping with no tillage and association of *Trofolium repens* and *Medicago polimorfa*)

			LT	LRscv	LRccv
1995	Soil loss	(ton ha^{-1})	3.00	3.72	2.34
	Runoff	(mm)	76	132	53
	Annual precipitation : 603 mm				
	EI30: 196 N h^{-1}				
1996	Soil loss	(ton ha^{-1})	5.02	7.31	1.54
	Runoff	(mm)	30	98	11.2
	Annual precipitation: 607 mm				
	EI30: 218 N h^{-1}				

On the Eastern hillside of the Sierra Nevada, *Prat* et al (1997a) carried out field scale (700 m^2) erosion studies where they measured erosion rates in recently reclaimed *tepetates* under managements similar to those we assessed in Tlalpan. In their experiment, the “monoculture” system is equivalent to our traditional management, with use of mineral fertilizers and no associated crop. Their system called “associated crop and O.M.” is similar to our organic management, with application of 40 t ha^{-1} fresh manure in 2003 and 20 t ha^{-1} the following years, and use of associated crops.

They found that in average, crop association and incorporation of organic matter reduced erosion rates to 2 t ha^{-1} compared with 7.8 t ha^{-1} under monoculture system. However, they obtained the same effect with crop association and mineral fertilization, suggesting that the effect of vegetation cover prevails upon the effect of organic fertilization. The erosion rates they reported are smaller than those we obtained in Tlalpan. This difference in mainly explained by the fact that rainfall erosivity in San Miguel Tlaixpan (the name of the place where their experimental site was located) over the period 1993-1996 was only 205 N h^{-1} on average (*Prat*, 1997), whereas in Tlalpan over the period from 2003 to 2005, the R factor was on average 305 N h^{-1}. Besides this difference, our results are consistent with their conclusions that vegetation cover plays a major role in controlling erosion rates in the first years after fragmentation.

5.2.4. Evolution of erosion rates

Our results clearly highlighted the high sensibility of recently fragmented *tepetates* to soil erosion, with soil loss rates up to 3 times higher than in reclaimed *tepetates* cultivated for more than 15 years. After such period of time, *tepetates* seem to have reached a stable level below acceptable soil loss rates. Some uncertainties remain though as of how fast erosion rates decrease and how many years are required before reclaimed *tepetates* can be considered stables. This is a fundamental question to design and implement sustainable rehabilitation programs.

In chapter 4.4.2, we showed that soil loss variance in reclaimed *tepetates* depends on erosivity, SOC and vegetation cover. We thus expect the evolution of erosion rates to depend on the evolution of these three parameters. Assuming that i) rainfall erosivity is a random parameter, with independent behavior from one year to another; ii) vegetation cover is a parameter that can be controlled by management practices (type of crop, fertilization) at each cropping cycle; then over time, the evolution of erosion rates is linked to the evolution of SOC content and, as a result, to C accumulation rates.

Yet, little is known about C accumulation in soils with initial SOC content almost inexistent such as reclaimed *tepetates*. Most recent studies on C accumulation or sequestration rates in agricultural lands deal with SOC variation after agricultural management changes (e.g. review by *Post and Kwon,* 2000), such as change from conventional tillage (CT) to no tillage (NT) (*West and Post*, 2002). The latter reported that when changing from CT to NT, it is possible to sequester 0.57 ± 0.14 Mg C ha^{-1} yr^{-1}, with SOC reaching a new equilibrium after 15 to 20 years. Lal et al. (1998; cited by *FAO*, 2004), quantified carbon sequestration potential for different technological options in drylands. For compost application, they suggested C sequestration rates of 0.10 to 0.20 Mg ha^{-1} yr^{-1}, similar to C sequestration potential for agriculture intensification or conservation tillage, but less than that of water conservation and management (0.10 to 0.20 Mg ha^{-1} yr^{-1}).

Baez et al. (2002) suggested that C accumulation in reclaimed *tepetates* followed a logarithmic increase in time, regardless of the type of management. In the case of maize monocropping, Baez et al. observed that SOC content tends to become stable after the first decade and argued that SOC content could hardly increased even after 50 or 100 years due to the limited amount of organic matter incorporated in this type of agricultural management.

Our results showed that the fragmentation and the subsequent cultivation of tepetates induced by itself a carbon sequestration process. Cultivation, even with low OM inputs such as the conventional management, provided enough organic material (roots and harvest residues) to sequester around 0.2 Mg C ha^{-1} yr^{-1} (02-C) in the top 20 cm soil. The same C sequestration rate (0.2 Mg C ha^{-1} yr^{-1}) was also measured 16 years after fragmentation (86-C). This “baseline” C sequestration rate can be multiplied by 4, to 0.8 Mg C ha^{-1} yr^{-1} with additional organic matter inputs in the years following fragmentation. The implementation of organic farming after 16 years of conventional farming did increase SOC content and C sequestration to 0.61 Mg C ha^{-1} yr^{-1}. However, the SOC increase was not correlated to any significant decrease in sediment rates. This observation suggests the existence of a threshold value of approximately 3.4 mg g^{-1} at 0-10 cm (Figure 23) above which: i) SOC has no further effect on soil erosion; or ii) differences in SOC are not large enough to produce significant differences in runoff and erosion rates at field scale.

Assuming linear accumulation rates presented in table A-19 (0-10 cm) and the regression model proposed in table 11:

i. Reclaimed *tepetates* could reach SOC content higher than 3.4 mg g^{-1} at 0-10 cm depth (stability threshold) after 7 years of cultivation under organic management and after 21 years under conventional management.

ii. Assuming an average year (erosivity = 279 N h^{-1}), erosion rates in reclaimed tepetates could drop below tolerable rates (10 t ha^{-1}) after 3 years under organic management and after 9 years under conventional management.

These estimations seem realistic for the organic management. For conventional management, the mean accumulation rates observed over the first 4 years after fragmentation (0.09 mg g^{-1} yr^{-1}) is lower than the estimated mean accumulation rates in plots reclaimed in 1986 over a period of 16 years (0.15 mg g^{-1} yr^{-1}). If we take into account this value instead of the one we observed over a period of 4 years, tolerable erosion rates could be reach after 7 years instead of 9 years and the stability threshold could be reach after 17 years instead of 21 years under conventional management. In any cases, organic management after fragmentation can reduce the critical period when reclaimed *tepetates* present high erodibility by 2 to 3 time compared to conventional management.

5.3. Effect of organic management on soil structure

5.3.1. Aggregate stability dynamic and organic management

Aggregate stability expresses the resistance of aggregates to breakdown when subjected to potentially disruptive processes (*Hillel*, 2004). Aggregate stability is affected by soil texture, clay mineralogy, organic matter, cations concentration, iron and aluminium oxides and $CaCO_3$ (*Le Bissonnais*, 1995). We will focus on the effect of organic matter since the primary soil characteristics of the reclaimed *tepetates* we studied are similar, and because differences between managements and age of rehabilitation are mainly based on soil organic carbon content.

Organic matter enhances formation and stability of aggregates by bonding and/or holding particles together (*Oades*, 1984). More recently, several studies have demonstrated that the hydrophobicity of organic matter also greatly contributes to aggregate stability by decreasing wettability of aggregates, reducing the magnitude of slaking and differential swelling (*Chenu et al.*, 2000; *Goebel et al.*, 2005; *Zaher et al.*, 2005).

The ANOVA of percolation stability test revealed a positive effect of age of rehabilitation (2002-plots against 1986-plots) and of organic management on aggregate stability, regardless of the age of reclamation. This observation (Figure 17) suggests that aggregate percolation stability is the result of the combination of:

i. Time-driven stability that develops over the years during the rehabilitation process, and which is related to SOC content
ii. Management-driven stability, independent from the age of rehabilitation, which is related to the incorporation of fresh organic material (crop residues, compost or manure)

Results from 2005 (Figure 18, Table A- 17) complement this observation by showing that:

i. At the beginning of the rainfall season, a few weeks after incorporation of fresh organic matter, we observed a peak of stability in organic management. 02-O obtained similar percolation values than 86-C and 86-I, although SOC content in 02-O is lower than in 86-C and 86-I. This observation indicates that the stability provided by the incorporation of fresh organic matter (management driven stability) prevails upon the stability provided by SOC content (time driven stability). It would also explain why SOC and PS are weakly related.
ii. At the end of the rainfall season, percolation stability in 2002-plots, both under conventional and organic management, dropped below the percolation stability measured in

1986-plots. This observation suggests that the effect of fresh organic matter incorporation on percolation stability is short-lasting (3 to 4 months).

These results are coherent with several studies that showed that the stability of macroaggregates is not related to SOC but to other organic compounds (*Tisdall and Oades*, 1982). *Perfect* and *Kay* (1990) found that increases in wet-aggregate stability did not correlate with increases in total organic carbon content, suggesting that some components of the organic carbon pool were more actively involved in stabilizing aggregates than others. *Golchin* et al. (1995) concluded that neither total organic matter nor total O-alkyl Carbon content was closely correlated with aggregate stability, and suggested that only a part of soil carbon or carbohydrate was involved in aggregate stability. They also found that particulate organic matter occluded within aggregates was better correlated with aggregate stability.

The peak of stability observed in organic management a few weeks after organic matter inputs is coherent with contemporary models of aggregates formation and stabilization. According to the model of aggregate formation proposed by *Puget* et al. (2000), when fresh organic material from plants is incorporated into the soil matrix, it is rapidly colonized by microbial decomposers. Fungal hyphae and other by-product of the microbial activity, such as extra cellular polysaccharides, bind soil particles to the particulate OM. It refers to what *Tisdall* and *Oades* (1982) had called “transient” binding agents, responsible for the aggregation of macroaggregates (>250 µm). According to these authors, polysaccharides are produced rapidly after addition of organic materials, and the effect of transient binding agents on water stable aggregation can starts 2 to 3 weeks after the addition of organic materials, depending on the nature of these materials. *Watts* et al. (2001) investigated how soil structure responded when fresh organic materials were added to poor quality degraded arable soils and concluded that the incorporation of dried grass leaves into degraded soil increased aggregation and that the process of aggregation was microbiologically mediated. *Plante* and *McGill* (2002) demonstrated the formation of macroaggregates by incorporation of tracers 9 days after tillage. They found that a maximum of 40 to 60 % tracers were incorporated into >1-mm aggregates after 72 days. Using the same percolation stability test, *Fechter-Escamilla* et al. (1997b) were able to show evidence of short term structural stability increase in the upper horizon of reclaim *tepetate* induced by ground cover of *Trifolium repens* and *Medicago polimorfa*. They attributed this observation to the increased microbial activity enhanced by favourable soil moisture regime and roots development provided by the cover crops.

The seasonal decrease of PS can be attributed to seasonal fluctuations of roots and microbial biomass and/or level of organic stabilizing constituent (*Perfect et al.*, 1990a). Indeed, even though transient binding agents are produced rapidly after incorporation of OM, they are also decomposed rapidly by microorganisms (e.g. *Oades*, 1993). In soils with low OM, the macroaggregates breakdown resulting from raindrop impact during the rainfall season leads to exposure and decomposition of the new and young OM enclosed in the macroaggregates formed at the beginning of the growing season, after the incorporation of fresh organic matter (*Plante and McGill*, 2002). As decomposition of the incorporated OM proceeds, the microbial growth and production of biopolymers decrease, together with their aggregating action. We think that aggregate breakdown by raindrop impact during the rainfall season may expose the OM enclosed in macroaggregates, and accelerate its decomposition, resulting in a rapid decrease of the aggregate stability.

The fact that at the end of the season (2005) PSw was higher in 1986-plots than in 2002-plots showed that the stability related to SOC is more recalcitrant and long lasting than the stability related to the incorporation of fresh organic matter.

Covaleda et al. (2007) conducted a more detailed analysis of carbon dynamic in reclaimed tepetates in Tlalpan using fractionation techniques. They concluded that: i) the C incorporated (manure, compost) is stored primarily in macroaggregates (>0.2 mm), this aggregate-size fraction being the most sensitive to management practices; ii) in the medium term, the C stored in the smallest aggregates (<0.05 mm) increased. These results are coherent with the model of aggregate hierarchy (*Tisdall* and *Oades*, 1982; *Oades* and *Waters*, 1991) which proposed that micro-aggregates (<250 μm) are bound together into macro-aggregates (>2000 μm) and stabilized by a network of roots and hyphae and by transient binding agents such as microbial- and plant-derived polysaccharides. *Oades* (1984) later showed that the formation of microaggregates occurs within macroaggregates and is enhanced by the decomposition of temporary binding agents. This mechanism implies that the SOC in microaggregates is more recalcitrant, whereas the SOC in macroaggregates more labile (*Degens*, 1997). *Puget* et al. (1995) also demonstrated that the SOM responsible for the stability of macroaggregates was younger than the one present in microaggregates. This conceptual model has been confirmed by several studies (*Jastrow et al.*, 1996; *Six et al.*, 2000b; *Christensen*, 2001) and is widely accepted.

In that respect, *Shepherd* et al (2002) also highlighted the importance of young SOM in soil structural development and stressed out that to achieve aggregate stability and the advantages that this conveys, frequent input of fresh organic matter was required. Thus, the authors argued it is not the farming system per se that is important in promoting better physical condition, but the amount and quality of organic matter returned to a soil. Indeed, organic material with low C:N ratio are more rapidly decomposed and enhance the formation of macroaggregates, but their effect on structural stability is transient. High C:N material (small cereal straw, maize stalks) are decomposed slowly and favors formation of microaggregates inside macroaggregates (*Oades*, 1984). The formation and stabilization of microaggregates provide gradual effect on soil structural stability and long term effect on carbon sequestration (*Blanco-Canqui and Lal*, 2004).

In reclaimed *tepetates*, it is therefore recommended to: i) incorporate fresh residue with low C:N ratio (manure, compost, green manure) every year to enhance quick and short term aggregate stability and macroaggregates formation, ii) incorporate high C:N crop residues to enhance C sequestration and longer term structural stability, iii) promote roots biomass which is a significant source of stable SOC.

5.3.2. Porosity and infiltration

The pore size distribution of a soil depends, in the first instance, on the particle size distribution (*Smith et al.*, 1978), and deviations from this basic relationship is related to the structuring influences of various factors (*Aylmore and Sills*, 1978). In reclaimed *tepetates*, porosity and pore size distribution is primary characterized by a dominance of very fine pores (<0.2 µm) related to the percentage of clay and fine silt in *tepetates*. Within years, no significant differences were observed in total porosity or bulk density between managements or age of rehabilitation, apart from the volume of pores <0.2 µm significantly higher in 02-plots plots than in 86-plots.

5.3.2.1. Presence and effect of fragments on porosity in recently reclaimed tepetates.

Recently fragmented *tepetates* consist of *tepetate* fragments. Therefore, void space consists of intra-fragment porosity (equal to original *tepetates* porosity), and inter-fragment porosity, related to the arrangement of fragments. Over time, fragment content decreases as primary particles are released, and aggregate content increases, as primary particles bound with organic compounds and polyvalent cations (*Baez et al.*, 2002). Since the volume of micropores in *tepetate* t3 in the Block of Tlaxcala is approximately 22 % (*Werner*, 1992) and higher than in cultivated soils, it is coherent to obtain higher microporosity in recently reclaimed *tepetates* than in R86.

Fechter-Escamilla and *Flores* (1997) suggested that total porosity in *tepetates* recently fragmented should be corrected to take into account the presence of large fragments inherited from the original matrix. They stated that sampling with 100 cm^3 cylinder tends to overestimate the soil's fine fraction (< 2 mm). They estimated that fragments > 2 mm occupy up to 50 % soil weight in recently reclaimed *tepetates*. This approach suggests that total porosity in recently reclaimed *tepetates* should be lower than in *tepetates* with several years of reclamation since part of the soil consists of dense original *tepetate* material. However, volume of soil fragments was not measured in our study and this assumption could not be checked.

5.3.2.2.Effect of management on soil porosity

Pore structure and porosity development is intimately linked to aggregation, as both mechanisms are affected by the same factors. Soil biology and soil porosity have profound reciprocal effect (*Oades*, 1993): soil structure forms the habitat for micro-organisms which control residue decomposition rates and can influence, in fine, the aggregation and the development of pore space. Using X-ray tomography analyzes, *De Gryze* et al (2006) were able to show that decomposition of residues increased the overall void porosity and changed the pore morphology due to the proliferation of fungal hyphae near fresh residues. However, they found no relationship between water-stable aggregation and the changes in pore structure, suggesting that pore stability rather than pore morphology plays a role in the formation of aggregates after the addition of residue. *Schjonning* et al. (2007) showed that incorporation of cattle manure or green manure increased SOC and improved hydraulic properties of the soil 5 to 6 years after implementation of new management practices. In the Sahel region in soils affected by hardening process during dry season, the application of compost at a rate of 5 t ha^{-1} every two years in addition to mineral fertilization improved infiltration in the short term (3 years), even in soil tilled on an annual basis (*Ouattara et al.*, 2007).

In our experiment, no significant differences were observed between management and/or age of reclamation. This observation could be attributed to the effect of intensive cultivation on pore structure and pore size distribution. Tillage mechanically breaks pore continuity and hinders biopores formation (*Oades*, 1993). In the ridge-tillage cropping system (maize, broad bean, beans) extensively used in Mexican highlands and in our experiment, agricultural practices include up to 5 soil tillages: disc ploughing, harrowing, initial ridging (seedbed), first ridging (weeding) and second ridging (weeding and ridge reversal). Such tillage frequency prevents biota-induced porosity to develop and tends to homogenized pore structure in all management systems. Therefore, the expected positive effect of organic management on soil porosity could be inhibited by too frequent tillage. The work of *Wuest* (2001) suggests however that tillage affects in priority biopores over 1 mm, whereas biopores <1 mm would not be significantly affected by tilled and no-tilled systems. It is then possible that the method used to assess soil porosity was not adapted or precise enough to assess differences in porosity between management.

5.3.3. About tillage and residue management

Developing conservation tillage and residue management methods to improve soil structure have been identified as a priority for soil management in the tropics (*Lal*, 2000). Most soil conservation practices recommend to decrease soil disturbance to encourage soil biological processes to enhance soil structure development, soil aggregation and stabilization, and SOC sequestration (*Bronick and Lal*, 2005). Extensive literature have been published on the effect of tillage/no tillage on carbon dynamics and sequestration (*Follett*, 2001; *Hobbs*, 2007; *Pagliai et al.*, 2004; *Blanco-Canqui and Lal*, 2004; *Bronick and Lal*, 2005; *Jimenez and Lal*, 2006; *Swift*, 2001; *West and Post*, 2002; *Paustian et al.*, 2000; *Six et al.*, 1999; *Conant et al.*, 2007).

In Mexico, reduced tillage and residue management research have shown positive results on soil erosion and soil structure. Tillage combined with residues cover has been recommended on Vertisols in Tamaulipas (*Roldan et al.*, 2007) to improve soil physical properties and C sequestration. On a cambisol in semi arid western Mexico, no tillage and direct sowing under mulch (from 1.5 to 4.5 t ha^{-1} residues) decreased erosion rates by 50 to 90 % compared to conventional cropping, while increasing SOC by 25 to 29% and maize yields by 170 to 190 % (*Scopel et al.*, 2005). On andisols in the Patzcuaro basin, no tillage improved soil quality properties (*Roldan et al.*, 2003) and erodibility (*Tiscareno-Lopez et al.*, 1999) in comparison to conventional tillage, in direct proportion to residues inputs.

However, reduced or no tillage is not adapted to all type of soils. On a loamy soil (25 % clay, comparable to clay content in Tlalpan), *Carof* et al. (2007) found that conventional tillage showed higher saturated hydraulic conductivity and porosity compared to no tilled soil in the arable layer. *Lipiec* et al. (2006) obtained similar results in a silt loam Eutric Fluvisol (25 % clay, 62 % silt and 13 % sand). They concluded that the higher contribution of large flow-active pores under conventional tillage enhanced infiltration and water storage capacity compared to reduced and no tillage systems.

In reclaimed *tepetates*, characterized by fine texture, poor structural development and low permeability, *Fechter-Escamilla* et al. (1997b) showed that tillage increased infiltration by breaking structural crusts and increasing macro porosity compared to reduced tillage. The authors concluded that vegetation cover had greater effect on reducing soil erosion than reduced tillage and suggested that conservation farming in reclaimed *tepetates* consists of intensive tillage with high vegetation cover. Similar findings were recently reported in Mexican volcanic highlands by *Govaerts* et al. (2006; 2007). They concluded that zero tillage combined with crop residues retention improved chemical and physical conditions of the soil, but on the contrary zero tillage with removal of residues led to low aggregate stability, high penetration resistance, surface slaking and high runoff.

The success and benefit of reduced tillage greatly depends on the type of soil, climate and the possibility to combine this technique with residue cover. Further studies are therefore required to evaluate if reduced tillage and residue management practices are adapted to reclaim deteriorated volcanic ash soils such as *tepetates*.

6. Conclusion

The medium term field scale experiment carried out in this investigation constitute a substantial step forward to the knowledge and understanding of soil erosion dynamics in reclaimed *tepetates*. The results obtained give a first evaluation of the effect of organic farming on soil erosion and soil structure.

Effect of organic farming on soil erosion

Over the period, erosion rates were three to four times higher in 1986-plots than in 2002-plots. In recently fragmented *tepetates*, organic farming decreased significantly soil loss compared to conventional management, but in plots reclaimed in 1986, no significant differences were observed between managements. The study confirmed the high erodibility of *tepetates* after fragmentation, but gave further evidences that soil loss in reclaimed *tepetates* cultivated for several years are below tolerable rates, assuming terraces were initially well designed with slope of around 3-4 %. It appeared clearly that SOC content is the main parameter controlling annual erosion rates in reclaimed *tepetates*. The evolution of erosion rates is therefore dependant on carbon accumulation rates. By increasing organic matter incorporation, organic farming enhanced C accumulation and decreased significantly erosion rates compared to conventional farming, within the first years after fragmentation. According to our prediction model, and assuming average erosivity, erosion could drop below tolerable rates (10 t ha^{-1} yr^{-1}) three years after fragmentation under organic farming, and after seven years under conventional farming. Differences in SOC content in plots reclaimed in 1986 had no significant effect on soil erosion, suggesting a threshold (~3.4 mg C g^{-1} in the top 10 cm soil) above which the effect of SOC content on soil erosion in reclaimed *tepetates* is reduced.

For single events, the multiple regression quantified the effect of vegetation cover on soil erosion and highlighted the importance of providing high vegetation cover in the first stage of the rehabilitation, when SOC content is still very low. In that respect, multiple cropping such as oat associated with vetch proved to be excellent alternative by increasing production and vegetation cover in comparison to oat alone. Crop nutrition is another critical aspect that must be addressed to enhance crop development and provide optimum vegetation cover.

Effect of organic farming on soil structure

The analysis of aggregate stability showed that when fresh organic matter is incorporated to the soil, the liberation of transient binding agents induced a peak of stability in macroaggregates a few weeks after incorporation. The study demonstrated that organic farming in reclaimed *tepetates* enhanced the formation and stabilization of macroaggregates, which should in turn promote the formation of microaggregates and the stabilization of SOC in the medium term. Regular incorporation of fresh organic matter in recently reclaimed *tepetates* is therefore a way to enhance soil structural development and carbon sequestration during rehabilitation.

There were no evidence that organic farming improves total porosity and pore size distribution in reclaimed *tepetates*. There were no indication neither that porosity increases over time during the rehabilitation process, suggesting that differences in runoff and erosion rates are not due to differences in infiltration in the profile but to reduced infiltration caused by surface crusting and sealing.

Overall, organic farming had a positive impact on soil erosion and soil structure compared to conventional farming. However, the relationship between soil structure and soil erosion could not be clearly established, mainly because of methodological flaws. Detailed monitoring of carbon content and aggregate stability is still required to understand better the dynamic of organic carbon in reclaimed tepetates and its impact on soil erosion. The study highlighted the key role of vegetation cover in the first stage after rehabilitation and raised the question of plant nutrition and fertilization strategy. The application of organic amendments requires a volume of organic material, either farmyard manure or biomass for compost, which may not be available to all smallholders in the area. Therefore, as long as the market for organic products is not developed and a certification system established, the use of mineral fertilizers in combination to organic amendments is recommended to ensure optimum plant nutrition, both for production purposes and for soil conservation purposes. In that sense, the improved management convey the benefit of OM input on soil structural improvement, and the flexibility of mineral fertilization to meet plants nutrimental requirement. Such farming system seems to be the best adapted to local farmer's conditions and could be therefore the most sustainable of all three management practices compared in this investigation. It is now necessary to evaluate the performances of improved management in recently reclaimed *tepetates*. Specific research is also required to evaluate the cost effectiveness of organic farming and its profitability on the medium and long term in comparison to other farming systems.

Finally, there is a strong research need to explore and evaluate other conservation and rehabilitation strategies such as reduced tillage and residue cover management in deteriorated volcanic ash soils areas.

Summary

"*Tepetates*" are hardened layers in the profile of soils from volcanic origin. After erosion of the overlying soil horizon, the *tepetates* show up on the surface. In the Mexican highlands, along the Trans-Mexican Volcanic Belt, this phenomenon has caused the emergence of vast degraded and sterile areas. The State of Tlaxcala is one of the most affected, with 15 % of the State area covered by bare *tepetates*. The rehabilitation of *tepetates* is a way to increase arable lands and mitigate environmental impact caused by high superficial runoff. Previous research experiences showed that soil erosion control is critical to achieve sustainable *tepetates* rehabilitation. The application of organic amendments have been repeatedly recommended to increase fertility and soil physical properties after fragmentation, but there is little data available on the effect of organic farming on soil erosion during the rehabilitation process. The aim of this research is to evaluate the effect of organic farming on soil erosion and soil structure at field scale and under natural conditions.

A four years experiment was set up in Tlaxcala, Mexico. Erosion and runoff rates were measured in five terraced plots of 580 to 2200 m^2 and with 3-4 % slope. Three plots were fragmented in 1986 and two in 2002. Three farming managements were compared: The "conventional", with mineral fertilization and no incorporation of O.M.; the "improved", with mineral fertilization and incorporation of crop residues, and the "organic" with organic fertilization. Soil structure was assessed by total porosity, pore size distribution and aggregate stability.

Annual precipitation ranged between 507 mm in 2005 to 805 mm in 2003, with annual erosivity of 195 N h^{-1} and 345 N h^{-1} respectively. In plots reclaimed in 2002, soil loss ranged from 8.6 to 19.1 t ha^{-1} yr^{-1} under conventional management and from 5.5 to 14.1 t ha^{-1} yr^{-1} under organic farming. In plots reclaimed in 1986 soil loss ranged from 1.1 to 5.6 t ha^{-1} yr^{-1} with no significant difference between managements. The incorporation of fresh organic matter in organic farming provided short term increase in aggregates stability, regardless of the age of rehabilitation. However, aggregate stability was not significantly correlated to SOC nor to erosion rates. Multiple regression analysis showed that for annual values, SOC is the main factor controlling erosion rates in reclaimed *tepetates*, explaining 64 % of soil loss variance and 79 % of runoff variance. The evolution of erosion rates is therefore dependant on carbon accumulation rates.

After fragmentation, organic farming increased carbon sequestration rate to 0.8 Mg C ha^{-1} yr^{-1} compared to 0.22 Mg C ha^{-1} yr^{-1} in conventional management. In plots reclaimed in 1986, carbon sequestration ranged from 0.21 Mg C ha^{-1} yr^{-1} in conventional management to 0.37 Mg C ha^{-1} yr-1 in improved management and 0.61 Mg C ha^{-1} yr-1 in organic management. Erosion rates in terraced reclaimed *tepetates* could decrease below tolerable value (< 10 t ha^{-1} yr^{-1}) three years after fragmentation under organic farming, compared to seven years under conventional farming.

Results also confirmed the key role played by vegetation cover (accounting for 27 % of soil loss variance for single events) and emphasize the importance of crop nutrition and crop association to control erosion. Improved management provided

Total porosity ranged from 44.8 % on average in 2003 to 50.4 % on average in 2005. We observed no significant effect of management or age of rehabilitation on soil porosity and pore size distribution, suggesting that high tillage intensity during the cropping season which prevented significant changes in porosity between managements.

This three years study demonstrated that organic farming has a positive effect on soil erosion during rehabilitation of *tepetates*. However, unless a market for organic products is developed and a certification system established, we recommend organic amendments to be complemented with mineral fertilization to ensure optimum vegetation cover and erosion control.

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Appendix 1. Rain erosivity

Table A- 1: Selected characteristics of rainfall events in Tlalpan from 1991 to 1997 and from 2002 to 2005. Soil loss value is the mean soil loss value in all plots.

Year	Category	Number		Depth		EI30		Max I30	Soil loss	
			%	mm	%	N/h	%	mm/h	t/ha	%
1991	< 1mm	17	15.3%	8.7	1.1%	0.0	0.0%	0.2		
	1-4.99 mm	47	42.3%	123.3	15.3%	9.3	2.6%	3.5		
	5-9.99 mm	18	16.2%	136.1	16.9%	19.8	5.5%	7.6		
	10-19.9 mm	21	18.9%	292.9	36.4%	94.9	26.5%	14.6		
	20-29.9 mm	6	5.4%	144.1	17.9%	91.8	25.6%	24.7		
	> 30 mm	2	1.8%	98.7	12.3%	142.1	39.7%	57.4		
	max rain	06/09/1991		60.6	7.5%	76.5	21.4%	51.0		
	total	111		803.8		357.9				
1992	< 1mm	18	14.5%	12.2	1.5%	0.2	0.1%	1.4		
	1-4.99 mm	53	42.7%	135.6	16.9%	14.0	5.2%	4.3		
	5-9.99 mm	29	23.4%	209.9	26.2%	34.4	12.6%	7.9		
	10-19.9 mm	17	13.7%	229.8	28.6%	77.1	28.4%	15.5		
	20-29.9 mm	3	2.4%	64.9	8.1%	11.9	4.4%	10.2		
	> 30 mm	4	3.2%	150.1	18.7%	134.1	49.3%	38.0		
	max rain	05/06/1992		42.1	5.2%	28.4	10.4%	31.5		
	total	124		802.5		271.7				
1993	< 1mm	17	17.7%	9.3	1.4%	0.2	0.1%	1.4		
	1-4.99 mm	33	34.4%	83.1	12.5%	4.9	2.3%	3.2		
	5-9.99 mm	22	22.9%	157.5	23.8%	31.1	14.7%	9.3		
	10-19.9 mm	17	17.7%	233.5	35.2%	69.1	32.7%	13.3		
	20-29.9 mm	5	5.2%	108.8	16.4%	58.0	27.5%	23.9		
	> 30 mm	2	2.1%	70.6	10.7%	47.8	22.6%	29.5		
	max rain	06/07/1993		38.1	5.7%	19.7	9.3%	23.5		
	total	96		662.8		211.2				
1994	< 1mm	18	17.3%	11.5	1.6%	0.3	0.1%	1.5		
	1-4.99 mm	46	44.2%	103.9	14.4%	7.4	1.7%	3.4		
	5-9.99 mm	16	15.4%	121.9	17.0%	24.7	5.7%	9.6		
	10-19.9 mm	17	16.3%	246.2	34.2%	102.2	23.5%	17.2		
	20-29.9 mm	4	3.8%	96.5	13.4%	92.8	21.3%	36.7		
	> 30 mm	3	2.9%	139.1	19.3%	208.2	47.8%	50.3		
	max rain	27/06/1994		67.1	9.3%	147.7	33.9%	79.0		
	total	104		719.1		435.5				
1995	< 1mm	16	18.6%	8.1	1.3%	2.5	1.3%	1.5		
	1-4.99 mm	26	30.2%	54.1	9.0%	3.1	1.6%	3.4		
	5-9.99 mm	22	25.6%	164.1	27.2%	33.4	17.0%	9.3		
	10-19.9 mm	16	18.6%	223.5	37.1%	58.7	29.9%	12.6		
	20-29.9 mm	5	5.8%	115.2	19.1%	56.0	28.5%	20.7		
	> 30 mm	1	1.2%	38.2	6.3%	42.8	21.8%	47.6		
	max rain	04/07/1995		38.2	6.3%	42.8	21.8%	47.6		
	total	86		603.3		196.5				
1996	< 1mm	19	20.0%	8.8	1.4%	0.1	0.0%	0.8		
	1-4.99 mm	29	30.5%	81.7	13.5%	6.4	2.9%	3.7		
	5-9.99 mm	27	28.4%	197.8	32.6%	33.9	15.5%	8.3		
	10-19.9 mm	17	17.9%	232.8	38.3%	85.4	39.1%	16.5		
	20-29.9 mm	2	2.1%	42.2	6.9%	24.2	11.1%	23.9		
	> 30 mm	1	1.1%	44.1	7.3%	68.3	31.3%	61.9		
	max rain	22/07/1996		44.1	7.3%	68.3	31.3%	61.9		
	total	95		607.4		218.3				
1997	< 1mm	27	26.5%	10.2	1.8%					
	1-4.99 mm	36	35.3%	98.8	17.9%					
	5-9.99 mm	20	19.6%	136.1	24.6%					
	10-19.9 mm	15	14.7%	208.1	37.6%					
	20-29.9 mm	3	2.9%	69.3	12.5%					
	> 30 mm	1	1.0%	31.0	5.6%					
	max rain	05/07/1997		31.0	5.6%					
	total	102		553.4						

Table A-1 (follow) Selected characteristics of rainfall events in Tlalpan from 1991 to 1997 and from 2002 to 2005. Soil loss value is the mean soil loss value in all plots

Year	Category	Number		Depth		EI30		Max I30	Soil loss	
			%	mm	%	N/h	%	mm/h	t/ha	%
2002	< 1mm	66	44.6%	25.5	4.8%	0.2	0.1%	0.6		
	1-4.99 mm	55	37.2%	131.4	24.8%	9.4	5.1%	3.3		
	5-9.99 mm	10	6.8%	74.1	14.0%	15.3	8.3%	9.4		
	10-19.9 mm	12	8.1%	164.5	31.0%	68.5	37.2%	17.7		
	20-29.9 mm	4	2.7%	101.9	19.2%	41.4	22.5%	20.2		
	> 30 mm	1	0.7%	32.7	6.2%	49.2	26.8%	57.6		
	max rain	30/10/2002		32.7	6.2%	49.2	26.8%	57.6		
	total	148		530.1		184.0				
2003	< 1mm	123	56.2%	39.5	4.9%	0.1	0.0%	0.2		
	1-4.99 mm	50	22.8%	119.9	14.9%	7.7	2.2%	3.1	0.03	0.3%
	5-9.99 mm	17	7.8%	108.9	13.5%	15.8	4.6%	7.3	0.46	4.8%
	10-19.9 mm	21	9.6%	297.3	36.9%	121.8	35.3%	18.1	3.70	38.7%
	20-29.9 mm	5	2.3%	125.1	15.5%	83.3	24.1%	29.9	0.62	6.5%
	> 30 mm	3	1.4%	114.7	14.2%	116.2	33.7%	41.0	4.74	49.6%
	max rain	02/06/2003		40.8	5.1%	22.7	6.6%	13.9	0.30	3.1%
	total	219		805.4		344.9			9.54	
2004	< 1mm	161	60.5%	46.7	6.2%	0.3	0.1%	0.3		
	1-4.99 mm	64	24.1%	152.9	20.2%	11.9	3.2%	3.5	0.04	0.6%
	5-9.99 mm	18	6.8%	128.9	17.1%	25.1	6.7%	9.4	0.20	2.6%
	10-19.9 mm	18	6.8%	259.8	34.4%	117.6	31.2%	18.4	1.90	24.7%
	20-29.9 mm	4	1.5%	103.7	13.7%	83.8	22.3%	33.4	2.68	34.8%
	> 30 mm	1	0.4%	63.8	8.4%	138.0	36.6%	79.2	2.88	37.4%
	max rain	17/09/2004		63.8	8.4%	138.0	36.6%	27.9	2.24	29.1%
	total	266		755.8		376.7			7.71	
2005	< 1mm	152	66.4%	44.5	7.7%	0.2	0.1%	0.2		
	1-4.99 mm	43	18.8%	103.2	17.9%	8.3	4.3%	3.4	0.00	0.0%
	5-9.99 mm	17	7.4%	126.8	22.0%	22.9	11.7%	8.9	0.23	6.3%
	10-19.9 mm	14	6.1%	209.4	36.3%	81.5	41.7%	16.7	1.92	53.5%
	20-29.9 mm	2	0.9%	50.0	8.7%	46.1	23.6%	37.3	0.02	0.5%
	> 30 mm	1	0.4%	43.6	7.6%	36.3	18.6%	37.3	1.42	39.7%
	max rain	31/08/2005		43.6	7.6%	36.3	18.6%	12.4	0.36	10.0%
	total	229		577.4		195.3			3.6	
Mean	< 1mm	57.6	40.1%	20.5	3.0%	0.4	0.1%	0.8		
(1991-2005)	1-4.99 mm	43.8	30.5%	108.0	16.0%	8.3	3.0%	3.5	0.02	0.3%
	5-9.99 mm	19.6	13.7%	142.0	21.0%	25.6	9.2%	8.7	0.30	4.3%
	10-19.9 mm	16.8	11.7%	236.2	35.0%	87.7	31.4%	16.1	2.50	36.1%
	20-29.9 mm	3.9	2.7%	92.9	13.8%	58.9	21.1%	26.1	1.11	15.9%
	> 30 mm	1.8	1.3%	75.1	11.1%	98.3	35.2%	50.0	3.01	43.4%
	max rain			45.6	6.8%	63.0	22.5%	40.6	0.97	13.9%
	total	143.6		674.6		279.2			6.9	

Appendix 2. Soil loss and runoff

Table A- 2: Annual soil loss, runoff, runoff coefficient and sediment discharge in Tlalpan. Different letter indicates significant difference at P<0.05.

		86-I	86-O	86-C	02-C	02-O
Soil loss	2003	4.5	5.5	4.6	19.1	14.1
	2004	2.3	4.2	5.6	16.2	10.2
	2005	1.1	1.4	1.3	8.6	5.5
	Mean	2.6	3.7	3.8	14.6	9.9
	P<0.05	a	a	a	b	c
Runoff	2003	51.2	49.3	70.4	265.2	169.2
	2004	57.0	81.7	98.2	209.0	146.1
	2005	26.2	31.4	39.2	164.9	140.4
	Mean	44.8	54.1	69.3	213.0	151.9
	p<0.05	a	a	a	b	c
Runoff coefficient	2003	10%	10%	13%	42%	26%
	2004	13%	20%	24%	46%	30%
	2005	11%	11%	14%	48%	36%
	Mean	11%	14%	17%	45%	31%
sediment discharge	2003	43.3	50.4	47.7	78.3	63.3
	2004	36.8	53.0	56.4	68.3	60.8
	2005	35.5	37.8	42.7	48.8	38.8
	Mean	38.5	47.1	48.9	65.1	54.3

Table A- 3: Distribution of soil loss by rainfall event size from 2003 to 2005 in Tlalpan.

Soil loss			86-I (C)		86-O (D)		86-C (E)		02-C (R1)		02-O (R2)		Total	
year	category	number	ton/ha	%	ton/ha	%	ton/ha	%	ton/ha	%	ton/ha	%	ton/ha	%
2003	1-4.99 mm	2							0.12	*1%*	0.01	*0%*	0.13	*0%*
	5-9.99 mm	6	0.18	*4%*	0.18	*3%*	0.17	*4%*	1.02	*5%*	0.76	*5%*	2.31	*5%*
	10-19.9 mm	17	0.96	*22%*	1.55	*28%*	1.62	*36%*	8.54	*45%*	5.80	*41%*	18.48	*39%*
	20-29.9 mm	5	0.05	*1%*	0.05	*1%*	0.15	*3%*	2.22	*12%*	0.65	*5%*	3.11	*7%*
	> 30 mm	4	3.28	*73%*	3.71	*68%*	2.61	*57%*	7.17	*38%*	6.90	*49%*	23.68	*50%*
	Max (42.1 mm)	30/06/03	3.23	*72%*	3.68	*67%*	2.40	*53%*	3.53	*19%*	5.32	*38%*	18.16	*38%*
	Total	34	4.46		5.48		4.55		19.07		14.13		47.70	
2004	1-4.99 mm	3							0.14	*1%*	0.06	*1%*	0.20	*1%*
	5-9.99 mm	3	0.03	*2%*	0.13	*3%*	0.11	*2%*	0.40	*2%*	0.33	*3%*	1.01	*3%*
	10-19.9 mm	9	0.29	*13%*	0.92	*22%*	1.15	*21%*	5.20	*32%*	1.96	*19%*	9.52	*25%*
	20-29.9 mm	5	0.80	*35%*	1.68	*40%*	2.13	*38%*	5.70	*35%*	3.07	*30%*	13.39	*35%*
	> 30 mm	2	1.16	*51%*	1.49	*35%*	2.20	*39%*	4.74	*29%*	4.81	*47%*	14.40	*37%*
	Max (63.8 mm)	17/09/04	0.90	*39%*	1.09	*26%*	1.61	*29%*	3.48	*22%*	4.14	*40%*	11.21	*29%*
	Total	22	2.28		4.24		5.59		16.18		10.23		38.53	
2005	1-4.99 mm													
	5-9.99 mm	4	0.02	*2%*	0.07	*5%*	0.06	*5%*	0.61	*7%*	0.36	*7%*	1.13	*6%*
	10-19.9 mm	11	0.70	*65%*	0.81	*58%*	0.98	*74%*	4.18	*48%*	2.91	*53%*	9.58	*54%*
	20-29.9 mm	1							0.07	*1%*	0.02	*0%*	0.09	*0%*
	> 30 mm	3	0.36	*33%*	0.51	*37%*	0.28	*21%*	3.76	*44%*	2.19	*40%*	7.10	*40%*
	Max (17.5 mm)	28/07/05	0.49	*45%*	0.42	*30%*	0.63	*48%*	1.99	*23%*	1.47	*27%*	5.00	*28%*
	Total	19	1.08		1.40		1.31		8.62		5.48		17.89	
Mean	1-4.99 mm	2.5							0.13	*1%*	0.04	*0%*	0.16	*0%*
	5-9.99 mm	4.3	0.08	*3%*	0.13	*3%*	0.12	*3%*	0.68	*5%*	0.48	*5%*	1.48	*4%*
	10-19.9 mm	12.3	0.65	*25%*	1.09	*29%*	1.25	*33%*	5.97	*41%*	3.56	*36%*	12.52	*36%*
	20-29.9 mm	3.7	0.42	*16%*	0.87	*23%*	1.14	*30%*	2.66	*18%*	1.25	*13%*	6.34	*18%*
	> 30 mm	3.0	1.60	*61%*	1.90	*51%*	1.70	*44%*	5.23	*36%*	4.63	*47%*	15.06	*43%*
	Max		1.54	*59%*	1.73	*47%*	1.55	*40%*	3.00	*21%*	3.65	*37%*	11.46	*33%*
	Total	25.0	2.61		3.71		3.82		14.63		9.95		34.71	

Table A- 4: Distribution of runoff by rainfall event category from 2003 to 2005 in Tlalpan.

Runoff			86-I (C)		86-O (D)		86-C (E)		02-C (R1)		02-O (R2)		Total	
Year	category	number	mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
2003	1-4.99 mm	2							3.5	*1%*	0.4	*0%*	3.9	*1%*
	5-9.99 mm	6	1.8	*4%*	1.8	*4%*	2.6	*4%*	12.5	*5%*	5.2	*3%*	24.0	*4%*
	10-19.9 mm	17	20.4	*40%*	19.2	*39%*	21.5	*30%*	98.6	*37%*	70.2	*41%*	229.9	*38%*
	20-29.9 mm	5	5.1	*10%*	5.0	*10%*	12.0	*17%*	69.7	*26%*	25.3	*15%*	117.0	*19%*
	> 30 mm	4	23.9	*47%*	23.4	*47%*	34.3	*49%*	80.8	*30%*	68.1	*40%*	230.5	*38%*
	Max (42.1 mm)	30/06/03	20.9	*41%*	21.0	*43%*	25.3	*36%*	37.2	*14%*	37.0	*22%*	141.4	*23%*
	Total	34	51.2		49.3		70.4		265.2		169.2		605.3	
2004	1-4.99 mm	3			0.3	*0%*			2.8	*1%*	1.2	*1%*	4.2	*1%*
	5-9.99 mm	3	1.1	*2%*	2.6	*3%*	1.3	*1%*	5.2	*2%*	4.4	*3%*	14.6	*2%*
	10-19.9 mm	9	8.8	*15%*	17.9	*22%*	22.0	*22%*	70.7	*34%*	34.3	*23%*	153.7	*26%*
	20-29.9 mm	5	18.0	*32%*	31.1	*38%*	36.5	*37%*	68.7	*33%*	50.2	*34%*	204.5	*35%*
	> 30 mm	2	29.1	*51%*	29.8	*36%*	38.4	*39%*	61.6	*29%*	56.0	*38%*	215.0	*36%*
	Max (63.8 mm)	17/09/04	25.4	*44%*	25.2	*31%*	32.1	*33%*	43.4	*21%*	45.8	*31%*	171.8	*29%*
	Total	22	57.0		81.7		98.2		209.0		146.1		592.0	
2005	1-4.99 mm												0.0	*0%*
	5-9.99 mm	4	0.6	*2%*	3.0	*9%*	1.6	*4%*	10.3	*6%*	8.8	*6%*	24.2	*6%*
	10-19.9 mm	11	13.3	*51%*	17.0	*54%*	14.4	*37%*	66.2	*40%*	48.3	*34%*	159.3	*40%*
	20-29.9 mm	1							6.3	*4%*	2.7	*2%*	9.0	*2%*
	> 30 mm	3	12.4	*47%*	11.4	*36%*	23.2	*59%*	82.1	*50%*	80.5	*57%*	209.6	*52%*
	Max (43.6 mm)	31/08/05	5.5	*21%*	7.0	*22%*	9.5	*24%*	24.2	*15%*	37.1	*26%*	83.3	*21%*
	Total	19	26.2		31.4		39.2		164.9		140.4		402.1	
Mean	1-4.99 mm	2.5			0.3	*1%*			3.1	*1%*	0.8	*1%*	4.2	*1%*
	5-9.99 mm	4.3	1.1	*3%*	2.5	*5%*	1.8	*3%*	9.3	*4%*	6.1	*4%*	20.9	*4%*
	10-19.9 mm	12.3	14.2	*32%*	18.0	*33%*	19.3	*28%*	78.5	*37%*	50.9	*34%*	180.9	*34%*
	20-29.9 mm	3.7	11.5	*26%*	18.0	*33%*	24.2	*35%*	48.2	*23%*	26.1	*17%*	128.1	*24%*
	> 30 mm	3.0	21.8	*49%*	21.5	*40%*	32.0	*46%*	74.9	*35%*	68.2	*45%*	218.4	*41%*
			17.3	*39%*	17.7	*33%*	22.3	*32%*	34.9	*16%*	39.9	*26%*	132.2	*25%*
	Total	25.0	44.8		54.1		69.3		213.0		151.9		533.1	

Appendix 3. Vegetation cover

Table A- 5: Vegetation cover measured in Tlalpan from 2002 to 2005. Different letter indicates significant difference (ANOVA repeated measures)

Year	Date	Days*	86-C	86-I	86-O	02-C	02-O
2002	12-Jul	27	13.5%	20.9%	14.1%		
	05-Aug	50	22.0%	28.4%	24.4%	8.3%	20.4%
	12-Aug	57	24.2%	20.9%	27.7%	12.6%	28.7%
	29-Aug	74	29.8%	38.5%	35.7%	29.5%	20.9%
	10-Sep	85	44.6%	41.5%	30.4%	34.9%	19.4%
	18-Sep	93	47.5%	42.1%	64.0%	20.5%	27.8%
	25-Sep	100	44.2%	46.3%	58.6%	40.6%	37.9%
	01-Oct	106	78.8%	75.8%	64.5%	32.1%	39.0%
	21-Oct	126	76.1%	76.3%	71.0%	41.2%	36.0%
	12-Nov	147	55.0%	67.0%	69.7%	31.1%	43.6%
	Mean		**43.5%**	**46.1%**	**46.0%**	**27.9%**	**30.4%**
	P<0.05		**a**	**a**	**a**	**b**	**b**
2003	14-Jul	31	41.3%	60.8%	48.6%	33.2%	46.9%
	24-Jul	41	69.8%	91.0%	72.4%	45.9%	79.1%
	07-Aug	54	82.0%	98.1%	95.8%	44.5%	85.0%
	26-Aug	73	68.5%	90.9%	94.1%	38.8%	89.6%
	22-Sep	99	37.6%	87.4%	64.0%	33.5%	85.0%
	Mean		**60.9%**	**83.9%**	**73.6%**	**39.2%**	**77.1%**
	P<0.05		**a**	**b**	**c**	**d**	**c**
2004	**Estimation**	100	**77.5%**	**87.5%**	**79.0%**	**35.0%**	**70.0%**
			+- 5%	**+- 5%**	**+- 5%**	**+- 5%**	**+- 5%**
2005	20-Jul	28	2.1%	8.9%	6.3%	5.2%	4.6%
	28-Jul	36	8.3%	21.1%	18.8%	10.1%	11.3%
	05-Aug	43	18.3%	48.4%	38.9%	16.6%	18.2%
	11-Aug	49	40.3%	67.4%	56.8%	31.5%	30.6%
	18-Aug	56	66.3%	80.7%	74.5%	35.1%	37.1%
	25-Aug	63	78.1%	86.6%	81.1%	42.2%	43.5%
	01-Sep	69	76.4%	82.7%	86.4%	43.0%	61.4%
	08-Sep	76	71.2%	86.4%	86.2%	34.7%	43.0%
	15-Sep	83	72.3%	89.1%	86.8%	45.0%	57.4%
	22-Sep	90	76.2%	88.5%	88.1%	46.0%	55.5%
	29-Sep	97	77.7%	89.5%	89.4%	50.5%	56.7%
	06-Oct	104	80.9%	89.6%	91.5%	54.5%	63.2%
	13-Oct	111	75.5%	90.8%	90.0%	39.2%	44.5%
	20-Oct	118	67.2%	90.3%	83.8%	34.7%	43.6%
	27-Oct	125	62.2%	83.4%	79.9%	27.5%	32.5%
	03-Nov	131	47.9%	70.4%	64.0%	32.2%	29.0%
	Mean		**54.2%**	**69.0%**	**65.9%**	**32.2%**	**37.2%**
	P<0.05		**a**	**b**	**b**	**c**	**c**

* Number of days after sowing.

Appendix 4. Soil properties and crop production

Table A- 6: Soil Organic Carbon (mg g^{-1}) and accumulation rate in Tlalpan from 2002 to 2005.

Depth	Management	SOC (mg g^{-1})					accumulation rate	
		2002	2003	2004	2005	Δ 02-05	mg C g^{-1} yr^{-1}	Mg C ha^{-1} yr^{-1}
0-20 cm	86-C	2.99	3.70	3.40	3.34	0.35	0.09	0.21
	86-I	3.21	3.50	3.83	3.83	0.61	0.15	0.37
	86-O	3.09	4.42	4.78	4.10	1.01	0.25	0.61
	02-C	1.08	0.81	1.45	1.43	0.36	0.09	0.22
	02-O	1.08	1.84	2.20	2.41	1.34	0.33	0.80
0-10 cm	86-C	3.23	3.72	3.50	3.37	0.14	0.04	0.04
	86-I	3.48	3.69	3.95	3.82	0.35	0.09	0.10
	86-O	3.43	4.69	4.85	4.20	0.78	0.19	0.23
	02-C	1.05	0.80	1.50	1.51	0.46	0.11	0.14
	02-O	1.05	2.03	2.35	2.40	1.35	0.34	0.40
10-20 cm	86-C	2.75	3.69	3.30	3.30	0.55	0.14	0.16
	86-I	2.95	3.31	3.70	3.83	0.88	0.22	0.26
	86-O	2.75	4.15	4.70	3.97	1.22	0.30	0.36
	02-C	1.10	0.82	1.40	1.36	0.26	0.06	0.08
	02-O	1.10	1.65	2.05	2.43	1.33	0.33	0.40

Table A- 7: Crop production in Tlalpan from 2002 to 2005. Different letter indicate significant difference at p<0.05 between plots.

		1986			2002		Mean
		Conventional	Improved	Organic	Convent.	Organic	
2002	Grain production	0.60	0.66	0.51	0.62	-	0.59
	p<0.05	*a*	*a*	*a*	*a*		
	Broad bean biomass	3.14	2.67	2.61	3.07	-	2.82
	p<0.05	*a*	*a*	*a*	*a*		
	Total biomass	3.88	3.94	4.03	3.07	-	3.90
	p<0.05	*a*	*a*	*a*	*a*		
2003	Vetch	-	2.48	2.43	-	2.44	2.45
	p<0.05		*a*	*a*		*a*	
	Oat	6.44	5.00	5.24	5.02	5.53	5.46
	p<0.05	*a*	*a*	*a*	*a*	*a*	
	Weeds	2.22	2.74	2.16	0.14	0.94	1.91
	p<0.05	*ab*	*a*	*ab*	*c*	*bc*	
	Total forage	8.66	10.22	9.82	5.17	8.91	8.94
	p<0.05	*ba*	*b*	*b*	*a*	*ab*	
2004	Maize grain	2.15	2.71	2.09	1.67	2.82	2.30
	p<0.05	*ab*	*a*	*ab*	*a*	*b*	
	Maize straw	3.76	5.17	5.38	2.71	5.49	4.60
2005	*Wheat grain*	5.23	6.15	4.49	2.70	1.77	4.52
	p<0.05	*ab*	*a*	*b*	*c*	*c*	

Table A- 8: Monitoring of soil water content (gravimetric) at 10 cm depth by TDR during 2004 cropping season.

	Plot				
Date	86-I	86-O	86-C	02-C	02-O
19/07/2004	0.11	0.16	0.16	0.19	0.11
02/08/2004	0.27	0.27	0.30	0.30	0.28
06/08/2004	0.25	0.27	0.29	0.26	0.27
16/08/2004	0.22	0.17	0.22	0.23	0.22
24/08/2004	0.23	0.25	0.26	0.27	0.24
10/09/2004	0.25	0.24	0.23	0.24	0.21
Mean	0.22	0.23	0.24	0.25	0.22
p<0.05 *	a	a	a	a	a

*ANOVA repeated measures

Table A- 9: Monitoring of soil water content (gravimetric) by tensiometers in 2005 (weighted average from measures done at 5, 10, 15, 25 and 40 cm depth).

	86-I	86-O	86-C	02-C	02-O
07/07/05	0.27	0.24	0.22	0.20	0.18
15/07/05	0.20	0.23	0.20	0.20	0.14
20/07/05	0.22	0.23	0.19	0.20	0.15
25/07/05	0.22	0.23	0.20	0.21	0.16
27/07/05	0.28	0.30	0.30	0.32	0.26
28/07/05	0.28	0.31	0.31	0.31	0.27
05/08/05	0.18	0.23	0.32	0.19	0.20
08/08/05	0.29	0.27	0.31	0.24	0.26
11/08/05	0.28	0.26	0.30	0.23	0.25
14/08/05	0.34	0.25	0.45	0.23	0.25
15/08/05	0.34	0.23	0.37	0.22	0.24
18/08/05	0.32	0.21	0.40	0.22	0.18
21/08/05	0.35	0.20	0.42	0.16	0.21
22/08/05	0.33	0.22	0.38	0.16	0.21
23/08/05	0.36	0.26	0.42	0.20	0.25
25/08/05	0.40	0.35	0.41	0.29	0.30
01/09/05	0.42	0.31	0.42	0.18	0.26
08/09/05	0.36	0.26	0.33	0.14	0.16
09/09/05	0.40	0.38	0.41	0.25	0.28
13/09/05	0.38	0.34	0.40	0.20	0.22
15/09/05	0.36	0.28	0.35	0.15	0.22
19/09/05	0.40	0.29	0.42	0.19	0.21
22/09/05	0.36	0.27	0.34	0.24	0.21
29/09/05	0.27	0.15	0.24	0.18	0.17
04/10/05	0.24	0.14	0.17	0.17	0.19
05/10/05	0.32	0.23	0.31	0.21	0.22
06/10/05	0.40	0.31	0.39	0.22	0.27
08/10/05	0.45	0.45	0.45	0.27	0.37
12/10/05	0.45	0.45	0.45	0.36	0.40
13/10/05	0.44	0.45	0.43	0.40	0.39
20/10/05	0.39	0.43	0.35	0.37	0.31
27/10/05	0.32	0.36	0.26	0.23	0.25
Mean	0.33	0.28	0.34	0.23	0.24
$p<0.05$ *	a	ab	a	b	b

*ANOVA repeated measures

Appendix 5. Soil loss and runoff prediction

Table A- 10 Data set used in the multiple regression

		86-I	86-O	86-C	02-C	02-O	TOTAL
Number of events in the model	2003	9	8	8	12	11	48
	2004	11	12	12	13	13	61
	2005	5	5	5	9	8	32
	TOTAL	25	25	25	34	32	**141**
% of events kept in the model	2003	36%	33%	33%	34%	32%	34%
	2004	73%	71%	75%	59%	62%	67%
	2005	45%	29%	42%	50%	42%	42%
	TOTAL	49%	43%	48%	45%	43%	**45%**
% of annual soil loss considered in the model	2003	89%	90%	92%	64%	70%	74%
	2004	90%	81%	84%	84%	82%	83%
	2005	95%	77%	84%	69%	73%	74%
	TOTAL	90%	85%	87%	72%	75%	**77%**

Table A- 11: Descriptive statistics of the variable used in the multiple regression

	RUNOFF	SOIL LOSS	DEPTH	KE wisch	I10 max	I30 max	EI10	EI30	SOC	COVER
N	141	141	141	141	141	141	141	141	141	141
Minimum	0.37	6.51	6.60	1.24	8.65	6.96	12.70	10.22	0.80	0.00
Maximum	45.75	5324.37	63.80	17.42	109.47	79.20	1379.53	1379.53	4.54	0.95
Median	4.81	260.66	17.09	4.07	42.95	27.45	179.52	105.91	3.32	0.43
Skewness	2.06	3.01	1.67	1.98	0.79	1.36	2.00	3.27	-0.21	0.09
Std. Error of Skewness	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Kurtosis	4.42	10.21	3.19	4.95	0.13	2.02	3.74	11.47	-1.29	-1.26
Std. Error of Kurtosis	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41

Table A- 12: Pearson coefficient of linear regression between soil loss and runoff and selected rain erosivity parameters

Variable	Predictor	86-I n=25	86-O n=25	86-C n=25	02-C n=34	02-O n=32	ALL n=141	average
LOGerosion	LOGdepth	0.45	0.33	0.38	0.66	0.55	0.41	0.48
	LOGKe	0.45	0.36	0.40	0.73	0.62	0.44	0.51
	LOGI10	0.43	0.39	0.33	0.79	0.70	0.45	0.53
	LOGI30	0.38	0.40	0.34	0.72	0.61	0.41	0.49
	LOGEI30	0.43	0.39	0.38	0.75	0.63	0.44	0.52
	LOGEI10	0.47	0.39	0.39	0.79	0.69	0.47	0.55
LOGrunoff	LOGdepth	0.70	0.70	0.72	0.86	0.83	0.65	0.77
	LOGKe	0.70	0.70	0.72	0.90	0.86	0.66	0.78
	LOGI10	0.59	0.51	0.49	0.77	0.79	0.52	0.63
	LOGI30	0.61	0.66	0.63	0.85	0.77	0.58	0.71
	LOGEI30	0.68	0.71	0.70	0.90	0.85	0.64	0.77
	LOGEI10	0.69	0.65	0.65	0.88	0.87	0.62	0.75

Table A- 13: Model summary and coefficients of multiple regression analysis for single event soil loss and runoff prediction in reclaimed tepetates

Variable	Predictor	Unstandardized Coeff.		Standardized Coeff.	R^2	R^2 Change
		B	S.E.	Beta		
LOGerosion	(Constant)	1.741	0.172			
	COVER	-1.017	0.113	-0.490	0.260	0.260
	LOGEI10	0.677	0.069	0.525	0.521	0.262
	SOC	-0.160	0.028	-0.314	0.616	0.094
LOGerosion	(Constant)	1.958	0.153			
	COVER	-1.087	0.113	-0.524	0.260	0.260
	LOGEI30	0.657	0.0662	0.530	0.529	0.270
	SOC	-0.154	0.027	-0.303	0.617	0.088
LOGerosion	(Constant)	1.651	0.193			
	COVER	-1.111	0.118	-0.535	0.260	0.260
	LOGdepth	1.287	0.141	0.505	0.514	0.255
	SOC	-0.144	0.028	-0.282	0.591	0.076
LOGrunoff	(Constant)	-0.325	0.124			
	LOGdepth	1.284	0.091	0.695	0.427	0.427
	SOC	-0.150	0.018	-0.408	0.633	0.206
	COVER	-0.335	0.076	-0.223	0.679	0.046
LOGrunoff	(Constant)	0.046	0.102			
	LOGEI30	0.621	0.0442	0.691	0.411	0.411
	SOC	-0.161	0.018	-0.436	0.638	0.227
	COVER	-0.303	0.076	-0.201	0.676	0.038
LOGrunoff	(Constant)	-0.113	0.120			
	LOGEI10	0.618	0.048	0.662	0.389	0.389
	SOC	-0.166	0.019	-0.450	0.620	0.231
	COVER	-0.234	0.079	-0.156	0.643	0.023
LOGerosion	(Constant)	1.959	0.057			
	LOGrunoff	1.046	0.052	0.759	0.686	0.686
	COVER	-0.756	0.078	-0.364	0.814	0.128

Table A- 14: Model summary and coefficients of multiple regression analysis for annual soil loss and runoff prediction in reclaimed tepetates.

Variable	Predictor	Unstandardized Coeff.		Standardized Coeff.	R^2 (adjusted)	R^2 Change
		B	S.E.	Beta		
Soil loss	(Constant)	9.75	2.73			
	SOC	-3.98	0.51	-0.83	0.64	0.64
	EI30	0.030	0.01	0.44	0.84	0.20
Soil loss	(Constant)	-4.83	1.95			
	Runoff	0.07	0.01	0.88	0.85	0.85
	EI30	0.015	0.01	0.21	0.89	0.04
Runoff	(Constant)	265.23	34.15			
	SOC	-37.50	8.16	-0.61	0.79	0.79
	Vmax	-144.82	50.72	-0.38	0.85	0.06
	EI30	0.207	0.07	0.23	0.91	0.05

Appendix 6. Aggregation

Table A- 15: Dry aggregate size distribution and Mean Weight Diameter (MWD) in Tlalpan. Different letter indicate significant difference (P<0.05) in mean MWD between plots (a, b, c) and between age of rehabilitation (x, y).

Year of rehab.	Management	Year	Aggregate size (mm)								MWD
			10 - 8	8 - 5	5 - 3.15	3.15 - 2	2 - 1	< 1	1 - 0.59	< 0.59	
1986	Conventional	2003	12.0%	16.3%	14.6%	12.5%	9.9%	34.6%			3.38
		2004	7.1%	11.5%	11.1%	8.8%	13.2%	*48.3%	12.4%	36.0%	2.47
		2005	11.1%	14.3%	14.7%	11.5%	12.2%	*36.2%	12.5%	23.6%	3.18
		Mean	*10.9%*	*15.0%*	*13.9%*	*11.6%*	*11.0%*	*34.6%*	*12.4%*	*30.7%*	*3.14 ab*
	Improved	2003	11.8%	14.7%	14.1%	11.9%	9.7%	37.8%			3.23
		2004	6.1%	10.9%	12.2%	9.4%	13.8%	*47.5%	12.0%	35.5%	2.41
		2005	8.8%	12.7%	15.4%	12.0%	12.2%	*38.9%	12.2%	26.8%	2.91
		Mean	*10.1%*	*13.6%*	*13.9%*	*11.4%*	*11.0%*	*37.8%*	*12.1%*	*31.8%*	*2.99 a*
	Organic	2003	12.7%	17.6%	16.0%	12.2%	9.5%	32.0%			3.55
		2004	8.4%	12.4%	12.8%	9.8%	12.7%	*43.9%	11.7%	32.2%	2.72
		2005	7.6%	12.3%	14.7%	12.2%	13.5%	*39.7%	15.3%	24.4%	2.79
		Mean	*11.0%*	*15.7%*	*15.1%*	*11.7%*	*10.8%*	*32.0%*	*13.2%*	*28.9%*	*3.23 b*
	Mean		**10.7%**	**14.7%**	**14.3%**	**11.6%**	**10.9%**	**34.8%**	**12.6%**	**30.4%**	**3.12 *x***
2002	Conventional	2003	11.5%	13.1%	12.1%	11.2%	9.7%	42.4%			3.03
		2004	6.9%	9.5%	12.3%	9.4%	11.3%	*50.5%	16.7%	33.8%	2.39
		2005	5.4%	9.7%	12.0%	10.5%	13.4%	*48.9%	17.2%	31.7%	2.31
		Mean	*9.0%*	*11.5%*	*12.1%*	*10.7%*	*11.0%*	*42.4%*	*17.0%*	*32.5%*	*2.69 c*
	Organic	2003	9.2%	12.7%	13.0%	13.9%	9.1%	42.2%			2.88
		2004	8.6%	11.5%	11.7%	9.8%	14.2%	*44.1%	12.6%	31.6%	2.66
		2005	6.0%	9.5%	9.5%	10.8%	14.1%	*50.1%	18.5%	31.6%	2.28
		Mean	*8.2%*	*11.6%*	*11.8%*	*12.3%*	*11.4%*	*42.2%*	*16.1%*	*31.6%*	*2.66 c*
	Mean		**8.6%**	**11.6%**	**12.0%**	**11.5%**	**11.2%**	**42.3%**	**16.6%**	**32.1%**	**2.67 *y***
Mean			10.1%	13.9%	13.7%	11.5%	11.0%	36.7%	13.9%	31.0%	2.99

* In 2004 and 2005, the fraction <1 mm is the sum of 1-0.59 and <0.59 mm fractions
MWD: Mean weight diameter
SD: Standard deviation

Table A- 16: Evolution of ASD and MWD during the 2005 cropping season in Tlalpan. Different letter indicates significant difference (P<0.05) in MWD between 2002-plots and 1986-plots within a date.

Date	Year	Management	< 0.59 mm	0.59 - 1 mm	1 - 2 mm	2 - 3.15 mm	3.15 - 5 mm	5 - 8 mm	8 - 10 mm	MWD
13/07/2005	1986	Conventional	30.5%	18.5%	9.5%	11.0%	11.1%	10.8%	8.7%	2.46
		Improved	36.4%	17.1%	8.9%	10.8%	12.4%	9.0%	5.4%	1.99
		Organic	29.0%	23.8%	9.7%	11.3%	11.4%	9.0%	5.8%	2.08
		Mean	32.0%	19.8%	9.3%	11.0%	11.6%	9.6%	6.6%	2.18 a
	2002	Conventional	36.7%	20.0%	9.4%	10.8%	11.2%	7.9%	4.0%	1.76
		Organic	31.4%	23.9%	9.4%	11.0%	11.3%	8.0%	5.0%	1.95
		Mean	34.0%	22.0%	9.4%	10.9%	11.2%	8.0%	4.5%	1.85 a
22/09/2005	1986	Conventional	9.9%	7.5%	13.7%	13.0%	19.0%	20.2%	16.6%	3.98
		Improved	12.1%	6.7%	13.3%	14.6%	20.0%	18.6%	14.8%	3.76
		Organic	12.0%	9.8%	16.6%	14.9%	19.7%	17.5%	9.6%	3.03
		Mean	11.3%	8.0%	14.5%	14.2%	19.6%	18.8%	13.7%	3.59 a
	2002	Conventional	27.5%	15.7%	15.8%	10.4%	13.2%	11.2%	6.2%	2.21
		Organic	30.8%	18.6%	17.0%	11.3%	6.2%	9.3%	6.7%	2.08
		Mean	29.2%	17.1%	16.4%	10.8%	9.7%	10.3%	6.5%	2.15 b
17/11/2005	1986	Conventional	30.5%	11.6%	13.5%	10.6%	14.1%	11.8%	8.1%	2.48
		Improved	31.8%	12.8%	14.3%	10.5%	13.8%	10.6%	6.2%	2.21
		Organic	32.3%	12.2%	14.1%	10.5%	13.1%	10.3%	7.5%	2.38
		Mean	31.5%	12.2%	14.0%	10.5%	13.6%	10.9%	7.3%	2.35 a
	2002	Conventional	30.8%	16.0%	15.1%	10.4%	11.8%	10.0%	6.0%	2.12
		Organic	32.7%	12.9%	15.8%	10.1%	10.9%	11.2%	6.4%	2.13
		Mean	31.8%	14.4%	15.5%	10.3%	11.3%	10.6%	6.2%	2.13 a

Table A- 17: Aggregate stability (PSw) in Tlalpan from 2003 to 2005. Different letters indicate significant difference (p<0.05) between plots (a, b, c) or between plots age of rehabilitation (x, y) within a year.

Year of rehabilitation		1986				2002		
Management		Conventional	Improved	Organic	*Mean*	Conventional	Organic	*Mean*
2003		236.5	302.4	442.1	*324.8*	170.2	254.0	*213.9*
	P<0.05	*a*	*a*	*b*	*x*	*a*	*a*	*y*
2004	furrow	624.1	700.4	978.7	*767.7*	346.6	925.9	*636.2*
	ridge	227.7	389.7	770.1	*462.5*	300.5	553.2	*426.8*
	mean	425.9	545.0	874.4	*615.1*	323.5	739.5	*531.5*
	P<0.05	*a*	*ac*	*b*	*x*	*a*	*bc*	*x*
2005	13 Jul.	100.2	129.5	179.1	*136.3*	61.2	146.1	*103.7*
	22 Sep.	105.9	157.9	133.0	*132.2*	52.7	103.0	*77.9*
	17 Nov.	88.1	55.9	107.7	*83.9*	22.1	34.2	*28.1*
	mean	98.1	114.4	139.9	*117.5*	45.3	94.4	*69.9*
	P<0.05	*a*	*ab*	*b*	*x*	*c*	*a*	*y*
Mean		259.3	329.5	498.6	*361.1*	162.3	308.7	*236.9*
	P<0.05	*ac*	*a*	*b*	*x*	*c*	*a*	*y*

Table A- 18: PS index in relation to aggregate size from 2003 to 2005

		Aggregate size	2003	2004			2005			
				furrow	ridge	Mean	13/07/05	22/09/05	17/11/05	Mean
1986	Conventional	0.59-1 mm	-	407.9	150.4	279.2	69.1	108.6	43.8	73.8
		1-2 mm	255.4	605.4	241.4	423.4	93.7	86.6	55.2	78.5
		2-3.15 mm	-	1033.7	296.5	665.1	158.3	124.6	178.6	153.8
		3.15-5 mm	222.9	-	-	-	-	-	-	-
	Improved	0.59-1 mm	-	451.5	285.3	368.4	83.5	151.8	38.7	91.3
		1-2 mm	277.1	731.0	377.7	554.3	122.2	136.4	39.3	99.3
		2-3.15 mm	-	955.0	530.3	742.6	208.1	180.2	99.7	162.7
		3.15-5 mm	321.2	-	-	-	-	-	-	-
	Organic	0.59-1 mm	-	577.6	467.3	522.4	100.4	126.2	53.2	93.3
		1-2 mm	350.1	1067.4	819.0	943.2	194.8	101.8	61.6	119.4
		2-3.15 mm	-	1391.0	1170.0	1280.5	332.0	172.4	233.4	245.9
		3.15-5 mm	483.0	-	-	-	-	-	-	-
2002	Conventional	0.59-1 mm	-	302.2	256.0	279.1	53.3	57.1	23.5	44.6
		1-2 mm	190.3	348.3	343.0	345.6	73.8	53.0	21.7	49.5
		2-3.15 mm	-	393.3	297.4	345.3	64.8	45.5	20.6	43.6
		3.15-5 mm	151.5	-	-	-	-	-	-	-
	Organic	0.59-1 mm	-	605.1	506.9	556.0	75.0	91.7	31.5	66.1
		1-2 mm	294.5	844.6	573.4	709.0	146.3	106.1	32.0	94.8
		2-3.15 mm	-	1405.6	629.9	1017.8	300.9	116.8	41.0	152.9
		3.15-5 mm	227.0	-	-	-	-	-	-	-

Appendix 7. Porosity

Table A- 19: Porosity and pore size distribution in 2003

Year = 2003		1986				2002			Mean
depth	Parameter	Conv.	Imp.	Organic	Mean	Conv.	Organic	Mean	
10	PT sat	42.7	42.8	45.1	43.5	48.2	43.9	45.9	44.1
	Bulk Density	1.2	1.3	1.2	1.2	1.1	1.2	1.2	1.2
	Fine pores <0.2 µm	18.9	19.6	17.4	18.7	18.2	20.2	19.3	18.8
	Pores 0.2 - 3 µm	8.7	9.7	10.2	9.5	8.8	10.6	9.8	9.6
	Pores 3 - 10 µm	2.8	3.4	3.0	3.1	2.7	2.5	2.6	3.0
	Medium pores 0.2-10 µm	11.6	13.1	13.2	12.6	11.5	13.1	12.4	12.5
	Pores 10 - 30 µm	4.1	4.3	4.2	4.2	5.1	4.2	4.6	4.3
	Pores30 - 50 µm	2.0	1.8	2.1	1.9	3.1	2.1	2.6	2.1
	Pores 50 - 120 µm	3.3	2.4	4.4	3.4	5.5	3.5	4.4	3.6
	Pores >120µm	3.0	1.5	3.8	2.8	4.8	0.8	2.6	2.7
	Large pores >10 µm	12.3	10.0	14.5	12.3	18.5	10.6	14.2	12.8
20	PT sat	44.4	45.0	45.6	45.0	45.3	45.7	45.5	45.2
	Bulk Density	1.3	1.2	1.3	1.3	1.2	1.2	1.2	1.3
	Fine pores <0.2 µm	20.4	19.0	19.8	19.8	21.0	21.2	21.1	20.1
	Pores 0.2 - 3 µm	10.9	10.3	10.7	10.6	11.0	10.5	10.8	10.6
	Pores 3 - 10 µm	2.9	3.0	3.3	3.1	2.4	2.7	2.5	2.9
	Medium pores 0.2-10 µm	13.7	13.3	14.0	13.7	13.4	13.2	13.3	13.6
	Pores 10 - 30 µm	4.0	4.4	4.4	4.3	4.0	4.0	4.0	4.2
	Pores30 - 50 µm	1.9	2.0	1.9	2.0	2.5	2.1	2.3	2.0
	Pores 50 - 120 µm	3.0	3.8	3.5	3.5	2.8	3.7	3.3	3.4
	Pores >120µm	1.3	2.5	2.0	1.9	1.6	1.6	1.6	1.8
	Large pores >10 µm	10.2	12.7	11.8	11.6	10.9	11.4	11.1	11.5
30	PT sat	43.7	45.2	45.8	45.0	44.6	44.9	44.7	44.9
	Bulk Density	1.3	1.3	1.2	1.2	1.3	1.2	1.2	1.2
	Fine pores <0.2 µm	20.4	20.8	19.4	20.2	21.7	22.5	22.1	20.7
	Pores 0.2 - 3 µm	8.6	8.7	10.2	9.2	10.6	9.5	10.0	9.4
	Pores 3 - 10 µm	3.3	3.1	2.9	3.1	2.3	2.1	2.2	2.8
	Medium pores 0.2-10 µm	11.8	11.8	13.1	12.3	12.8	11.6	12.2	12.3
	Pores 10 - 30 µm	4.2	4.2	4.6	4.3	3.6	3.0	3.3	4.1
	Pores30 - 50 µm	2.0	2.0	2.1	2.0	1.9	1.7	1.8	2.0
	Pores 50 - 120 µm	3.2	3.7	4.0	3.6	3.4	3.2	3.3	3.5
	Pores >120µm	2.2	2.7	2.7	2.5	1.2	2.8	2.0	2.4
	Large pores >10 µm	11.5	12.6	13.4	12.5	10.1	10.7	10.4	12.0
40	PT sat	43.6	45.8	45.5	45.0	46.6	43.9	45.1	45.0
	Bulk Density	1.3	1.2	1.3	1.3	1.2	1.3	1.2	1.3
	Fine pores <0.2 µm	20.6	21.4	20.8	21.0	22.5	23.1	22.8	21.4
	Pores 0.2 - 3 µm	8.3	9.4	10.1	9.2	9.9	10.8	10.4	9.5
	Pores 3 - 10 µm	3.7	3.2	3.0	3.3	2.1	2.4	2.3	3.1
	Medium pores 0.2-10 µm	11.9	12.7	13.1	12.5	12.0	13.2	12.6	12.6
	Pores 10 - 30 µm	4.4	4.2	4.5	4.4	2.8	2.9	2.9	4.1
	Pores30 - 50 µm	2.1	1.8	2.3	2.1	1.5	1.7	1.6	2.0
	Pores 50 - 120 µm	2.9	3.2	3.1	3.1	3.2	2.1	2.6	3.0
	Pores >120µm	1.6	2.6	1.7	2.0	4.6	1.0	2.6	2.1
	Large pores >10 µm	11.0	11.8	11.6	11.5	12.1	7.7	9.7	11.1
Mean	PT sat	43.6	44.8	45.5	44.6	46.1	44.6	45.3	44.8
	Bulk Density	1.3	1.3	1.2	1.3	1.2	1.2	1.2	1.2
	Fine pores <0.2 µm	20.1	20.3	19.4	19.9	20.8	21.7	21.3	20.2
	Pores 0.2 - 3 µm	9.1	9.5	10.3	9.7	10.2	10.3	10.2	9.8
	Pores 3 - 10 µm	3.2	3.2	3.1	3.1	2.4	2.4	2.4	2.9
	Medium pores 0.2-10 µm	12.3	12.7	13.4	12.8	12.5	12.8	12.7	12.7
	Pores 10 - 30 µm	4.2	4.3	4.5	4.3	3.9	3.5	3.7	4.2
	Pores30 - 50 µm	2.0	1.9	2.1	2.0	2.3	1.9	2.1	2.0
	Pores 50 - 120 µm	3.1	3.3	3.7	3.4	3.7	3.2	3.4	3.4
	Pores >120µm	2.0	2.3	2.5	2.3	2.8	1.6	2.2	2.3
	Large pores >10 µm	11.3	11.8	12.8	12.0	12.7	10.2	11.4	11.8

Table A- 20: Porosity and pore size distribution in 2004 (in ridge area)

Year = 2004		1986				2002			Mean
depth	Parameter	Conv.	Imp.	Organic	Mean	Conv.	Organic	Mean	
5	PT sat	47.8	47.1	45.3	46.7	46.0	50.3	48.2	47.1
	Bulk Density	1.2	1.2	1.2	1.2	1.2	1.1	1.2	1.2
	Fine pores <0.2 µm	15.5	14.6	15.0	15.0	16.9	18.8	17.8	15.7
	Pores 0.2 - 3 µm	11.8	13.6	12.0	12.5	12.3	8.5	10.4	12.0
	Pores 3 - 10 µm	3.2	2.6	2.6	2.8	3.0	2.6	2.8	2.8
	Medium pores 0.2-10 µm	15.0	16.2	14.6	15.2	15.3	11.1	13.2	14.7
	Pores 10 - 30 µm	4.8	4.8	4.7	4.8	4.6	5.0	4.8	4.8
	Pores30 - 50 µm	2.2	2.6	2.2	2.4	2.1	2.8	2.5	2.4
	Pores 50 - 120 µm	4.5	3.9	4.1	4.2	3.6	4.8	4.2	4.2
	Pores >120µm	5.8	4.9	4.8	5.2	3.6	7.9	5.7	5.3
	Large pores >10 µm	17.4	16.2	15.8	16.4	13.9	20.4	17.2	16.6
10	PT sat	47.5	47.5	46.6	47.2	47.5	50.4	48.9	47.6
	Bulk Density	1.3	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	Fine pores <0.2 µm	15.5	14.6	15.0	15.0	17.4	18.8	18.1	15.8
	Pores 0.2 - 3 µm	14.1	12.9	12.2	13.1	14.8	11.7	13.3	13.1
	Pores 3 - 10 µm	3.4	2.6	2.8	2.9	2.9	2.6	2.7	2.9
	Medium pores 0.2-10 µm	17.5	15.6	15.0	16.0	17.7	14.3	16.0	16.0
	Pores 10 - 30 µm	6.1	4.9	4.8	5.3	3.9	4.3	4.1	4.9
	Pores30 - 50 µm	1.7	2.7	2.5	2.3	2.4	2.6	2.5	2.3
	Pores 50 - 120 µm	3.3	4.3	4.2	3.9	3.6	5.3	4.4	4.1
	Pores >120µm	3.5	5.4	5.2	4.7	2.6	5.1	3.9	4.5
	Large pores >10 µm	14.5	17.3	16.7	16.1	12.4	17.3	14.9	15.8
20	PT sat	47.9	48.5	46.9	47.8	47.4	50.3	48.8	48.0
	Bulk Density	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	Fine pores <0.2 µm	15.7	15.5	14.9	15.3	17.9	18.2	18.1	16.0
	Pores 0.2 - 3 µm	13.7	11.8	12.5	12.7	12.3	13.1	12.7	12.7
	Pores 3 - 10 µm	2.7	2.5	2.5	2.6	2.8	2.2	2.5	2.6
	Medium pores 0.2-10 µm	16.4	14.4	15.0	15.3	15.1	15.2	15.2	15.2
	Pores 10 - 30 µm	4.8	4.8	4.0	4.5	4.4	3.9	4.2	4.4
	Pores30 - 50 µm	3.3	2.9	3.3	3.2	2.8	2.8	2.8	3.1
	Pores 50 - 120 µm	4.2	4.9	4.4	4.5	4.4	5.0	4.7	4.6
	Pores >120µm	3.6	6.1	5.2	5.0	2.7	5.1	3.9	4.7
	Large pores >10 µm	15.8	18.7	17.0	17.1	14.4	16.8	15.6	16.8
30	PT sat	49.9	47.9	46.7	48.2	49.3	49.8	49.5	48.5
	Bulk Density	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.2
	Fine pores <0.2 µm	16.5	15.7	15.8	16.0	17.9	18.3	18.1	16.5
	Pores 0.2 - 3 µm	10.5	12.6	12.3	11.8	11.2	11.4	11.3	11.7
	Pores 3 - 10 µm	2.8	2.5	2.6	2.6	2.7	2.5	2.6	2.6
	Medium pores 0.2-10 µm	13.3	15.1	14.9	14.4	13.8	13.9	13.9	14.3
	Pores 10 - 30 µm	5.0	5.1	4.5	4.9	4.9	4.4	4.6	4.8
	Pores30 - 50 µm	3.4	3.0	2.6	3.0	2.9	2.8	2.9	3.0
	Pores 50 - 120 µm	5.6	4.8	4.7	5.1	5.3	4.7	5.0	5.1
	Pores >120µm	6.2	4.2	4.1	4.8	4.6	5.7	5.1	4.9
	Large pores >10 µm	20.2	17.1	16.0	17.7	17.6	17.6	17.6	17.7
40	PT sat	46.9	46.0	44.9	46.0	47.6	46.8	47.2	46.4
	Bulk Density	1.2	1.2	1.3	1.2	1.2	1.2	1.2	1.2
	Fine pores <0.2 µm	16.9	15.6	16.0	16.2	17.9	19.0	18.4	16.9
	Pores 0.2 - 3 µm	13.2	12.0	12.0	12.5	10.9	12.5	11.6	12.2
	Pores 3 - 10 µm	2.7	2.4	3.1	2.7	3.1	2.3	2.7	2.7
	Medium pores 0.2-10 µm	15.8	14.4	15.1	15.2	14.0	14.8	14.4	15.0
	Pores 10 - 30 µm	4.0	4.5	4.8	4.4	5.9	4.1	5.1	4.6
	Pores30 - 50 µm	2.9	3.3	3.0	3.0	2.6	2.5	2.6	2.9
	Pores 50 - 120 µm	4.0	4.6	4.0	4.1	4.5	3.5	4.0	4.1
	Pores >120µm	3.3	3.6	2.1	3.0	2.6	3.0	2.8	2.9
	Large pores >10 µm	14.1	16.0	13.9	14.6	15.7	13.1	14.4	14.5
Mean	PT sat	48.0	47.5	46.1	47.2	47.5	49.6	48.5	47.6
	Bulk Density	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	Fine pores <0.2 µm	16.0	15.2	15.3	15.5	17.6	18.6	18.1	16.2
	Pores 0.2 - 3 µm	12.6	12.6	12.2	12.5	12.3	11.4	11.9	12.3
	Pores 3 - 10 µm	3.0	2.5	2.7	2.7	2.9	2.4	2.7	2.7
	Medium pores 0.2-10 µm	15.6	15.2	14.9	15.2	15.2	13.8	14.5	15.0
	Pores 10 - 30 µm	4.9	4.8	4.6	4.8	4.7	4.3	4.5	4.7
	Pores30 - 50 µm	2.7	2.9	2.7	2.8	2.6	2.7	2.6	2.7
	Pores 50 - 120 µm	4.3	4.5	4.3	4.4	4.3	4.7	4.5	4.4
	Pores >120µm	4.5	4.9	4.4	4.6	3.2	5.4	4.3	4.5
	Large pores >10 µm	16.5	17.1	16.0	16.5	14.8	17.1	15.9	16.4

Table A- 21: Porosity and pore size distribution in 2005

Year = 2005		1986				2002			Mean
Depth	Parameter	Conv.	Imp.	Organic	Mean	Conv.	Organic	Mean	
5	PT sat	50.8	52.7	51.9	51.8	51.9	54.9	53.4	52.2
	Bulk Density	1.2	1.1	1.2	1.2	1.1	1.1	1.1	1.1
	Fine pores <0.2 µm	15.4	15.0	14.4	14.9	16.9	18.8	17.8	15.7
	Pores 0.2 - 3 µm	11.9	11.3	13.2	12.1	12.4	10.5	11.5	11.9
	Pores 3 - 10 µm	3.7	3.5	3.2	3.4	3.5	3.7	3.6	3.5
	Medium pores 0.2-10 µm	15.5	14.7	16.4	15.6	15.9	14.2	15.0	15.4
	Pores 10 - 30 µm	5.6	5.8	5.3	5.6	5.0	7.3	6.1	5.7
	Pores30 - 50 µm	4.0	4.2	3.8	4.0	3.7	1.7	2.7	3.7
	Pores 50 - 120 µm	7.9	9.5	7.8	8.4	7.1	9.8	8.5	8.4
	Pores >120µm	2.4	3.5	4.2	3.3	3.3	3.3	3.3	3.3
	Large pores >10 µm	19.9	22.9	21.1	21.3	19.2	22.0	20.6	21.1
10	PT sat	52.1	53.6	51.4	52.3	52.6	54.7	53.7	52.7
	Bulk Density	1.1	1.1	1.2	1.1	1.2	1.1	1.1	1.1
	Fine pores <0.2 µm	15.3	15.2	14.5	15.0	16.9	18.8	17.8	15.7
	Pores 0.2 - 3 µm	10.6	9.4	13.0	11.0	11.5	9.8	10.7	10.9
	Pores 3 - 10 µm	3.3	3.4	3.0	3.2	3.4	2.9	3.2	3.2
	Medium pores 0.2-10 µm	14.0	12.8	15.9	14.2	14.9	12.8	13.8	14.1
	Pores 10 - 30 µm	4.8	5.6	5.1	5.2	5.3	5.0	5.1	5.2
	Pores30 - 50 µm	3.9	3.9	3.6	3.8	4.4	3.3	3.8	3.8
	Pores 50 - 120 µm	8.5	8.8	7.5	8.3	8.2	9.4	8.8	8.4
	Pores >120µm	5.5	7.3	4.9	5.9	3.0	5.6	4.3	5.5
	Large pores >10 µm	22.7	25.6	21.0	23.1	20.8	23.2	22.0	22.8
20	PT sat	51.7	52.4	48.7	50.9	50.2	53.5	51.9	51.2
	Bulk Density	1.1	1.1	1.2	1.1	1.1	1.1	1.1	1.1
	Fine pores <0.2 µm	15.5	15.7	14.8	15.3	17.7	18.2	18.0	16.0
	Pores 0.2 - 3 µm	10.4	8.2	11.8	10.1	9.6	10.0	9.8	10.1
	Pores 3 - 10 µm	3.0	3.0	2.9	2.9	2.8	2.9	2.9	2.9
	Medium pores 0.2-10 µm	13.3	11.2	14.7	13.1	12.4	12.9	12.7	13.0
	Pores 10 - 30 µm	5.4	5.3	4.5	5.1	4.4	4.6	4.5	4.9
	Pores30 - 50 µm	3.8	4.0	3.2	3.7	3.7	3.2	3.5	3.6
	Pores 50 - 120 µm	9.4	8.6	6.4	8.1	6.8	8.8	7.8	8.1
	Pores >120µm	4.3	7.6	5.0	5.6	5.1	5.9	5.5	5.6
	Large pores >10 µm	22.9	25.5	19.2	22.5	20.1	22.4	21.2	22.2
30	PT sat	47.6	50.0	47.7	48.4	51.0	51.6	51.3	49.1
	Bulk Density	1.1	1.1	1.2	1.2	1.1	1.1	1.1	1.1
	Fine pores <0.2 µm	16.1	16.1	15.6	15.9	17.9	18.3	18.1	16.5
	Pores 0.2 - 3 µm	10.2	8.9	12.4	10.5	11.6	9.5	10.5	10.5
	Pores 3 - 10 µm	2.9	2.6	2.7	2.7	2.9	2.8	2.8	2.8
	Medium pores 0.2-10 µm	13.1	11.5	15.1	13.2	14.4	12.4	13.4	13.3
	Pores 10 - 30 µm	4.5	5.2	3.6	4.4	4.8	4.9	4.9	4.5
	Pores30 - 50 µm	3.4	3.4	2.8	3.2	3.9	2.7	3.3	3.2
	Pores 50 - 120 µm	6.5	7.4	5.2	6.4	6.9	7.4	7.1	6.6
	Pores >120µm	4.0	6.2	5.4	5.2	3.1	5.8	4.5	5.0
	Large pores >10 µm	18.4	22.3	17.0	19.3	18.7	20.9	19.8	19.4
40	PT sat	45.8	47.4	44.6	46.0	48.1	47.0	47.6	46.4
	Bulk Density	1.2	1.2	1.3	1.2	1.2	1.2	1.2	1.2
	Fine pores <0.2 µm	16.9	15.3	16.1	16.0	18.5	18.9	18.7	16.8
	Pores 0.2 - 3 µm	10.3	13.2	14.0	12.7	11.2	13.8	12.5	12.6
	Pores 3 - 10 µm	3.0	2.6	2.8	2.8	2.5	2.2	2.3	2.6
	Medium pores 0.2-10 µm	13.4	15.8	16.7	15.4	13.7	16.0	14.8	15.2
	Pores 10 - 30 µm	4.3	4.4	3.7	4.2	3.4	2.9	3.2	3.9
	Pores30 - 50 µm	3.2	3.0	2.9	3.0	2.9	2.2	2.5	2.9
	Pores 50 - 120 µm	6.1	6.0	4.1	5.4	4.7	4.3	4.5	5.2
	Pores >120µm	1.9	2.9	1.0	2.0	4.9	2.7	3.8	2.5
	Large pores >10 µm	15.5	16.3	11.7	14.6	15.9	12.2	14.1	14.4
Mean	PT sat	49.8	51.2	49.0	50.0	50.8	52.4	51.6	50.4
	Bulk Density	1.2	1.1	1.2	1.2	1.2	1.1	1.1	1.2
	Fine pores <0.2 µm	15.8	15.5	15.0	15.4	17.6	18.6	18.1	16.1
	Pores 0.2 - 3 µm	10.7	10.2	12.9	11.2	11.3	10.7	11.0	11.2
	Pores 3 - 10 µm	3.2	3.0	2.9	3.0	3.0	2.9	3.0	3.0
	Medium pores 0.2-10 µm	13.9	13.2	15.8	14.3	14.3	13.6	14.0	14.2
	Pores 10 - 30 µm	5.0	5.3	4.5	4.9	4.6	4.9	4.8	4.9
	Pores30 - 50 µm	3.7	3.7	3.3	3.5	3.7	2.6	3.2	3.4
	Pores 50 - 120 µm	7.8	8.1	6.2	7.4	6.8	7.9	7.3	7.4
	Pores >120µm	3.7	5.5	4.2	4.5	3.9	4.7	4.3	4.4
	Large pores >10 µm	20.1	22.5	18.2	20.3	18.9	20.1	19.5	20.1

Table A- 22: Pore size distribution at 5 cm depth in ridge and furrow areas in a maize cropping system in 2004. Different letters indicate significant difference between ridge and furrow areas.

		1986			2002		Mean
	Parameter	Conventional	Improved	Organic	Conventional	Organic	
Ridge	PT sat	49.7	48.6	46.3	47.4	52.1	48.6 a
	Bulk Density	1.1	1.1	1.2	1.2	1.1	1.1
	Fine pores <0.2 µm	15.1	15.2	15.1	16.9	18.7	15.8 a
	Pores 0.2 - 3 µm	11.8	12.6	10.9	11.5	8.6	11.3 a
	Pores 3 - 10 µm	3.3	2.6	2.4	3.0	2.5	2.7 a
	Medium pores 0.2-10 µm	15.0	15.1	13.3	14.5	11.1	14.1 a
	Pores 10 - 30 µm	4.7	4.6	4.8	5.0	4.5	4.7 a
	Pores30 - 50 µm	1.6	2.7	2.3	1.9	2.7	2.2 a
	Pores 50 - 120 µm	5.5	4.5	4.4	3.9	4.9	4.7 a
	Pores >120µm	7.8	6.6	6.2	5.3	10.1	7.1 a
	Large pores >10 µm	19.6	18.3	17.8	16.1	22.3	18.7 a
Furrow	PT sat	45.8	45.5	44.3	44.6	48.6	45.6 b
	Bulk Density	1.2	1.2	1.3	1.3	1.2	1.2
	Fine pores <0.2 µm	15.9	14.1	14.8	16.8	18.8	15.6 a
	Pores 0.2 - 3 µm	11.8	14.6	13.1	13.1	8.4	12.6 a
	Pores 3 - 10 µm	3.1	2.7	2.7	2.9	2.8	2.8 a
	Medium pores 0.2-10 µm	14.9	17.3	15.8	16.1	11.2	15.4 a
	Pores 10 - 30 µm	4.9	5.0	4.5	4.3	5.4	4.8 a
	Pores30 - 50 µm	2.9	2.5	2.1	2.3	2.9	2.5 a
	Pores 50 - 120 µm	3.5	3.4	3.7	3.3	4.6	3.6 b
	Pores >120µm	3.8	3.2	3.4	1.9	5.7	3.5 b
	Large pores >10 µm	15.1	14.1	13.7	11.7	18.6	14.5 b