CHAPTER 8

Soil Restoration and Conservation: The "Tepetates" – Indurated Volcanic Soils – in Mexico

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INTRODUCTION

The soils of the high volcanic plateaus of Mexico frequently show indurated horizons, locally called "tepetates" (which means stone matting in Nahuatl). They occur mainly after erosion of the superficial soil on the piedmonts of the volcanic massifs and the plateaus, thus denuding quasi-sterile areas. In the Mexico valley at the foot of the Sierra Nevada and in Tlaxcala State, they account for between 30 and 40% of the soils dedicated to food crops and they affect most of the rural population. The shortage of agricultural soils is a serious problem in this overpopulated area close to Mexico City (Figure 8.1). Therefore, considerable effort has been made for about 20 years, both locally and with international assistance, to try to reclaim tepetates into fertile soils and to control erosion.

In order to convert these soils back to productive agriculture, a cultivation sequence is used:

1. "Roturation" (deep subsoiling, deep ploughing, and disc harrowing) to split up and loosen the tepetate in order to allow water and air to infiltrate.
2. Terracing, generally at reduced slope and following contours.

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* Unfortunately died in an airplane crash at Bogota, 20th April 1998.

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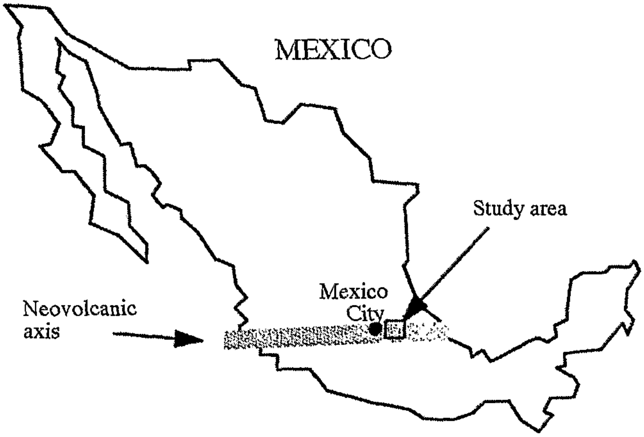

Figure 8.1 Location of the tepetate soils in Mexico

3. An organic and/or mineral fertilisation to replace the original lack of nitrogen, phosphorus and organic manure (humus, microorganisms).
4. A crop rotation adapted to the farmers' experience with wheat or barley first, then with maize and beans. Ridging must be employed with maize; this is a complex operation over three periods. In May, a furrow is made by a mouldboard plough and the maize is sown. In July manual weeding is carried out after emergence and the maize begins to be earthed-up; in August this is completed and ridges and depressions characterise the crop field.

Production approaches average for the region after 3 or 5 years of cultivation (Marquez et al., 1992; Quantin, 1992). Initial studies conducted by the European Community (CCE-STD2) between 1989 and 1992 were devoted to understanding tepetates (features, origin and properties); to the measurement of erosion in small plots; and finally to the agronomic and socio-economic consequences of agricultural reclamation. A subsequent study has tested at small-plot scale the regeneration and conservation of the indurated volcanic soils elsewhere in South America (mainly in Ecuador and Mexico). The major results are given in a synthesis elsewhere (Quantin, 1992). This chapter highlights the results of the first programme measuring erosion in small plots in the Mexico valley and Tlaxcala State as well as the success of agricultural production in the first years of recultivation. It also reports the initial results of the water balance and erosion studies (Prat et al., 1993).

Erosion was studied in small experimental plots, most of them being 22 × 2 m (Wischmeier standards) and with a mean slope ranging from 8 to 9%. The tepetates tested were of two types, t_2 and t_3 (Quantin, 1992), with a fragipan consistency (hard when dry and friable when moist). They contain 30–40% clay but are weakly cemented, probably by silica. Their total porosity ranges from 40 to 55%, but their macroporosity is low, generally lower than 5% and sometimes even zero, so that hydraulic conductivity is lower than 1 mm h^{-1} and air porosity is very limited. Thus, they outcrop after soil erosion and remain sterile.

Measurements were made in four stations (San Miguel Tlaixpan, El Carmen, Matlalohcan and Tlalpan) at similar altitude (2,500 to 2,600 m), slope (8 to 9%) and climate (average air temperature 13°C, rainfall 700–800 mm). They enabled local variations in the rainfall regime and intensity to be tested. A cultivated agricultural soil (bare or with maize ridging) was compared with a tepetate denuded by erosion, and with a bare "*roturé*" tepetate or one covered with a cultivated plant (flat cultivation of wheat, or maize ridging). Rainfall (rainfall intensity pattern), the volume of runoff water and the weight of eroded soil were measured. Periodic measurements of soil moisture, density–porosity and particle size were also made and the evolution of the surface features – the formation of crusts, the decrease in the size of aggregates and the infiltration rate – were observed.

RAINFALL EROSIVITY

The hygrothermic climatic regime is of "ustic–isomesic" type (mean temperature 13°C, mean rainfall 700–800 mm). The rainy season from May to October during the summer period alternates with a six month dry and somewhat colder season. The analysis of rainfall erosivity was carried out on the 1991 rainfall patterns recorded in the four stations. The EI.30 Wischmeier index (1958) was converted into American units in order to be comparable with other data from the literature. Calculations were also made in international units of I.30 ($\mathrm{mm\,h^{-1}}$) and EI.30 ($\mathrm{MJ\,ha^{-1} \times mm\,h^{-1}}$). The AIm erosivity index (Lal, 1976) was also calculated (Baumann, 1992).

Rainfall and the cumulative index of erosivity at the four stations are shown in Table 8.1. Rainfall was about 100 mm higher on the Tlaxcala slope (El Carmen, Tlalpan and Matlalohcan) facing the Texcoco slope in the Mexico valley (San Miguel Tlaixpan). Thus, there is a slope effect from the eastern to western sides of the Sierra Nevada. Moreover, given that there is the same total amount of rainfall on the Tlaxcala slope, there is variation in number of rainy days and particularly their intensity and erosivity index. EI.30 ranged from 234 to 429. The more irregular the rainfall regime (at Matlalohcan), the more erosive it appeared to be. This effect is confirmed by the runoff and erosion recorded (see below).

The calculated values of the erosivity index in 1991 ranged from 200 to 429, considered low to medium by Roose (1981) for a "tropical dry" area. The frequency of highly erosive rainfall events is actually very limited with reference to the calculated

Table 8.1 Rainfall and rainfall erosivity in 1991

	Rainfall		Erosivity	
Station	*H* (mm)	*N* (days)	EI.30[a]	AIm[b]
San Miguel T.	669	99	200	
El Carmen	779	120	234	261
Tlalpan	803	112	357	330
Matlalohcan	775	96	429	418

[a] Wischmeier index, American units. [b] Lal index

Table 8.2 Rainfall frequency at different levels of intensity and erosivity

I.30[a]	PE 25–30		ME 30–50	FE >50	
EI.30[b]	100–200	200–400	400–1000	>1000	Total
San Miguel T.	4	–	–	–	4
El Carmen	–	3	3	–	6
Tlalpan	–	3	3	2	8
Matlalohcan	–	9	3	1	13

[a] I.30: mm h^{-1}. [b] EI.30: MJ ha^{-1} × mm h^{-1}. PE: weakly erosive, ME: moderately erosive, FE: highly erosive

values I.30 and EI.30 and to the results of soil loss observed after each rainfall. Table 8.2 shows these exceptional rainfall events and classifies them by order of erosive intensity for each station.

Given a similar rainfall regime, each station is therefore distinguished by the amount and particularly the intensity of erosive rainfall events. Thus there are few erosive events each year, but they are responsible for 60–80% of the total erosion.

The values of the AIm index proposed by Lal (1976) for tropical areas are close to those of EI.30. The calculation of EI.30 for short rainstorms may be less accurate; it affects the annual cumulated value and it is not precise enough to establish a correlation with the intensity of runoff and erosion. It would be necessary to make a more precise analysis of the rainfall intensity at a time step of 10 minutes, or even of 5 minutes, for a better understanding of the effect of high rainfall intensities during a short period of time.

RUNOFF AND EROSION

Measurements were made over 2 years following tepetate "roturation". Runoff and erosion data obtained from four stations in a year when the same cultivated plant (maize ridging) was used in all the stations are shown in Table 8.3. In the same year rainfall erosivity, observation of the soil water regime and of the evolution of the surface features during the rainy season were measured.

The tepetates t_2 and t_3 denuded by erosion show a similar behaviour. The average annual runoff rate is close to 70%. It is not total, for initial rainfall and small rainfall events infiltrate through shrinkage cracks. But runoff reaches 80–90% when there are heavy rainstorms. Erosion is normally low, ranging from 5 to 10 t ha^{-1} yr^{-1} (except in t_3 at Tlalpan) due to the compactness and stability of the original tepetate.

A single deep "subsoiling" of the denuded tepetate decreased runoff by nearly half, 40%, and erosion by 2 t ha^{-1} yr^{-1}. There was also an improvement in the infiltration and surface roughness, without any destabilisation of aggregates. The effect of a complete "roturation" of the denuded tepetate (deep subsoiling followed by several deep ploughings and disc harrowings in order to get an optimum aggregate in the first year followed by a deep ploughing in the second year) varied with the rainfall erosivity. In the less erosive station (San Miguel Tlaixpan), the runoff rate ranged

Table 8.3 Measurement of soil loss and runoff from tepetates

Station	Treatment	Plot length (m)	Erosion (t ha^{-1})	Runoff (%)
San Miguel Tlaixpan	Bare tepetate t_3	22	5.05	88[a]
	Ploughed, bare T	22	21.89	44[a]
	T, L + B, bare	22	1.04	12[a]
	T, L + B, maize	22	1.24	5[a]
	T, L + B, maize	10	1.18	5[a]
	Soil, L + B, bare	22	1.1	12[a]
	Soil, L + B, maize	22	1.79	11[a]
El Carmen	t_3 Bare tepetate	3	8.0	70[b]
	t_2 Bare tepetate	3	6.3	67[b]
	t_2 T, L bare	22	78.0	34[b]
	t_2 T, L + B, maize	22	23.0	11[b]
Tlalpan	t_3 Bare tepetate	3	41.0	68[b]
	t_2 Bare tepetate	3	7.5	65[b]
	t_3 T, L bare	22	128.0	43[b]
	t_3 T, L + B, maize	22	26.0	21[b]
Matlalohcan	t_3 Bare tepetate	6	8.8	75[b]
	t_3 T, R + shrubs	6	26.0	61[b]
	Soil, bare	22	47.0	34[b]
	Soil, savanna	22	0.3	10[b]

T: Tepetate (t_2 or t_3), L: subsoiled and ploughed, R: subsoiled, B: ridged.
[a] Average estimate of the three most erosive rainfalls. [b] % of the total rainfall

from 10 to 20% and erosion amounted to 21 t ha^{-1} yr^{-1} In the Tlaxcala area, characterised by heavier rainstorms, runoff ranged from 30 to 40%. In the station characterised by moderately erosive rainstorms (El Carmen) erosion increased rapidly to 72–78 t ha^{-1} yr^{-1} and in the station characterised by two highly erosive rainstorms (Tlalpan) to 128 t ha^{-1} yr^{-1}). Without any soil-conserving practices or vegetative cover, the "*roturé*" and ploughed tepetate is therefore highly erodible. Fine aggregates in these soils are unstable.

The effect of ridging, whether the cultivated tepetate was devoid of vegetation or planted with maize, was spectacular in the less erosive station (San Miguel Tlaixpan): runoff was reduced to 5% under maize and to 12% on bare soil, and erosion was reduced to 1 t ha^{-1} yr^{-1} in both cases. But given the rainfall intensity, even under maize, runoff increased to 10% in the moderately erosive station (El Carmen) and to 20% in the most erosive station (Tlalpan). Erosion increased dramatically to 23 t ha^{-1} yr^{-1} in tepetate t_2 at El Carmen and to 26 t ha^{-1} yr^{-1} in tepetate t_3 at Tlalpan. Above a certain threshold therefore, runoff may no longer be controlled, ridges may break and erosion may be strong. Moreover, maize whose growth is too late has a less obvious effect on erosion in the weakly erosive stations (San Miguel Tlaixpan), but the comparison with a bare ridged soil was not made in the most erosive stations.

In original soil (before any accelerated erosion), under natural shrubby savanna, there was only a low runoff rate of around 10% and almost no erosion, even though this was at the most erosive station (Matlalohcan). At that station, however, the same

Table 8.4 Measurements of erosivity and runoff on bare tepetate in 1992

Rainfalls			
number	%	EI.30 (MJ ha^{-1} × mm h^{-1})	Runoff (%)
40	59	< 7	< 40
15	22	7–25	40–50
10	15	25–80	50–70
3	4	> 80	> 70

soil devoid of its vegetation cover showed runoff increased to 34% and erosion to 47 t ha^{-1} yr^{-1}. The effect of ridging was effective in the weakly erosive station on the bare soil as well as in the soil cultivated with maize; it restrained runoff to 11–12% and erosion to 1–2 t ha^{-1} yr^{-1}. This result was similar to that observed in the cultivated tepetate, although the soil was less stable than the tepetate. It would undoubtedly be different in more erosive rainstorms, but measurements have not been made. No observation has been made either on the cultivated soil and on the bare unridged soil, in the weakly erosive station.

In a subsequent year, new measurements were made in the natural tepetate (t_3, at San Miguel Tlaixpan), but in a large plot of 1,800 m^2 (instead of 44 m^2) and with a slope of 8–10% (Prat et al., 1993) in order to control for any size effects. The rainfall regime was similar to that previously observed (90 rainy days, three to four erosive rainstorms only). Table 8.4 shows the erosivity and runoff values as related to the amount of rainfall during the observation period (78 rainfall events).

During the observation period, the total soil loss amounted to about 10 t ha^{-1} yr^{-1}, about double the amount measured in the small plot at San Miguel Tlaixpan, but the same order of magnitude as in the whole four stations (5 to 10 t ha^{-1} yr^{-1}). The runoff rate of erosive rainstorms (EI.30 > 80) was higher than 70%. Thus, the larger plot confirmed the original results.

The results for tepetates can be compared to those observed in the cangahua in Ecuador (Custode et al., 1992) during a 5-year period (1987–91) for a mean rainfall of 660 mm, similar to the less erosive San Miguel Tlaixpan station, but with a steeper slope of 22% (Table 8.5).

The runoff rates measured on original soil can be compared to those reported by

Table 8.5 Runoff and erosion on cangahua in Ecuador

	Runoff (%)		
Treatment	Mean	Max.	Erosion (t ha^{-1})
Bare cangahua, surface cultivated	20–30	60–90	96.6
Traditionally cultivated cangahua	7–14	30–55	18.9
Improved cultivated cangahua	2–9	9–55	4.5

Roose (1981) in a "tropical dry" area on "ferruginous tropical" soils with an annual mean rainfall of 850 mm: these ranged from 10 to 15% under savanna, from 35 to 43% on bare soil, and from 10 to 40% on cultivated soil. Erosion was also very low under savanna, ranging from 0.2 to 0.7 $\mathrm{t\,ha^{-1}\,yr^{-1}}$; moderate on cultivated soil ranging from 1 to 14 $\mathrm{t\,ha^{-1}\,yr^{-1}}$; but somewhat less high on bare soil ranging from 10 to 35 $\mathrm{t\,ha^{-1}\,yr^{-1}}$. As a whole, the ranges are similar.

EVOLUTION OF SURFACE FEATURES

Surface features were recorded according to Casenave and Valentin's method (1989) in plots of "*roturé*" tepetate and soil cultivated with ridged maize and on a bare "*roturé*" tepetate (Jerome, 1992). Six observations were made, at the beginning and at the end of the three cultivation periods (from sowing to the first weeding; up to the second weeding and ridging of maize up to harvesting). Features recorded included crust formation (structural and depositional), erosion patterns, aggregate slaking, modifications in the surface relief as well as measurements of porosity, infiltration rate and soil moisture. The observations followed the soil processes which lead to runoff and erosion.

In the case of the soil and tepetate cultivated with ridged maize, modifications occurred due to the formation of surface and structural crusts on ridges and of depositional crusts in depressions. In the soil, this was rapid, for the total slaking of aggregates was rapid and considerable (50–80% by the end of cultivation). In the cultivated tepetate, the changes were slower and more gradual, for the aggregates of more than 2 mm were more stable and their slaking was only partial (decrease in size). During the first cultivation period (up to the first weeding), the changes were slow, aggregates were stable and infiltration remained rapid. But during the second period and above all the third period, the process became more rapid: the aggregate slaking increased; the crust formation became more intense and general; porosity decreased close to the original conditions prevailing before "roturation"; the infiltration rate slowed down considerably to low levels (Table 8.6). Thus, runoff and sensitivity to erosion became higher. In fact, the aggregates smaller than 2 mm slaked completely

Table 8.6 Development of porosity and infiltration rate

	1		2		3	
Cultivation period	Early	Late	Early	Late	Early	Late
Tepetate porosity	58.1	53.2	57.7	54.3	51.1	50.6
Infiltration rate on ridge ($\mathrm{mm\,h^{-1}}$)	96	45	48	28	21	10
Infiltration rate on furrow ($\mathrm{mm\,h^{-1}}$)	52	16	24	12	8	2
Soil porosity	56.4	50.9	55.3	51.5	50	48.9
Infiltration rate on ridge ($\mathrm{mm\,h^{-1}}$)	68	32	16	8	10	4
Infiltration rate on furrow ($\mathrm{mm\,h^{-1}}$)	52	0	12	2.4	5	0

Initial tepetate porosity = 44%. Infiltration rate = 0.3–0.5 $\mathrm{mm\,h^{-1}}$

and gave rise to the formation of crusts and soil loss. A laboratory experiment had showed that an "optimum" aggregate should be no smaller than about 3 mm. Thus, excessive fragmentation of tepetate (harrowing, weeding) into a fraction smaller than 2 mm gives rise to encrusting, runoff and erosion. Contrary to previous belief, the ploughed tepetate is not stable, even under maize; aggregates decreased in size, those smaller than 2 mm slaked, the material becomes packed and encrusted. The clear implications are that cultivation techniques must limit fragmentation by avoiding pulverisation; other devices and methods need to be tested. The Mexican method of maize ridging, divided into three successive operations of ploughing, weeding and earthing up, intensifies fragmentation and is therefore dangerous. It would be advisable to ridge in one operation and to sow maize in the ridge. Moreover, ridges should be partitioned so that they could not be suddenly breached by high rainstorms.

In the case of the "*roturé*" bare tepetate, the originally cloddy surface was gradually covered with a structural crust through the slaking of fine aggregates; then a depositional crust was formed in small depressions. Runoff increased and the surface became covered with rill-erosion which grew deeper when rainstorms were heavy and erosion became stronger. Thus, without any cultivation, the cultivated tepetate became easily erodible by heavy rainstorms.

AGRONOMIC IMPLICATIONS

Analyses of tepetates in laboratory and greenhouse experiments showed that this material displayed certain constraints which are responsible for its sterility: low macroporosity and hydraulic conductivity, lack of organic matter, of nitrogen and phosphorus and of symbiotic microorganisms specific to cultivated plants (e.g. maize and bean). But the material also showed properties suitable for fertile soil regeneration: 30–40% clay which permits (after structural improvement) a good retention of water and provision of micronutrients, a high microporosity, good structural stability, neutral or weakly alkaline pH, and an adequate content of Ca, Mg, K, and micro-elements. Thus, the reclamation of an agricultural soil can be rapid, profitable and sustainable, providing a good structure has been restored and through moderate fertilisation with nitrogen and phosphorus (according to crop requirements) and if possible manuring.

Manual agricultural reclamation of tepetates had already started before Spanish colonisation, with organic enrichment and using soil-conserving terraces ("metepantles"). These practices fell into disuse but presently are being reintroduced, using mechanisation and, of course, changed crops and fertilisation techniques. An agronomic, productivity and economic assessment of the experimental plots (Marquez et al., 1992) as well as socio-economic observations of the farming community (Zahonero, 1992) indicate that sustainable use is achievable, under adequate support conditions.

Fertility and productivity increased steadily for 3 to 5 years after the start of cultivation. Not all crops were initially successful; maize and beans did not yield well even on a well-loosened and fertilised tepetate soil, while wheat and vetch achieved

Table 8.7 Crop yields on tepetates (t ha^{-1})

	Maize	Bean	Broad bean	Wheat	Vetch
First year[a]	0–0.2	0.1–0.2	0.3–0.8	2–4[c]	2–4[d]
Third year[a]	2.2–2.5	–	–	1.5	–
Fifth year[a]	2.5–3.1				
Mean[b]	1.8	0.75	1.33	2	

[a] *Year of cultivation since "roturation"; with mineral fertilisation without organic manure*
[b] *Mean of the yields observed in the area*
[c] Wheat in experimental plots and fine texture; in other plots 1–2 t ha^{-1} (mean 15)
[d] Vetch in experimental plots, dry matter yield

normal yields (Marquez et al., 1992, Navarro and Zebrowski 1992). Table 8.7 shows an experimental comparison of four traditional plants (wheat, maize, bean and broad bean) and vetch (a green manure).

The cultivated tepetates can yield wheat, vetch and, less successfully, broad beans from their first year of cultivation, but not maize and beans. It is necessary to obtain a rather fine texture (< 2 mm), but this carries the considerable risk of increased erodibility referred to above. Without manure, a fine soil and a moderate mineral fertilisation of N/P 120/60 can yield 4 t ha^{-1} of wheat, 4 t ha^{-1} of vetch and 0.4 t ha^{-1} of broad bean. With manure and 60 units of P without addition of nitrogen, wheat can yield 6 t ha^{-1}, vetch 6 t ha^{-1} and broad bean 0.8 t ha^{-1}. In this case, nitrogen fertilisation is of no value, decreasing the wheat yield. Failure of maize and bean cultivation in the first year seems to be due to a deficiency of symbiotic microorganisms which are necessary for good plant nutrition (Alvarez-Solis et al., 1992; Ferrera, pers. comm.). In order to provide organic fertilisation of "*roturé*" tepetates in the absence of manure or compost, vetch or a fodder grass such as oats need to be used as green manure. The soil enrichment of specific symbionts then allows a satisfactory yield of maize and bean.

After 2 to 5 years of cultivation, maize and bean yields improved. In the second year, maize yielded from 1.2 to 1.7 t ha^{-1} in experimental plots without manure but with mineral fertilisers (N/P 120/80). In the third year, maize yields ranged from 2.2 to 2.5 t ha^{-1}, and in the fifth year, from 2.5 to 3.1 t ha^{-1}, which was high (mean for the region 1.8 t ha^{-1}).

Reclaimed tepetates are a significant, even necessary, agricultural soil resource for small farms of < 20 ha per family (Zahonero, 1992). The terrace works are also good protection against erosion. Crop rotation has been adapted to the year of recultivation: wheat in the first year, then maize associated with broad bean or bean. By the third year of cultivation, productivity reaches levels similar to normal soils in the region. By about 8 years, the initial costs of reclamation can be repaid (farmers receive State assistance) through the cash crops (wheat, barley). Subsistence crops (maize, broad bean, bean) then prevail gradually over cash crops. Profitability for farms of less than 15 ha, which are marginally self-sufficient, is less certain because the financial yield of cash crops does not allow repayment: here State assistance would be necessary to enable works to be carried out at a lower cost.

CONCLUSIONS

Overall, tepetates of fragipan type, once they have been correctly used, are a sustainable agricultural resource with good productivity. This resource is a necessity particularly for farms of < 20 ha per family. Erosive rainstorms in the areas of Mexico and Tlaxcala are few, so "*roturé*" tepetate is rather stable and not very erodible provided too fine a fragmentation (*c.* 2 mm) is avoided. Ridging associated with maize cultivation is very effective in low-erosive situations; but it is inadequate in areas experiencing highly erosive rainstorms ($I.30 > 50\,\mathrm{mm\,ha^{-1}}$). Without any ridging or vegetative cover, cultivated tepetates rapidly become unstable and highly erodible. Repeated cultivation techniques (ploughings + two weedings and earthing up for maize in Mexico) make slaking of aggregates more rapid which leads to crust formation, runoff and erosion. Therefore, it is necessary to limit the fragmentation of tepetates by reducing tillage frequency. Moreover, partitioned ridges must be constructed to reduce the risks of erosion by high rainstorms.

A "*roturé*" tepetate improved by a moderate mineral fertilisation (N 60–120, P 60) or an organic one (manure + P 60) can be productive from the first year for plants such as wheat and vetch and less productive for broad bean. It is not productive for maize and bean, due to deficiency in symbiotic microorganisms. However, maize yield is satisfactory by the third year and becomes optimum within 5 years. Organic improvement (manure or green manure) and the insemination of symbionts could speed up the process. The operation becomes profitable, leading to recovery of initial costs within 8 years, but additional State assistance (works at a lower cost, loan at reduced interest) is required for small farms of 15 ha or below.

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