Conservation Tillage and Crop Residue Mulching Rapidly Restored Soil Structure and Microbial Activity on Degraded Maize Fields in the Patzcuaro Watershed (Mexico)

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Abstract: A field experiment with seven soil management treatments was implemented in a degraded soil of the Patzcuaro Watershed in central Mexico to evaluate maize cropping with conventional tillage (CT), no-tillage under varying percentages of soil crop residue coverage (0%, 33%, 66% and 100%), and no-tillage under 33% of soil coverage together with planted leguminous species (Vicia sp. and Phaseolus vulgaris L.). The treatments of no-tillage under soil crop residue coverage were established in 1995 and the leguminous species were planted in 1998. Two years after planting leguminous species, the alternative management treatments had increased total organic carbon, biodegradable C fractions, such as water soluble C, water soluble carbohydrates and biomass C, and aggregate stability compared to CT treatment. The highest increase in aggregate stability was found in the no-tillage with 33% of soil crop residue coverage treatment (28% greater than CT treatment). In particular, the use of no-tillage, preserving a moderate amount of crop residue (33%) and planted leguminous species rapidly improved soil quality. Assayed conservation tillage practices can provide an alternative technology for carrying out a sustainable agriculture in the Patzcuaro watershed, which can be extrapolated to similar areas elsewhere.

Keywords: microbial biomass C, conservation management, aggregate stability, microbial activity

1 Introduction

Intensive maize cropping based on conventional tillage has been carried out in Mexico for several decades. The loss of soil fertility with along the reduction of soil water holding capacity and structural stability, due to erosion by water and wind, are reflected in a constant increase of fertilisation rates by farmers to maintain a competitive crop productivity in economic terms. Conventional tillage (CT) includes practices such as disking and ploughing, which considerably promote the loss of soil organic matter (SOM), with the consequent CO_2 increment in the atmosphere contributing to global warming, and disruption of soil aggregates. In contrast, it has been widely reported that, when changing from conventional to conservation agriculture, the soil increases its organic matter content over time, and enhances soil aggregation and the water content in its profile (Paré *et al*., 1999). Increased C storage has frequently been observed in soils under conservation tillage, particularly with no-tillage (NT) (Dao, 1998). Application of crop residue also results in erosion control because it protects surface aggregates against the effects of rain drops (Perret *et al*., 1999).

Soil quality is largely governed by organic matter content, which is dynamic and responds effectively to changes in soil management. The level of SOM is determined by biological, chemical and physical soil properties that control microbial activity. In this way, soil enzyme activities and microbial biomass have been shown to be sensitive indicators of differences between sustainable cropping systems

(Kennedy and Papendick, 1995). However, there are relatively few studies that relate these biological parameters to the improvements obtained following the application of conservation tillage practices.

The study reported here is part of a Mexico-Spain project to identify best management practices that could restore cropland in the Patzcuaro Watershed in central Mexico. Indicators of soil erosion such as soil losses and runoff, water infiltration, soil moisture and crop yields have been previously tested by Tiscareño *et al.* (1999). The objective of our study was to assess the response of soil quality indicators, physical and biological (enzyme activities and microbial biomass), to conservation management practices, based on no-tillage, the addition of crop residue and the planting of leguminous species, in degraded maize fields on the Patzcuaro watershed, and to determine whether these indicators provide a good assessment of the system's sustainability.

2 Materials and methods

2.1 Site description

This research took place at Ajuno near the Patzcuaro Watershed in Central Mexico, a basin where hybrid maize (Zea mays L.) has been grown for more than 3500 years. The watershed is a closed basin, 956.2 km^2 in area, where runoff in the uplands drains into a single lake of 89.3 km^2. The average annual temperature is 14.5ºC, and rainfall averages 1002 mm per year, mostly distributed from June to October. The dominant soil type is Andisol, a sandy loam textured soil derived from volcanic ash, characterised by low organic carbon content (17.2 $g \bullet kg^{-1}$), very low bulk density (0.91 $g \bullet cm^{-3}$), easily erodible under dry or wet conditions due to its poor structure and slightly acid (pH=5.98).

2.2 Experimental design and layout

Seven runoff plots of USLE-type, 25 m long by 4 m wide, with a 9% slope, were established at Ajuno experimental site. In these plots, seven soil management treatments were assayed: 1) conventional tillage (CT); 2) no-tillage with 0% of residue soil cover (NT-0); 3) no-tillage with 33% of residue soil cover (NT-33); 4) no-tillage with 66% of residue soil cover (NT-66); 5) no-tillage with 100% of residue soil cover (NT-100); 6) no-tillage with 33% of residue soil cover and with planting of Veza (L1=leguminous Vicia sp.) (NT-L1-33) and 7) no-tillage with 33% of residue soil cover and with planting of ayocote bean (L2=leguminous Phaseolus vulgaris L.) (NT-L2-33). CT involved a plough-type soil movement, row building and two cultivations in the ridges. Chopped maize residue was applied to provide 33%, 66% and 100% soil coverage over the runoff plot as measured with a pin-type soil cover meter. During June 1995, rain-fed maize (a local variety) was sown to establish treatments 1 to 5, whereas treatments 6 and 7 were sown in 1998. Each runoff plot was planted at 40,000 plants ha^{-1} and fertilised with 60-60-00 kg NPK ha^{-1}. At sampling time in June 2000, each experimental plot was divided longitudinally in to four areas (four pseudo-replicates per treatment). Four samples of each treatment (one per pseudoreplicate) were collected. Each sample consisted of six bulked sub-samples (150 cm^3 cores) randomly collected at 0 cm—15 cm depth from the soil.

2.3 Chemical, biological, biochemical and physical analyses

Total organic C was determined by Yeomans and Bremner's method (1989) In soil aqueous extracts, water soluble carbon was determined by wet oxidation with $K_2Cr_2O_7$ and measurement of the absorbance at 590 nm (Sims and Haby, 1971) and water soluble carbohydrates was determined by the method of Brink *et al.* (1960).

Microbial biomass C was determined using a fumigation-extraction method (Vance *et al.*, 1987).

Dehydrogenase activity was determined following Skujins' method (1976) modified by García *et al.* (1997). For this, 1 g of soil at 60% of its field capacity was exposed to 0.2 mL of 0.4% INT (2-*p*-iodophenyl-3-*p*-nitrophenyl-5-phenyltetrazolium chloride) in distilled water for 20 h at 22℃ in darkness. The INTF (iodo-nitrotetrazolium formazan) formed was extracted with 10 mL of methanol by shaking vigorously for 1 min and filtration through a Whatman N 5° filter paper. INTF was measured spectrophotometrically at 490 nm.

Urease and N-α-benzoyl-L-argininamide (BAA) hydrolyzing protease activities were determined by measuring the NH_4^+ released in the hydrolysis reaction after addition of urea and BAA, respectively (Nannipieri *et al*., 1980).

Phosphatase and *β*-glucosidase activities were determined using as substrates *p*-nitrophenyl phosphate disodium (PNPP, 0.115 M) and p-nitrophenyl-β-D-glucopyranoside (PNG, 0.05 M), respectively. Two millilitres of 0.1 M maleate buffer at pH 6.5 and 0.5 mL of substrate were added to 0.5 g of soil and incubated at 37°C for 90 min. The reaction of phosphatase activity was stopped by cooling at 2°C for 15 min. Then, 0.5 mL of 0.5 M $CaCl_2$ and 2 mL of 0.5 M NaOH were added, and the mixture was centrifuged at 4000 rpm for 5 min. To stop the reaction of *β*-glucosidase activity, tris-hydroxymethyl aminomethano was used according to Tabatabai (1982). The *p*-nitrophenol (PNP) formed was determined in a spectrophotometer at 398 nm (Tabatabai and Bremner, 1969).

The percentage of stable aggregates was determined by the method described by Lax *et al*. (1994). A 4 g aliquot of sieved (0.2 mm-4 mm) soil was placed on a small 0.250 mm sieve and wetted by spray. After 15 min the soil was subjected to an artificial rainfall of 150 mL with an energy of 270 $J \cdot m^{-2}$. The remaining soil on the sieve was put in a previously weighed capsule (T), dried at 105℃ and weighed (1). Then, the soil was soaked in distilled water and, after 2 h, passed through the same 0.250 mm sieve with the assistance of a small stick to break the remaining aggregates. The residue remaining on the sieve, which was made up of plant debris and sand particles, was dried at 105ºC and weighed (P2). The percentage of stable aggregates with regard to the total aggregates was calculated by (P1–P2)×100/(4–P2+T).

2.4 Statistical analysis

Treatment effects on measured variables were tested by analysis of variance, and comparisons among means were made using a Least Significant Difference (LSD) multiple range test calculated at $P<0.05$. Statistical procedures were carried out with the software package Statgraphics for Windows 7.0.

3 Results and discussion

Total organic carbon (TOC) in soil was significantly affected by the assayed alternative management treatments (Table 1). It is worthy to note that TOC increased even with the NT treatment (about 12% higher than the CT treatment). CT increases the rate of organic matter decomposition and C mineralisation. The highest increase in TOC (about 47%) was found in the NT treatment using full soil coverage with crop residue (NT-100). Practices that increase TOC may substantially benefit soil quality and long-term sustainability (Salinas-García *et al*., 1997).

Table 1 Changes in carbon fractions of the soil in response to different conservation management practices (*n*=4)

Treatments	TOC ($g \cdot kg^{-1}$)	WSC ($\mu g \cdot g^{-1}$)	WSCH ($\mu g \cdot g^{-1}$)
CT	28.5a*	235b	30a
NT-0	32.0b	203a	31a
NT-33	34.5c	327c	34ab
NT-66	38.0d	345cd	36bc
NT-100	42.0e	426e	44e
NT-L1-33	34.3c	353d	42de
NT-L2-33	33.0bc	343cd	39cd

CT= conventional tillage; NT-0= no-tillage without residue addition; NT-33= no-tillage with 33% of residue soil cover; NT-66= no-tillage with 66% of residue soil cover; NT-100= no-tillage with 100% of residue soil cover; NT-L1-33= no-tillage with 33% of residue soil cover and with planted L1 (leguminous Vicia sp.) and NT-L2-33== no-tillage with 33% of residue soil cover and with planted L2 (leguminous Phaseolus vulgaris). TOC: total organic carbon; WSC: water soluble carbon; WSCH: water soluble carbohydrates.

*Values in columns sharing the same letter do not differ significantly ($P<0.05$) as determined by the LSD test.

Labile C fractions (water soluble C and water soluble carbohydrates), which account for a small fraction of soil organic matter, are used by the soil microbial biomass as an energy source for metabolic activity. The study of these fractions is also important in agricultural soils, since it determines the microbial activity of the soils (Janzen *et al*., 1992). The increases observed in both C fractions were due to the crop residue applied, because there were no significant differences in the contents of water soluble C (WSC) and water soluble carbohydrates (WSCH) between the NT and CT treatments (Table 1). The treatment of NT with 100% of crop residue coverage (NT-100) exhibited the highest values of WSC and WSCH.

Microbial biomass C can be considered as a sensitive indicator of soil quality and it is closely related to soil fertility (Paul and Voroney, 1989). Decomposition of plant residues in soil releases essential nutrients, such as nitrogen, phosphorus and sulphur, required for both plant and microbial growth. Incorporation of such residues in soil promotes microbial activity (Martens *et al*., 1992). In fact, biomass C was significantly increased in all the treatments of NT with application of crop residue to soil, with respect to conventional tillage (Table 2), so the values of biomass C decreased in the order: NT-100>NT-66=NT-L1-33=NT-L2-33>NT-33>NT-0=CT. It is worth noting the increase in biomass C with the NT-100 treatment (148% higher than the CT treatment). The C-biomass/TOC ratio is considered by some authors as a good index of the changes in soil organic matter (Insam and Merschak, 1997). The higher values of this ratio were found in the treatment NT-100 and the treatments of NT with 33% of coverage and planting of L1 and L2 leguminous species (Table 2). This indicates the high soil organic matter turnover of such treatments.

Enzyme activities were largely favoured by the assayed alternative soil management treatments (Table 2). In general, soil enzymes are good markers of soil fertility since they are involved in the cycling of the most important nutrients. Dehydrogenase activity was favoured by the presence of leguminous plants and by high levels of crop residue coverage (66% and 100% coverage). Urease and protease-BAA are involved in the N cycle and they were stimulated by both leguminous plants (NT-L1-33 and NT-L2-33) and crop residue application to soil, which increase the N substrates in the soil (Garcia *et al*., 1997). The phosphatase activity is a measure of microbial demand, which increases with the addition of fresh organic matter to the soil. We found the highest values of phosphatase activity in soils with addition of crop residue. β-glucosidase only increased in the treatments that preserve crop residue in soil, suggesting that the crop residue applied increased the rate of C cycling.

Table 2 Changes in biochemical properties in response to different conservation management practices (*n*=4)

	CT	NT-0	NT-33	NT-66	NT-100	NT-L1-33	NT-L2-33
C-Biomass ($\mu g \cdot g^{-1}$)	264a*	303ab	345b	426c	654d	495c	488c
C-Biomass/TOC (%)	0.93a	0.94a	1.00a	1.12a	1.56b	1.45b	1.48b
Dehydrogenase (μg INTF g^{-1} soil)	98a	79a	105a	149b	234c	254c	235c
Urease (μmol NH_3 g^{-1} h^{-1})	0.34a	0.76b	0.80b	1.51d	3.10e	1.07c	1.04c
Protease-BAA (μmol NH_3 g^{-1} h^{-1})	0.20a	0.35a	0.27a	0.65b	2.04d	0.99c	0.71b
Phosphatase (μmol PNP g^{-1} h^{-1})	70a	102b	135cd	142d	220e	122c	129cd
β-glucosidase (μmol PNP g^{-1} h^{-1})	98a	95a	196d	228e	219e	144c	129b

CT= conventional tillage; NT-0= no-tillage without residue addition; NT-33= no-tillage with 33% of residue soil cover; NT-66= no-tillage with 66% of residue soil cover; NT-100= no-tillage with 100% of residue soil cover; NT-L1-33= no-tillage with 33% of residue soil cover and with planted L1 (leguminous Vicia sp.) and NT-L2-33= no-tillage with 33% of residue soil cover and with planted L2 (leguminous Phaseolus vulgaris). TOC: total organic carbon.

*Values in rows sharing the same letter do not differ significantly ($P<0.05$) as determined by the LSD test.

Soil biomass C and enzyme activity increased as productivity improved upon no-tillage and addition of crop residue (Tiscareño *et al*., 1999). The enhanced levels of soil enzyme activity promoted the recycling of nutrients in the soil ecosystem. In fact, crop yields have improved when applying no-tillage and crop residue as mulch. No-tillage with 100% residue cover improved grain yield by 0.7 Mg/ha compared to maize under conventional tillage (Tiscareño *et al*., 1999).

It is well known that soil organic matter plays a key role in the formation and stabilisation of soil aggregates. However, changes in aggregate stability following land use changes have been observed without changes in total SOM content (Puget *et al*., 1999). These results may indicate that only some organic matter fractions are involved in soil structural stability. Extracellular polysaccharides, from bacteria or fungi, and root mucilages are typically a very labile SOM fraction which is important as a binding agent of soil aggregates (Roldán *et al*., 1996). No-tillage may promote fungal growth and the proliferation of fungal hyphae that contribute to macroaggregate formation (Beare *et al*., 1994). Reduced aggregation and increased turnover of aggregates in CT, compared to NT, is a direct function of immediate physical disturbance due to ploughing. First, tillage continually exposes new soil to wet-dry cycles at the soil surface (Beare *et al*., 1994), thereby increasing the susceptibility of aggregates to disruption. Second, ploughing changes soil conditions, such as temperature, moisture and aeration, and increases the decomposition rates of the litter. Thus, the turnover of aggregates is faster in CT than in NT, resulting in a greater loss of SOM in CT (Six *et al*., 1999). All the alternative soil management treatments increased the percentage of stable aggregates with respect to conventional tillage (Fig.1). The highest increase was observed in no-tillage with 33% of soil crop residue coverage (about 28% greater than the CT treatment) and in NT-L2-33, in spite of the shorter time passed since the establishment of the NT-L2-33 treatment. Non-tilled soils with addition of crop residue are enriched in labile organic matter, which has a great impact on soil structure by increasing aggregation (Lu *et al*., 1998). Likewise, the increase of soil aggregate stability by the no-tillage treatments can be attributable to the increases observed in microbial activity of such soils.

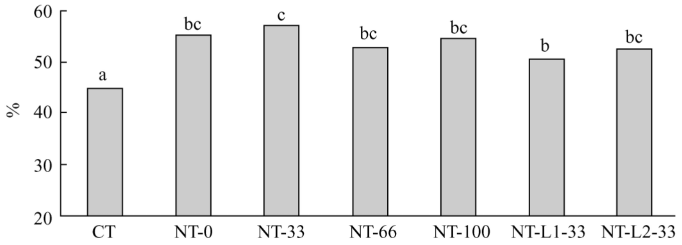

Fig.1 Changes in percentage of stable aggregates in response to different conservation management practices (*n*=4). (CT= conventional tillage; NT-0= no-tillage without residue addition; NT-33= no-tillage with 33% of residue soil cover; NT-66= no-tillage with 66% of residue soil cover; NT-100= no-tillage with 100% of residue soil cover; NT-L1-33= no-tillage with 33% of residue soil cover and with planted L1 (leguminous <u>Vicia</u> sp.) and NT-L2-33= no-tillage with 33% of residue soil cover and with planted L2 (leguminous <u>Phaseolus vulgaris</u>). Values with the same letter are not significantly different values at $P< 0.05$, according to LSD test.

It should also be mentioned that soil losses are reduced by 80% by leaving 33% of the crop residue in no-tillage compared to no surface cover in no-tillage, since the residue provides an adequate protective soil cover to prevent soil degradation (Tiscareño *et al*., 1999). This was largely attributed to reductions in runoff and nitrogen losses and improvement of soil water retention, and could also be related to an increase of structural stability shown in this study.

It can be concluded that restoration of soil structure and microbial activity in degraded croplands is feasible through implementing no-tillage technology, and by applying crop residue and planting leguminous species in inter-cropping periods. In particular, the combined treatment of no-tillage, 33% soil crop residue coverage and planting of leguminous species can be considered as an effective technology, due to its rapid improvement of soil quality, for carrying out a sustainable agriculture in the Patzcuaro watershed, which can be extrapolated to similar areas elsewhere.

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