



No-tillage, crop residue additions, and legume cover cropping effects on soil quality characteristics under maize in Patzcuaro watershed (Mexico)

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Abstract

Intensive maize (*Zea mays* L.) cropping based on conventional tillage practices has resulted in soil quality degradation in the Patzcuaro Watershed in central Mexico. A field experiment with seven soil management treatments was implemented on a sandy loam Andisol to evaluate the impact on soil quality of maize cropping with conventional tillage, no-tillage with varying percentages of surface residue coverage (0, 33, 66 and 100%), and no-tillage with 33% residue coverage together with cover crops of either *Vicia* sp. or *Phaseolus vulgaris* L. The treatments of no-tillage under crop residue coverage were established in 1995 and the leguminous species were planted in 1998. By 2000, the alternative management treatments had increased soil enzymes, soil organic C, biodegradable C fractions such as water soluble C, water soluble carbohydrates, and microbial biomass C, and soil wet aggregate stability, compared to the CT treatment. Wet aggregate stability was increased by adopting no-tillage and even further by additional residue. Most soil quality characteristics improved in direct proportion to residue inputs. The use of no-tillage management together with a moderate amount of crop residue (33%) and planted to leguminous species rapidly improved some soil quality characteristics. We conclude that conservation tillage practices can provide an alternative technology contributing to sustainable agriculture in the Patzcuaro watershed of Mexico, which can be extrapolated to similar areas elsewhere in Latin America.

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1. Introduction

Intensive maize cropping based on conventional tillage (CT) with disking and ploughing has been tra-

ditional in Mexico for several decades. This has led to a loss of soil fertility and reduction of soil water holding capacity and soil structural stability, by facilitating erosion by water and wind, and is reflected in a constant increase in the rates of fertilisers used by farmers to maintain crop productivity (Harrington, 1996). Land degradation due to intensive CT agriculture has been detrimental in countries where annual

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crop species are cultivated under steep-slope conditions. Unfortunately, it is in these areas where soil nutrients and organic matter are lost most rapidly, due to annual cropping systems and soil erosion (Tiscareño et al., 1999).

CT promotes loss of soil organic matter (SOM), which leads to disruption of soil aggregates contributing to erosion and CO₂ increase in the atmosphere, contributing to global warming. In contrast, when management is changed from CT to conservation tillage agriculture, SOM may increase with time (Dao, 1998) and enhance soil aggregation and available water content (Paré et al., 1999). However, other authors have reported that only small changes in soil aggregation (Hamblin, 1980) and SOM occur (Carter and Rennie, 1982). Recently, Campbell et al. (2001) reported that the conversion to no-tillage (NT) management may not always result in an increase in soil C or N without adequate fertility.

Application of crop residue also results in erosion control because it protects surface aggregates against the effects of rain drops (Perret et al., 1999). Crop residue presents several beneficial agricultural effects, such as reduction of weed problems and chemical fertiliser use (Michellon and Perret, 1994), and restoration of soil fertility with reactivation of the soil macro- and microfauna (Boyer et al., 1996).

No-tillage, which represents an alternative to CT, has been adopted by many Latin American countries, based on results of field experiments carried out in developed countries (Tiscareño et al., 1999). However, several questions have emerged regarding the system of NT to adopt and the amount of crop residues that should be left on the field to minimise soil erosion. In Mexico, as in some other areas of the world (Sain and Barreto, 1996), the adoption of conservation technology can fail because of technical factors: insufficient crop residues, as a result of low system productivity and/or for economic reasons, due to the high value of residue used as forage (Erenstein, 1996). For most of the Americas, there is a scarcity of local information on how NT technology can benefit the regional soils and improve, or at least maintain crop yields without increasing the application of inorganic fertilisers. This is particularly relevant in Mexico where land is dominated (60%) by volcanic soils that differ in physical and chemical characteristics from the non-volcanic soils. Taking the above-mentioned problems into

account, it is necessary to develop alternative farming systems to ameliorate soil fertility and improve plant growth, as compared with current farming systems.

Soil quality is largely governed by SOM, which is dynamic and responds effectively to changes in management. The level of SOM is determined by biological, chemical and physical properties of soil that control microbial activity (Cole et al., 1987). 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). There are a number of studies on NT and soil biological characteristics.

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 loss and runoff, water infiltration, soil moisture and crop yields have been previously discussed by Tiscareño et al. (1999). The objective of this paper was to assess the response of physical and biological soil quality indicators to adoption of conservation management practices, such as adoption of NT, the addition of crop residues and the planting of leguminous species, in degraded maize fields located on the Patzcuaro watershed.

2. Materials and methods

2.1. Site description

This research was conducted at Ajuno experimental site, belonging to the National Center for Sustainable Agriculture of the National Institute for Agricultural and Forestry Research (INIFAP). Ajuno is a basin near the Patzcuaro Watershed in central Mexico, where maize (*Zea mays* L.) has been grown for 3500 years (Watts and Bradbury, 1982). The watershed is a closed basin, 956 km² in area, where runoff in the uplands drains into a single lake of 89 km². The average annual temperature is 14.5 °C, and rainfall averages 1000 mm per year, mostly distributed from June to October. The dominant soil type is Andisol (Table 1), a sandy loam textured soil derived from volcanic ash, with very low bulk density (0.91 g cm⁻³), easily erodible under dry or wet conditions due to its poor structure (Cabrera, 1988) and is slightly acidic in pH.

Table 1
Characteristics of the soil (0–15 cm depth) at the initiation of the experiment (June 1995)

pH (H ₂ O)	5.98
EC (dS m ⁻¹)	0.15
Sand (%)	55
Silt (%)	35
Clay (%)	10
Total organic C (g kg ⁻¹)	17.2
Total organic N (g kg ⁻¹)	1.4
P available (μg g ⁻¹)	8
K extractable (μg g ⁻¹)	483
Bulk density (g cm ⁻³)	0.91

2.2. Experimental design and layout

Seven USLE-type runoff plots (25 m long, 4 m wide, 9% slope) were established on a representative site of the Patzcuaro Watershed where seven soil management treatments were investigated: (1) CT; (2) no-tillage with 0% residue cover (NT-0), i.e. all crop residues removed; (3) no-tillage with 33% residue cover (NT-33) (about 3 t crop residues ha⁻¹); (4) no-tillage with 66% residue cover (NT-66) (about 5 t crop residues ha⁻¹); (5) no-tillage with 100% residue cover (NT-100) (about 7 t crop residues ha⁻¹); (6) no-tillage with 33% residue cover and planting of vetch (*Vicia* sp.) (NT-L1-33); (7) no-tillage with 33% residue cover and planting of ayocote bean (*Phaseolus vulgaris* L.) (NT-L2-33). CT involved a plough-type soil movement with a maximum tillage depth ranging from 15 to 25 cm, row building and two cultivations in the furrows. CT is the prevalent local farming system, occurring on approximately 40% of the total watershed area, while NT is a soil management practice not yet used in the watershed. Maize residue consisted of chopped corn stalks from a previous harvest, which C/N ratio was about 60. 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. NT treatments were sprayed before planting with paraquat (0.4 kg ha⁻¹) and glyphosate (0.72 kg ha⁻¹) as needed for weed control. In the months of June since 1995, rain-fed maize (a local variety) was sown in all the plots. Seeds of vetch and ayocote bean were sown in the months of January and June since 1998, respectively, with a seeding rate of 40 kg ha⁻¹ for each species.

The harvesting of vetch and ayocote bean were on May and November, respectively. The plant cover for both leguminous species was about 70%. Each runoff plot was planted with maize at 40 000 plants ha⁻¹ and fertilised with 60–60–00 kg NPK ha⁻¹ as basal dose. Another 60 kg N ha⁻¹ was applied 30 days after planting. For the two leguminous crops a basal fertiliser application without N was applied.

At sampling time in June 2000, each experimental plot was divided longitudinally into four areas (four subplots per treatment). Four soil samples of each treatment (one per subplot) were collected. Each sample consisted of six bulked subsamples (150 cm³ cores) randomly collected at 0–15 cm depth. Field-moist soil samples were divided in two subsamples. One soil subsample was sieved at 2 mm and stored at 2 °C for biological and biochemical analysis and another soil subsample was allowed to dry at room temperature. An aliquot of air-dried soil was sieved to <2 mm for physico-chemical and chemical analysis and another aliquot sieved to collect 0.2–4 mm aggregates for stability measurements.

2.3. Soil analyses

Soil pH and electrical conductivity (EC) were measured in a 1:5 (w/v) aqueous extract. Particle size distribution was determined using the pipette method after oxidation of the organic matter with H₂O₂ and stirring in a sodium hexametaphosphate solution. Total organic nitrogen (TON) was determined by the Kjeldhal method, and the total organic C (TOC) was determined by oxidation with potassium dichromate in a sulphuric medium and excess dichromate evaluated using Mohr's salt (Yeomans and Bremner, 1988). Available P (with sodium bicarbonate, Olsen et al. (1954)) was determined by colorimetry, according to Murphy and Riley (1962). Extractable K (with ammonium acetate) was determined by flame photometry (Scholleberger and Simon, 1954).

Water soluble carbon (WSC) in soil aqueous extracts (1:5, w/v) was determined by wet oxidation with K₂Cr₂O₇ and measurement of the absorbance at 590 nm (Sims and Haby, 1971) and water soluble carbohydrate (WSCH) 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 (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 °C in darkness. The iodo-nitrotetrazolium formazan (INTF) formed was extracted with 10 ml of methanol by shaking vigorously for 1 min and filtration through a Whatman No. 5 filter paper. The INTF was measured spectrophotometrically at 490 nm.

Urease and *N*- α -benzoyl-L-argininamide (BAA) hydrolyzing protease activities were determined in 0.1 M phosphate buffer at pH 7; 1 M urea and 0.03 M BAA were used as substrates, respectively. Two milliliters of buffer and 0.5 ml of substrate were added to 0.5 g of sample, which was incubated at 30 °C (for urease) or 39 °C (for protease) for 90 min. Both activities were determined as the NH_4^+ released in the hydrolysis reaction (Nannipieri et al., 1980).

Phosphatase activity was determined using *p*-nitrophenyl phosphate disodium (PNPP, 0.115 M) as substrate. 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 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. The *p*-nitrophenol (PNP) formed was determined in a spectrophotometer at 398 nm (Tabatabai and Bremner, 1969). Controls were made in the same way, although the substrate was added before the CaCl_2 and NaOH.

β -Glucosidase was determined using *p*-nitrophenyl- β -D-glucopyranoside (PNG, 0.05 M; Hayano and Tubaki, 1985, modified by Masciandaro et al., 1994) as substrate. This assay is based on the release and detection of PNP. Two milliliters of 0.1 M maleate buffer at pH 6.5 and 0.5 ml of substrate was added to 0.5 g of sample and incubated at 37 °C for 90 min. The reaction was stopped with tris-hydroxymethyl aminomethano (THAM) according to Tabatabai (1982). The amount of PNP was determined in a spectrophotometer at 398 nm (Tabatabai and Bremner, 1969).

The percentage of water stable aggregates was determined by the method described by Lax et al. (1994). A 4 g aliquot of sieved (0.2–4 mm) air-dried soil was placed on a 0.25 mm sieve (7.5 cm diame-

ter) and wetted by spray. After 15 min the soil was subjected to an artificial rainfall of 150 ml with an energy of 270 J m^{-2} . The remaining soil on the sieve was put in a previously weighed capsule (*T*), dried at 105 °C and weighed (P_1). Then, the soil was soaked in distilled water and, after 2 h, passed through the same 0.25 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 105 °C and weighed (P_2). The percentage of stable aggregates relative to the total aggregates was calculated as $(P_1 - P_2) \times 100 / (4 - (P_2 - T))$.

2.4. Statistical analysis

Treatment effects on measured variables were tested by analysis of variance, and comparisons among treatment 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

Soil EC was not affected by any of the treatments (Table 2). There was no clear tendency of soil pH by the adoption of conservation practices. Available soil *P* was significantly increased by the adoption of NT with respect to CT (Table 2). However, the planting of leguminous cover crops resulted in available *P* values similar to CT. Neither addition of crop residues nor the presence of legumes had a significant effect on soil extractable *K* (Table 2).

The planting of legumes did not affect TON, at least not relative to NT-33 (Table 2). Total organic N was greater with residue additions of $\geq 66\%$ than without residues or CT. In contrast to TON, TOC increased with all residue additions relative to CT (Table 2). Similar to TON, TOC was not influenced by legume plantings. The difference in TOC between CT and NT-0 was likely due to the difference in soil disturbance and its influence on rate of SOC decomposition; but the difference due to residues was likely reflecting differences in C inputs. It was surprising to find that TON did not mimic the TOC responses as found by most other workers (Salinas-García et al., 1997). When C/N

Table 2

Physico-chemical properties, nutrient concentration, organic carbon, organic nitrogen and carbon fractions of the soil in response to different management practices ($n = 4$)

Treatments	pH (H ₂ O)	EC ¹ (dS m ⁻¹)	P available (μg g ⁻¹)	K extractable (μg g ⁻¹)	Total organic C (g kg ⁻¹)	Total organic N (g kg ⁻¹)	C/N	WSC ² (μg g ⁻¹)	WSCH ³ (μg g ⁻¹)
CT ⁴	5.49a*	0.233a	7.7a	433bc	28.5a*	1.3a	22abc	235b	30a
NT-0 ⁵	5.93cd	0.200a	13.5c	437bc	32.0b	1.3a	25cd	203a	31a
NT-33 ⁶	6.05d	0.195a	10.7b	370ab	34.5c	1.5ab	23cd	327c	34ab
NT-66 ⁷	5.79bc	0.220a	10.1b	401abc	38.0d	1.7b	23bcd	345cd	36bc
NT-100 ⁸	5.65ab	0.243a	13.8c	478c	42.0e	1.7b	25d	426e	44e
NT-L1-33 ⁹	5.89bcd	0.250a	9.7ab	335ab	34.3c	1.7b	20ab	353d	42de
NT-L2-33 ¹⁰	5.75bc	0.223a	8.7ab	379ab	33.0bc	1.7b	20a	343cd	39cd

¹ Electrical conductivity.

² Water soluble carbon.

³ Water soluble carbohydrates.

⁴ Conventional tillage.

⁵ No-tillage without residue addition.

⁶ No-tillage with 33% of residue soil cover.

⁷ No-tillage with 66% of residue soil cover.

⁸ No-tillage with 100% of residue soil cover.

⁹ No-tillage with 33% of residue soil cover and with planted L1 (leguminous *Vicia* sp.).

¹⁰ No-tillage with 33% of residue soil cover and with planted L2 (leguminous *P. vulgaris*).

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

ratio varies between 20 and 30, such as was found in all treatments of our study, nitrification and immobilisation rates are in equilibrium and this fact could explain why there was no net gain or loss of N between CT and NT-0.

Labile C fractions, such as WSC and WSCH, only accounted for a small fraction of SOM, but are used by the soil microbial community as an energy source for metabolic activity. The study of these fractions is important in agricultural soils, since they determine soil microbial activity (Janzen et al., 1992) and perform a structural function (Metzger and Yaron, 1987). Like TOC, there was a direct relationship between crop residue rate and these two water soluble fractions (Table 2). However, unlike TOC, growing legumes in the soil generally increased these water soluble fractions relative to NT-33.

Microbial biomass C can be considered a sensitive indicator of soil quality and is closely related to soil fertility (Paul and Voroney, 1989). Decomposition of plant residues in soil releases essential nutrients, such as N, P and S, required for both plant and microbial growth. Microbial biomass C responded to the treatments in a similar manner to the water soluble C fractions; i.e., increasing with adoption of NT, in

direct proportion to residue addition and with growing of legumes in the system (Table 3). The ratio of biomass-C/TOC is regarded by some authors as a good index of the changes in SOM quality (Insam and Merschak, 1997). Higher values of this ratio were found only in the NT-100 treatment and in the treatments in which leguminous species were planted (Table 3).

The adoption of NT positively influenced urease and phosphatase activities; while other enzymes were unaffected (Table 3). As observed for the other soil characteristics, activity of all the enzymes increased in proportion to rate of crop residue addition. Urease and protease-BAA increased with the addition of crop residue due to N substrates in crop residues (García et al., 1997). Dehydrogenase, urease and protease-BAA activities increased with inclusion of legumes in the systems, but phosphatase was unaffected while β-glucosidase activity decreased. The increases observed in dehydrogenase point to the greater microbiological activity (García et al., 1997) as a consequence of the addition of crop residues and the presence of leguminous plants. In particular, a highly significant correlation ($r = 0.969$, $P < 0.05$) was found between dehydrogenase activity and the rate

Table 3
Biological, biochemical and physical properties in response to different management practices ($n = 4$)

Treatments	Biomass C ($\mu\text{g g}^{-1}$)	Biomass C TOC ¹ (%)	Dehydrogenase ($\mu\text{g INTF g}^{-1}$)	Urease ($\mu\text{mol NH}_3 \text{g}^{-1} \text{h}^{-1}$)	Protease ($\mu\text{mol NH}_3 \text{g}^{-1} \text{h}^{-1}$)	Phosphatase ($\mu\text{mol PNPg}^{-1} \text{h}^{-1}$)	β -Glucosidase ($\mu\text{mol PNPg}^{-1} \text{h}^{-1}$)	Aggregate stability (%)
CT ²	264a	0.93a	98a*	0.34a	0.20a	70a	98a	44.8a
NT-0 ³	303ab	0.94a	79a	0.76b	0.35a	102b	95a	55.2bc
NT-33 ⁴	345b	1.00a	105a	0.80b	0.27a	135cd	196d	57.1c
NT-66 ⁵	426c	1.12a	149b	1.51d	0.65b	142d	228e	52.6bc
NT-100 ⁶	654d	1.56b	234c	3.10e	2.04d	220e	219e	54.4bc
NT-L1-33 ⁷	495c	1.45b	254c	1.07c	0.99c	122c	144c	50.5b
NT-L2-33 ⁸	488c	1.48b	235c	1.04c	0.71b	129cd	129b	52.8bc

¹ Total organic carbon.

² Conventional tillage.

³ No-tillage without residue addition.

⁴ No-tillage with 33% of residue soil cover.

⁵ No-tillage with 66% of residue soil cover.

⁶ No-tillage with 100% of residue soil cover.

⁷ No-tillage with 33% of residue soil cover and with planted L1 (leguminous *Vicia* sp.).

⁸ No-tillage with 33% of residue soil cover and with planted L2 (leguminous *P. vulgaris*).

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

of crop residue added, suggesting that crop residues were an excellent source of carbon and energy for soil microflora. Soil enzymes are good indicators of soil fertility since they are involved in the cycling of the most important nutrients. Leguminous plants have the potential for biological N₂ fixation and this could have stimulated the activity of enzymes involved in the N cycle (urease and protease-BAA). Phosphatase activity is a measure of microbial demand, which increases with the addition of fresh organic matter to the soil (Dick, 1992). The highest values of phosphatase activity in soils were found with addition of crop residue. β -Glucosidase catalyses the hydrolysis of β -glucosides in soil, which contribute to the release of energy for soil microbial activity (García et al., 1998). β -Glucosidase only increased in the treatments that preserved crop residue on soil, suggesting that the crop residue applied increased the rate of C cycling.

Crop productivity improved upon adoption of NT management and addition of crop residues (Tiscareño et al., 1999). Estimates of belowground biomass and activity responded similarly.

All NT management treatments increased the percentage of water stable aggregates with respect to CT but there was generally no difference among NT treatments (Table 3). SOM plays a key role in the formation and stabilisation of soil aggregates (Oades, 1984; Lu et al., 1998). 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 SOM fractions are involved in soil structural stability or that stability changes are quicker to change than TOC. Extracellular polysaccharides from bacteria or fungi and root mucilages are important soil constituents that act as binding agents 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., 1993). Doran (1980) indicated that populations of fungi were significantly higher in the surface (0–7.5 cm) of NT soils than in the surface of plowed soil. These authors also found that microbial populations under NT decreased rapidly below the 7.5 cm depth. Reduced aggregation and increased turnover of aggregates in CT, compared to NT, is a direct function of immediate physical disturbance due

to ploughing. Tillage continually exposes new soil to wet-dry cycles at the soil surface (Beare et al., 1994), thereby increasing the susceptibility of aggregates to further disruption. Further, tillage changes soil conditions, such as temperature, moisture and aeration, and increases the decomposition rates of the litter. Thus, the turnover of aggregates is usually faster in CT than in NT system, resulting in a greater loss of SOM in CT (Six et al., 1999). Non-tilled soils with addition of crop residue are enriched in labile SOM at the surface, which has a great impact on soil structure by increasing aggregation (Beare et al., 1994; Lu et al., 1998). Likewise, the increase of soil aggregate stability by the NT treatments can be attributed to the increases observed in microbial activity of such soils. In our study tillage strongly reduced soil aggregation, this negative effect appearing to be mainly due to soil physical disturbance because there were few differences in microbiological activity between the CT and NT systems.

Tiscareño et al. (1999) reported that soil losses were reduced 80% by leaving 33% of the crop residue in NT compared to no surface cover with NT. They attributed this to reductions in runoff and N losses and improvement of soil water retention; but, our results suggest that this could also be related to an increase of soil structural stability.

We conclude that improvement in soil quality with restoration of soil structure, microbial activity and soil enzyme activities, in degraded croplands, is feasible by implementing NT technology, and by applying crop residues and planting leguminous species in inter-cropping periods. In particular, the combined treatment of NT, 33% crop residue coverage and planting of leguminous species can be considered an effective technology, due to its rapid improvement of soil quality, for carrying out sustainable agriculture in the Patzcuaro watershed. These principles can probably be extrapolated to similar areas elsewhere in Latin America.

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