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Tillage effects on maize yield in a Colombian savanna oxisol: Soil organic matter and P fractions

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Abstract

Soil organic matter (SOM) and phosphorus (P) fractions play a key role in sustaining the productivity of acid-savanna oxisols and are greatly influenced by tillage practices. In 1993, a long-term experiment on sustainable crop rotation and ley farming systems was initiated on a Colombian acid-savanna oxisol to test the effects of grain legumes, green manures, intercrops and leys as possible components that could increase the stability of systems involving annual cereal crops. Five agropastoral treatments (maize monoculture—MMO, maize–soybean rotation—MRT, maize–soybean green manure rotation—MGM, native savanna control—NSC and maize-agropastoral rotation—MAP) under two tillage systems (no till-NT and minimum tillage-MT) were investigated. The effects of NT and MT on SOM and P fractions as well as maize grain yield under the five agropastoral treatments were evaluated. Results showed that soil total C, N and P were generally better under no-till as compared to minimum-tilled soils. While P fractions were also generally higher under no-till treatments, SOM fractions did not show any specific trend. Seven years after establishment of the long-term ley farming experiment (5 years of conventional tillage followed by 2 years alternative tillage systems), MT resulted into moderately higher maize grain yields as compared to NT. The MGM rotation treatment had significantly higher values of maize yield under both tillage systems (4.2 Mg) compared to the NSC (2.3 Mg ha^{-1}). Results from this study indicate that the rotational systems (maize–soybean green manure and maize-pastures) improved the soil conditions to implement the no-till or minimum tillage systems on Colombian savanna oxisol.

Keywords: Soil organic matter fractions; Phosphorus fractions; Savanna; Legumes; Tillage; Maize yield

1. Introduction

Soil organic matter (SOM) is critical to sustainable agricultural productivity in tropical regions, especially in savanna ecosystems. It is an important factor affecting soil quality and long-term sustainability of agriculture (Doran and Parkin, 1994). Together with soil management, tillage in particular, SOM influences many physical, chemical and biological properties in highly weathered oxisols (Roth et al., 1987, 1992). Oxisols and ultisols dominate in the eastern plains of Colombia. These soils are infertile and are extensively and traditionally used for cattle ranching, with low management and almost no purchased inputs. Their productivity is consequently very low (Guimarães et al., 2004). However, long-term crop rotation, combined with appropriate tillage, may restore SOM levels that may increase crop yields in oxisols (Friesen et al., 1997; Freixo et al., 2002).

SOM is a source and sink for plant nutrients and plays a key role in the carbon cycle, since it accounts for the major terrestrial pool of this element (i.e. carbon)

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(Rounsevell et al., 1999). Organic matter fractionation has been found to increase the sensitivity to detect changes in SOM due to soil tillage and crop rotations (Janzen et al., 1992). Size-density fractionation enables assessment of labile pools of SOM that are more sensitive to differences in soil management, land use or cropping practices than soil total C (Barrios et al., 1996, 1997). Of practical significance to soil productivity is the fact that SOM is a major source of organic P. In these highly weathered and high P-sorbing soils, P maintained in organic pools may be better protected from loss through fixation than P flowing through inorganic pools (Phiri et al., 2001a).

Phosphorus is an important nutrient in relatively short supply in most natural ecosystems and is the primary limiting nutrient for crop production in highly weathered tropical soils (Linquist et al., 1997; Rao et al., 1999). The deficiency is mainly caused by strong adsorption of $H_2PO_4^-$ to Al and Fe oxides and hydroxides (sesquioxides), which turns large proportions of inorganic P into a form that is unavailable to plants (Fontes and Weed, 1996). However, plants growing in these soils have access to some P fractions (especially the soluble and moderately soluble fractions) that are best estimated by P fractionation procedures such as the one by Hedley (Tiessen and Moir, 1993; Friesen et al., 1997). This procedure involves sequential extraction of inorganic P (Pi) and organic P (Po) with increasingly aggressive reagents. This allows characterization of the different pools of Pi and Po that are supposed to be differentially available to plants (Beck and Sanchez, 1994; Phiri et al., 2001a,b, 2003a,b; Basamba et al., 2005a,b). Compared with the other major nutrients, P is by far the least mobile and available to plants in most soil conditions, particularly in oxisols and is therefore likely to be greatly affected by tillage. Mechanical manipulation of soil during tillage may increase the chances of contact between soil solution or fertilizer-derived P and exposed soil particles and this facilitates the formation of stable insoluble P compounds (Hinsinger, 2001; Picone et al., 2003). Tillage, notably 'no-tillage', affects some chemical characteristics related to soil acidity that may influence P availability, plant growth and yield (Ernani et al., 2002). Organic matter and P accumulate in the top few centimeters under 'no-tillage' compared with 'conventional tillage' (Selles et al., 1997; Díaz-Zorita and Grove, 2002), which may reduce Al toxicity (Rhoton, 2000). Other nutrients also accumulate near the surface in 'no-tillage' soils, causing increases in the concentration of electrolytes and P sorption. These effects may offset the benefits of SOM and P accumulation on Al toxicity in 'no-tillage' soils.

Recently, interest in long-term experiments has increased worldwide because they are the only means of identifying suitable indicators for early warning of productivity decline and ecosystem damage (Barnett et al., 1995; Bessam and Mrabet, 2003). Also, long-term data can be used in testing or evaluating predictive models. The objectives of this study were to evaluate the impact of minimum-tillage (reduced harrowing intensity followed by direct seeding), no-tillage (direct seeding) and crop rotation on: (a) soil organic matter fractions, (b) soil P fractions and (c) maize grain yield in a long-term experiment on an acid-savanna soil.

2. Materials and methods

2.1. Description of the study area

Studies were carried out at the CIAT-CORPOICA experimental station, Carimagua (4°37′N, 71°19′W and 175 m altitude) on the eastern plains of Colombia (Llanos Orientales). The area has two distinct climatic seasons, a wet season from the beginning of March to December, and a dry season from December to the first week of March. The mean annual rainfall and temperature in this area are 2240 mm and 27 °C, respectively. Before the beginning of the long-term experiment, the area was under native savanna vegetation (mostly *Andropogon* and *Trachypogon* grasses) and the predominant land use was extensive cattle ranching. Physiographically, the land is generally flat (slope $< 5\%$), typical of the Colombian savanna ecosystem. The soils are deep, have good physical properties but present chemical constraints such as high Al saturation, low organic C, available N and P (Friesen et al., 1997). They are well-drained silty clay loam oxisols, and are classified as Isohyperthermic fine-loamy Kaolinitic Tropeptic Haplustox in the USDA soil classification system (Soil Survey Staff, 1994).

2.2. Experimental design and treatments

The long-term experiment CULTICORE was established in 1993 to investigate sustainable crop rotation and ley farming systems for the acid-soil savannas (Fig. 1). The experimental design was a split-plot with four randomized block as (replications), with main plots assigned to upland rice-based (fertilizer lime) systems and maize-based (remedial lime) systems (Friesen et al., 1997). Only results for maize-based systems for the cropping year 2001 are reported in this study. This was the seventh rotational cropping after establishment of the experiment, but 2 years after the implementation

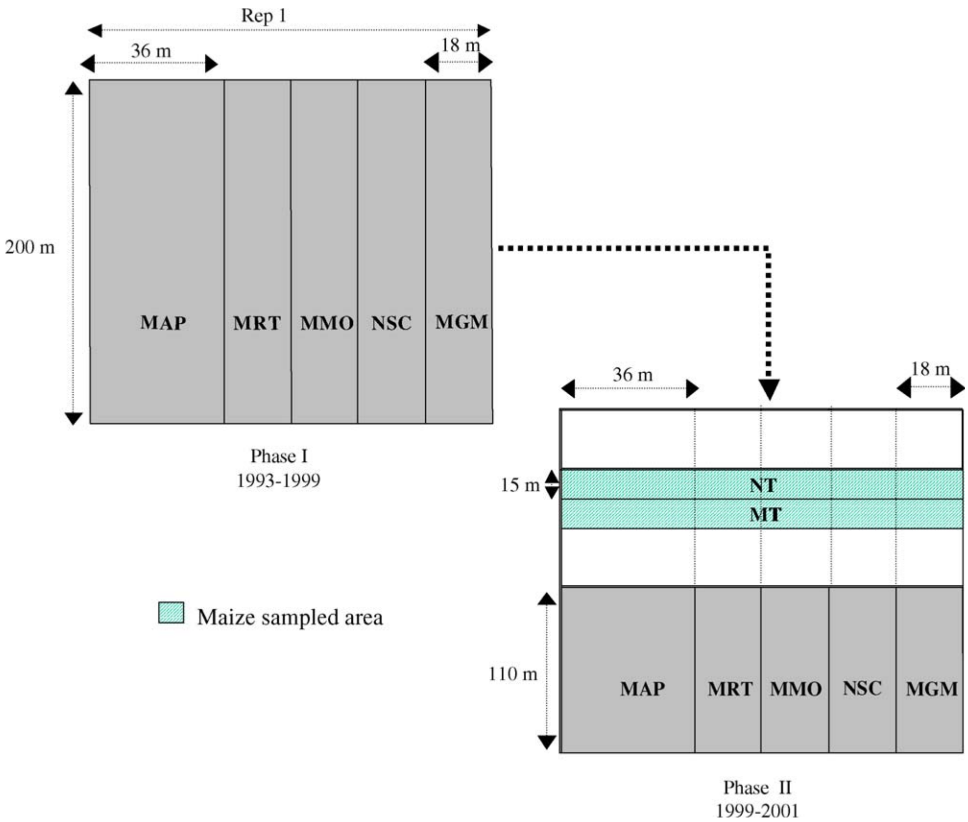

Fig. 1. CULTICORE experimental design in Phase I and new design during Phase II. Only one of four field repetitions has been shown for clarity.

of no-till (NT) and minimum tillage (MT) systems. The maize-based system treatments included: (a) maize monoculture (MMO), (b) maize–soybean rotation (MRT), (c) maize–soybean green manure rotation (MGM), (d) maize-agropastoral rotation (MAP) and (e) native savanna control (NSC). Soybean or green manure rotations occurred within the same year, whereby maize was sown in the first season and soybean in the second season. Pastures were sown simultaneously under maize in 1994 and again in 1998 and were grazed in the intervening 4 years. Native savanna plots were maintained for baseline comparisons and were used as a control to assess the effects of NT and MT on SOM and P fractions and maize grain yield. For the cropped systems, liming was done with 2000 kg ha^{-1} of dolomite prior to establishment of the experiment and maintained thereafter with annual applications of 200 kg ha^{-1}. Each maize crop received 120 kg-N ha^{-1} (split: 40 + 40 + 40), 80 kg-P ha^{-1} and 100 kg-K ha^{-1}. Legumes (soybean or green manure) received 20 kg-N ha^{-1}, 40 kg-P ha^{-1} and 60 kg-K ha^{-1}. Pastures were fertilized bi-annually with 20 kg-P ha^{-1}. The subplots were of size 0.36 ha (200 m × 18 m, 3600 m^2) for maize and soybean, but were 0.72 ha (200 m × 36 m, 7200 m^2) for treatment MAP to allow grazing by cattle and use conventional machinery (Amézquita et al., 2002).

A description of treatments is given in Table 1. Maize row-to-row and plant-to-plant distances were 80 and 15 cm, respectively. Tillage system NT in this study means that the plots were subjected to conventional tillage (CT) during the first 5-year period and were then sown with a direct drilling sowing machine, herein referred to as direct seeding (i.e. there was no intervention in the soil before planting). Conventional tillage involved use of disc harrows (3–4 passes) for soil preparation before each sowing period. Tillage system MT means that after 5 years of CT, one pass of chisel was done at soil depth of 30 cm during seedbed preparation where the distance between the chisel legs was 60 cm; a harrowing pass was done so as to have a better level of the soil for the sowing of maize and soybean, which were sown with direct-drilling machine (i.e. MT involved reduced harrowing intensity before planting). This means that after 5 years of being cultivated continuously with conventional tillage, the plots were sown with a direct-sowing machine (under both NT and MT), to determine if the cumulative effect of treatments had created suitable soil conditions for a

Table 1
Treatment description of the agropastoral/ley farming systems (CULTICORE Experiment, Carimagua)

Treatment	Agropastoral/ley farming system	Description
MMO	Maize monoculture	Maize grown in monoculture; one crop per-year in the first season; second season weedy fallow turned in with early land preparation at the end of rainy season
MRT	Maize–soybean rotation	Maize (1st season) and soybean (2nd season) in 1-year rotation; residues incorporated prior to planting in following season
MGM	Maize–soybean green manure rotation	Maize (1st season) and green manure (2nd season) in 1-year rotation. Legumes incorporated at maximum standing biomass levels in late rainy season
NSC	Native savanna (control)	Managed traditionally by burning annually during the dry season; not grazed
MAP	Maize-agropastoral rotation	Maize monocrop in year-1; *Panicum maximum/Glycine wightii/Arachis pintoi/Pueraria phaseoloides* pasture sown with rice in year-2; grazed to maintain legume content; rotated every 4 or 5 years depending on pasture composition

no-till system. Plots under NT would represent the cumulative effect of treatments, while plots under MT would represent an additional improvement of the soil physical conditions.

2.3. Soil sampling and laboratory analytical procedures

Soil samples were collected in April 2001 at 0–10 cm depth. Previous studies had shown that no statistically significant results occurred for SOM and P fractions at deeper layers (Phiri et al., 2001a,b, 2003a,b; Amézquita et al., 2002; Basamba et al., 2005a). Before collecting the soil samples, soil surface plant litter was carefully removed. A composite sample, consisting of 25 cores, was collected in a grid pattern from all experimental plots. Soil samples were air-dried, visible plant roots removed and then gently crushed to pass through a 2-mm sieve. The <2 mm fraction was used for all the analyses and fractionation procedures. All laboratory analyses were conducted in duplicate.

Total organic C was determined colorimetrically after wet oxidation with acidified potassium dichromate and external heating (Anderson and Ingram, 1993). Total N and P for whole soil were determined by digestion with concentrated sulphuric acid using selenium as a catalyst, followed by colorimetric determination with an auto analyzer (Skalar Sun Plus, the Netherlands).

Size-density fractionation of SOM was conducted as described by Phiri et al. (2001b). In short, an air-dried soil sample (250 g) was gradually wetted, then flooded with 2 litres of water, thoroughly mixed and sieved through two superimposed sieves of 250 μm (top) and 150 μm (bottom). A jet of water through the top sieve destroyed macro-aggregates. Materials retained on the sieves were washed and swirled in order to separate macroorganic matter (>150 μm) from mineral material by decanting. Swirling and decanting was repeated several times until no floating materials remained. The macroorganic matter was then density fractionated in a silica suspension (Ludox™, Du Pont) adjusted to 1.13 g cm^{-3}. The floating fraction (Ludox Light fraction; LL) was collected. The remaining fraction in the sieve was placed in Ludox adjusted to 1.37 g cm^{-3}. The new floating fraction was the Ludox intermediate fraction (LM), and the non-floating fraction, the Ludox heavy fraction (LH). All three fractions were washed with tap water, followed by deionized water, and then dried to a constant weight at 40 °C. After weighing, the SOM fractions were ground with a mortar and pestle to <0.3 mm and then analyzed for C, N and P (Carter, 1993).

Phosphorus fractionation was carried out by using a reduced sequential P fractionation procedure as described by Phiri et al. (2001b) and Tiessen and Moir (1993), where 0.5 g sieved (2-mm) soil samples were used. A sequence of extractants with increasing strength (H_2O, $NaHCO_3$, NaOH and $HClO_4$, respectively) was applied so as to subdivide the total soil-P into inorganic (Pi) and organic (Po) fractions. The following fractions were separated:

(a) Anion exchange resin membranes, in bicarbonate form, were used to extract freely exchangeable Pi, herein called Resin Pi. Potassium persulfate ($K_2S_2O_8$) was used to digest the Po remaining in the water in the resin Pi extraction stage.
(b) Labile Pi and Po sorbed to the soil surface, including some microbial P, was extracted using $NaHCO_3$ (sodium bicarbonate) at 0.5 M and pH 8.5.
(c) Pi more strongly bound to Fe and Al compounds and associated with humic compounds was extracted using NaOH (sodium hydroxide) at 0.1 M.
(d) $HClO_4$ (perchloric acid) was used to digest and extract the residue containing insoluble Pi and more stable Po forms (residual P).

Total P in the $NaHCO_3$ and NaOH extracts were measured after digestion with $K_2S_2O_8$, and organic P was calculated as the difference between total P and Pi in the $NaHCO_3$ and NaOH extracts, respectively. Total soil-P was determined by the $HClO_4$ digestion method as described by Olsen and Sommers (1982). Inorganic P concentrations in all the digests and extracts were measured colorimetrically by the molybdate-ascorbic acid method as described by Murphy and Riley (1962).

2.4. Maize grain yield and system productivity

Grain yields of maize were recorded after harvest in the year 2001. The grain yields were obtained by hand sampling in each sub-plot, with five rows of maize with a length of 10 m (4 m × 10 m (40 m^2)). Grain weights were converted to 19% of moisture content.

2.5. Statistical analysis

Analyses of variance (ANOVA) for soil chemical parameters, SOM parameters and maize grain yield data were conducted to determine the impact from tillage management (NT and MT) and agropastoral system treatments. Significant means were separated by the LSD test (SAS Institute Inc, 1999). Covariance analyses were conducted on soil data collected at the end of the first 5 years of the experiment in order to discriminate the impact of the new cropping systems and tillage management from earlier maize-based system treatments. Correlation analyses were performed using the treatment means. Mention of statistical significance in this study refers to $P < 0.05$.

3. Results and discussion

3.1. Soil chemical characteristics

Significant differences between tillage management (MT, NT) were found for total C and total N (Table 2). Soils under NT consistently showed greater total C and N values than those under MT. This is likely a result of greater SOM losses in MT as a result of some degree of soil disturbance due to the use of chisel compared to NT. These findings agree with results reported by Lal (1997) who has described no-tillage as an efficient soil management practice that improves soil chemical and physical characteristics in low fertility tropical soils. Furthermore, no-tillage has also been reported to induce accumulation of soil total P and other nutrients in tropical and sub-tropical soils through increased organic matter quantity (Pezzarossa et al., 1995).

Table 2
Effect of five agropastoral systems under no-tillage (NT) and minimum tillage (MT) management on total soil C, N and P

Parameters	Whole soils ($mg\ kg^{-1}$)	Significance level		
		Till.	Agr.	T × A
Soil C	24713	<0.0001	0.385	0.085
Soil N	1807	0.0022	0.0084	0.984
Soil P	348	0.0576	<0.0001	0.869

Significant differences were also found for total N and P among agropastoral system treatments (Table 2). Higher values for total N were found in MAP while for total P it was in MRT and MGM which received greater P inputs (Table 3). The presence of well adapted fast growing legumes as cover crops in MAP is likely to have made a significant contribution to soil total N stocks. Lowest total N values found in MGM corroborate high potential N loss due to leaching observed earlier in this agropastoral system treatment (Friesen et al., 1998; Thomas et al., 2004). Incorporation of soybean crop residues prior to the beginning of the rainy season may have facilitated faster decomposition and consequent release of nutrients under MRT during the rainy period. No statistically significant interactions were found between tillage management and agropastoral system treatments.

3.2. Soil phosphorus fractions and availability

Assessing available P among P fractions is critical to managing highly weathered soils such as oxisols and ultisols (Guo et al., 2000). It has been reported that P exists in soils in a multitude of chemical forms and pools that become available to plants at different time scales (Fixen and Grove, 1990). To characterize soil P availability, the Hedley fractionation method has been

Table 3
Effect of agropastoral systems under no-tillage (NT) and minimum tillage (MT) management on total soil C, N and P

Treatment no.	Total C (mg-C/kg)		Total N (mg-N/kg)		Total P (mg-P/kg)	
	MT	NT	MT	NT	MT	NT
MMO	24825	25950	1755	1963	369	374
MRT	23675	25213	1864	2012	401	412
MGM	23243	24350	1473	1585	387	418
NSC	21913	25913	1556	1737	251	260
MAP	24538	27325	1956	2133	292	318
SED[a]	877	1065	103	120	17	21

[a] SED: standard error of the difference in means.

widely used. This procedure, in its original (Hedley et al., 1982) or modified forms (Tiessen and Moir, 1993; Beck and Sanchez, 1994), removes the readily available P from the soil first with mild extractants and then the more stable P forms with stronger extractants. This has led to partitioning soil P fractions into three discrete pools, i.e. the readily available (biologically available and easily mineralizable), the moderately resistant (moderately and reversibly available) and the stable residual (sparingly available and highly resistant) P (Guo and Yost, 1998). The biologically available P (H_2O-Po, resin-Pi, $NaHCO_3$-Pi and $NaHCO_3$-Po) is always the first to be removed by plant roots from the soil and is available to plants in a relatively short time, i.e. from a few days to a few weeks (Cross and Schlesinger, 1995). Resin P is 'readily available' for plant uptake, whereas H_2O-Po and $NaHCO_3$-Po are 'readily mineralizable'. Moderately available P includes NaOH-Po and NaOH-Pi and is available to plants in the medium term, i.e. from a few months to a few years (Beck and Sanchez, 1994). Sparingly available and highly resistant P includes insoluble Pi and more stable Po forms that are available in the longer run, i.e. one or more crop cycles.

Significant differences between tillage management were found in selected P fractions: H_2O-Po, $NaHCO_3$-Po, $NaHCO_3$-Pt and NaOH-Po (Table 4). Agropastoral system treatments under MT generally presented higher H_2O-Po and NaOH-Po values than under NT while for $NaHCO_3$-Pi and $NaHCO_3$-Po the opposite trend was predominant (Fig. 2). These observations suggest that tillage treatments differentially influenced biologically available soil P. Accumulation of biologically available P fractions in the topsoil could be attributed to enhanced storage and cycling of P by

Table 4
Effect of five agropastoral systems under no-tillage (NT) and minimum tillage (MT) management on soil P fractions

Parameters	Means treatment	Significance level		
		Till.	Agr.	T × A
Po-H_2O	4.57	0.0005	0.133	0.507
Pi-Resin	18.63	0.950	0.032	0.982
Pi-Bicar	24.83	0.077	0.0016	0.897
Po-Bicar	10.54	0.0033	0.042	0.964
Pt-Bicar	35.36	0.030	0.0022	0.926
Pi-NaOH	103.44	0.371	0.0003	0.986
Po-NaOH	52.70	0.048	0.104	0.111
Pt-NaOH	153.14	0.773	0.0001	0.941
Pt-Resid	152.06	0.173	0.0037	0.425
Po-Sum	67.81	0.067	0.083	0.090
Pt-Sum	366.77	0.405	0.0006	0.990

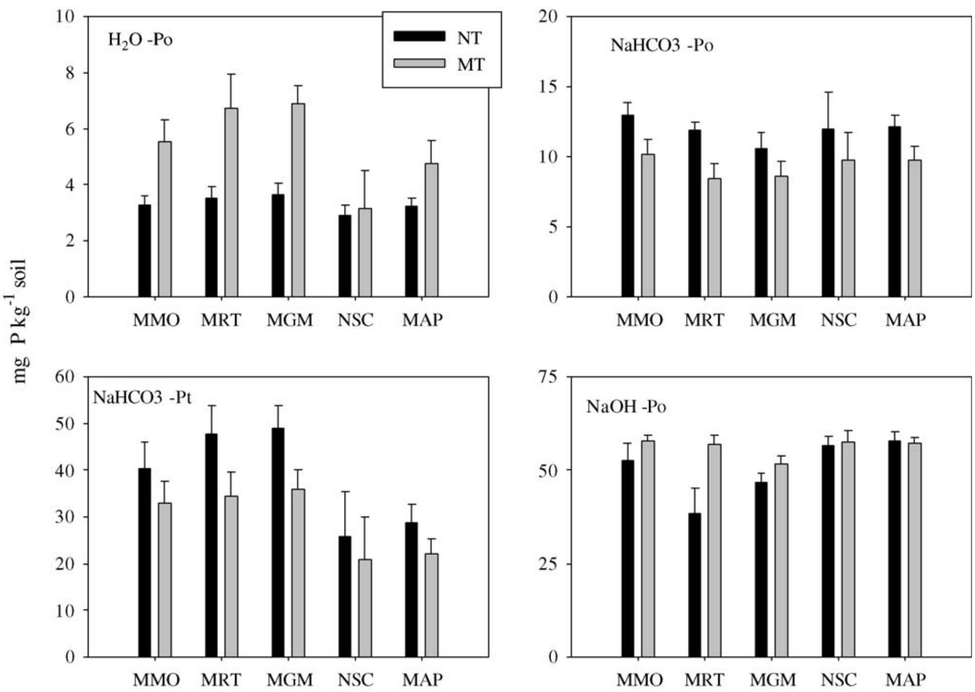

Fig. 2. Effect of no-till (NT) and minimum tillage (MT) on soil P-fractions of different agropastoral systems. Error bars refer to standard errors of the difference in means.

relatively higher SOM contents in this zone. Selles et al. (1997) determined the distribution of P fractions in a Brazilian oxisol under different tillage systems and found that the accumulation of high levels of biologically available P near the soil surface under the zero tillage system which followed a distribution pattern similar to the accumulation of organic residues in the soil. Organic P cycling is strongly controlled by the supply of P, normally greater in the presence of organic-rich materials.

All soil P fractions, except H_2O-Po and NaOH-Po and the Po-Sum showed significant differences among agropastoral system treatments (Table 4). Inorganic P fractions provided a clearer differentiation among treatments and higher values were generally found in MGM and MRT, while lower values were found in NSC and MAP (Fig. 3). As seen earlier, the timing of incorporation of soybean green manure during the rainy season seems to have enhanced faster decomposition and release of nutrients, including P. Highly weathered tropical soils are known to contain minerals such as goethite, hematite, gibbsite and kaolinite (Bartoli et al., 1992) that possess surface Fe–OH or Al–OH groups on which phosphate can be retained, and this may reduce its supply and availability (Iyamuremye et al., 1996). However, P availability can be improved if organic amendments, such as soybean green manure and crop residues, are added to these soils (Iyamuremye and Dick, 1996; Sanchez et al., 1997). P sorption sites of goethite can be blocked by organic matter fractions such as humic acids, causing much less P to be retained. Also, low molecular weight compounds such as oxalate and malate can have similar effect in blocking P-sorption sites, though these effects have been found to be only transient as reported by Afif et al. (1995) and Bhatti et al. (1998).

These results indicate that irrespective of tillage management, highly weathered soils readily incorporate P from cropping system treatments into the residual P fraction (Guo et al., 2000). This means that, in the long term, i.e. with more crop cycles, legume-based maize cropping systems may get access to this P fraction in these soils.

Results on P fractions indicate that NSC and MAP may be better management options in P cycling, since they retain more of Po. This finding has revealed that most of the P in treatments NSC and MAP was being stored in organic form. This may explain the significantly low values of the readily available and moderately resistant P fractions (both of which are inorganic P pools) observed under these agropastoral treatments in this study. Therefore, native savanna and grass + legume pastures under highly weathered and strongly P-sorbing oxisols may provide a better protection of P from loss through fixation, as P flowing through inorganic pools is easily fixed as compared to P in organic pools (Phiri et al., 2001a). This confirms our earlier findings indicating that, in highly weathered and P-deficient tropical soils, P availability for plant growth may depend more on biologically mediated organic P turnover processes than on the release of adsorbed inorganic P (Oberson et al., 2001).

3.3. Soil organic matter fractions

SOM and its different fractions are important in optimizing crop production, minimizing negative environmental impacts and thus improving soil quality. Physical fractionation of SOM has been useful in distinguishing specific carbon pools that are responsive to management (Cambardella and Elliot, 1992; Collins et al., 1997). Size-density fractionation can assess labile SOM fractions that are more sensitive to cropping practices than total organic carbon (Janzen et al., 1992; Barrios et al., 1996). Using size-density fractionation as described by Meijboom et al. (1995), Barrios et al. (1996, 1997) and Phiri et al. (2001b) three SOM fractions (i.e. Ludox light (LL), Ludox intermediate (LM) and Ludox heavy (LH) were recovered in this investigation.

Results on size-density fractionation of SOM using Ludox did not show any clear trend to detect tillage management or agropastoral system treatment effects (Table 5) compared to our earlier studies. While the LL fraction has usually been most responsive to soil management (Barrios et al., 1996, 1997; Phiri et al., 2001a,b), in this study tillage management only generated significant differences in dry weight, amount of P and % of total C and of total P represented by the LM fraction and amount of N in the LH fraction.

Greater LM dry weight values were generally found under MT management. Dry weights of SOM fractions decreased in the order LL > LM > LH. This was not consistent with findings by Barrios et al. (1996, 1997) in Alfisols from Kenya and Zambia, respectively who found LL > LH > LM. Nevertheless, while our LL dry weight values were about twice those reported for these tropical African soils, our LH values were more than eight times lower. Differences in recovery of SOM fractions may be attributed to differences in soil type and management (Hairiah et al., 1996). Also, the impact of the operator (researcher/technician) cannot be over looked, as differences in the washing and decanting processes prior to separating and collecting soil macroorganic matter as well as during collection of

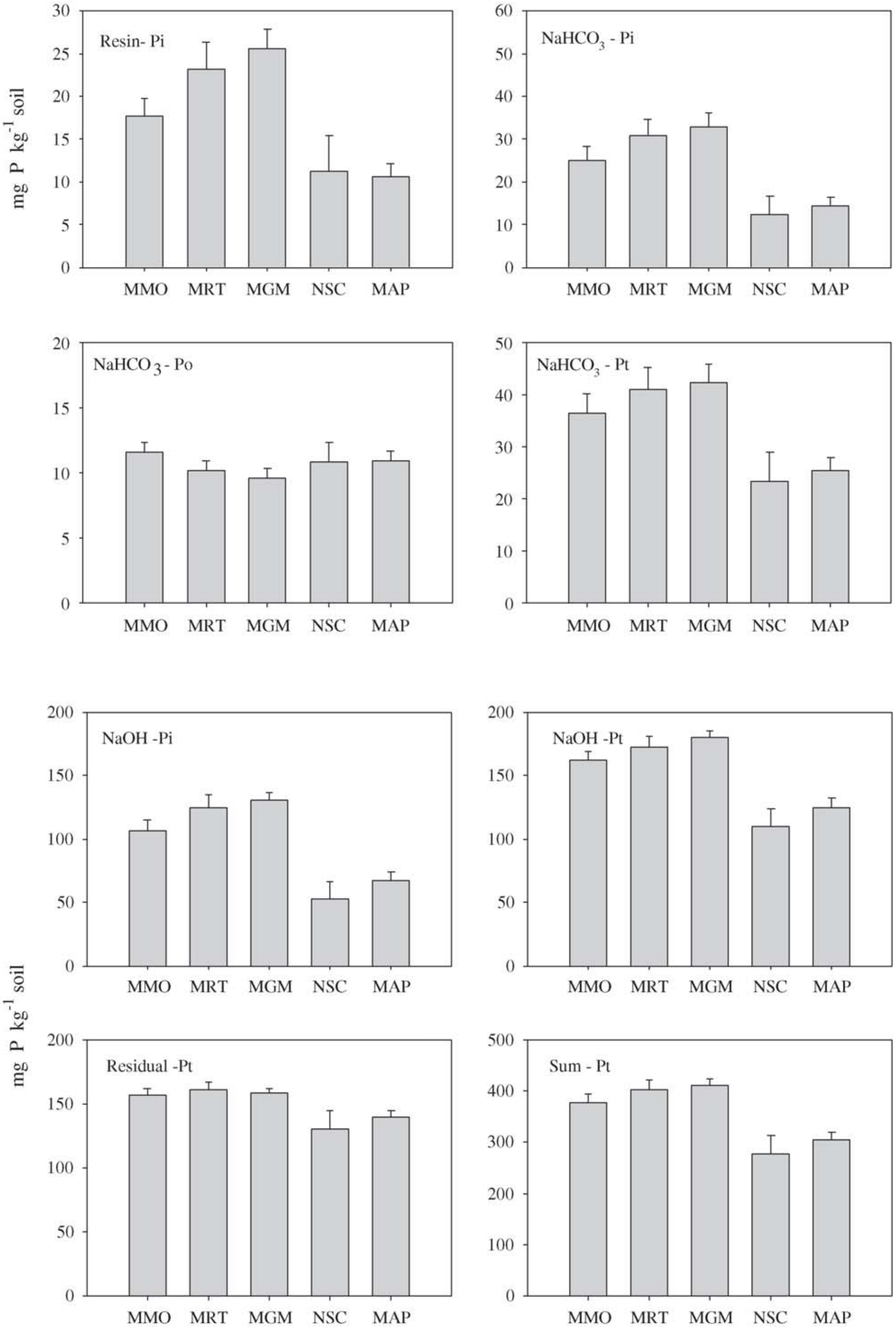

Fig. 3. Effect of agropastoral treatments on soil P-fractions. Error bars refer to standard errors of the difference in means.

the SOM fractions from the Ludox solution may all affect the amount recovered (Basamba et al., 2005a). The higher quantities of the LL SOM fraction confirm results from previous researchers that the LL fraction is critical in soil nutrient dynamics (Janzen et al., 1992; Boone, 1994; Barrios et al., 1997; Phiri et al., 2001b). Furthermore, our results show that the LH fraction makes a very small contribution to total SOM as reported before by several researchers (Hairiah et al., 1996; Barrios et al., 1997; and Phiri et al., 2001b) and

Table 5
Effect of five agropastoral systems under no-tillage (NT) and minimum tillage (MT) management on Ludox SOM fractions

Parameters	Treatment means			Significance level								
	LL	LM	LH	LL[a]			LM[a]			LH[a]		
				Till.	Agr.	T × A	Till.	Agr.	T × A	Till.	Agr.	T × A
Dry wt (g kg^{-1} soil)	2.05	0.42	0.11	0.611	0.226	0.395	0.045	0.863	0.045	0.805	0.037	0.489
Amount (mg kg^{-1} soil)												
C	894.7	164.3	31.5	0.666	0.251	0.442	0.0568	0.865	0.546	0.637	0.066	0.690
N	25.90	5.37	1.30	0.913	0.347	0.156	0.472	0.728	0.429	0.016	0.066	0.656
P	2.36	0.59	0.22	0.252	0.160	0.162	0.0387	0.766	0.255	0.726	0.0863	0.744
Soil C (% of total)	3.35	0.64	0.12	0.260	0.114	0.368	0.0065	0.690	0.421	0.130	0.0761	0.508
Soil N (% of total)	1.42	0.29	0.074	0.392	0.174	0.186	0.0764	0.392	0.174	0.127	0.0136	0.366
Soil P (% of total)	0.62	0.17	0.065	0.148	0.838	0.106	0.0054	0.567	0.261	0.249	0.327	0.827

[a] LL: Ludox light fraction (>150 μm, <1.13 g cm^{-3}); LM: Ludox intermediate fraction (>150 μm, 1.13–1.37 g cm^{-3}); and LH: Ludox heavy fraction (>150 μm, >1.37 g cm^{-3}).

therefore has very little significance in soil nutrient dynamics. No statistically significant interactions were found between tillage management and agropastoral system treatments except in the case of LM dry weight.

Tillage management generated significant differences in soil P fractions and also in the amount of P in the LM fraction. Amount of P was found significantly and negatively related to NaOH-Po ($r = -0.995$, $P < 0.001$) and the sum of Po ($r = -927$, $P < 0.05$). Although these results show additional evidence of the linkage between P and SOM fractions our earlier findings showed that the amount of P in LM was significantly related to $NaHCO_3$-Pi and $NaHCO_3$-Po (Phiri et al., 2001a,b). The negative relationship found indicates that the amount of P in LM significantly increases as NaOH-Po levels decrease. This finding suggests that soils in systems treatments evaluated, particularly under MT management, the moderately available soil P appears to have an important contribution to short-term P immobilization/mineralization dynamics.

Percent of total C and total P represented by LM were also significantly influenced by tillage in this study. However, it is likely that the LM contribution to nutrient dynamics is limited because at most it represents less than 0.8% of total soil C and 0.2% of total soil P. The same argument applies to the amount of N in LH. This finding agrees with results from Freixo et al. (2002) and Bessam and Mrabet (2003) that no-till systems on highly weathered soils produce high quality SOM in the long term, especially when legumes are incorporated into the cropping systems. The amounts of C, N and P decreased in the order LL > LM > LH. This is in agreement with results from Phiri et al. (2001b) and Basamba et al. (2005a) who observed a similar trend in the decrease in the amounts of the nutrients in SOM fractions in Andisols of the Cauca Department of Colombia. However, among the crop and pasture treatments studied, the results were rather mixed and there was no clearly dominant treatment as far as the quality of SOM fractions was concerned. Therefore, no trend has been identified.

3.4. Maize grain yield

In the 2001 cropping season the average maize yield under NT (3.07 mg ha^{-1}) was lower than under MT (3.61 mg ha^{-1}) as shown in Table 6. These results contrast with the 2000 cropping season when average maize yield for NT (3.57 mg ha^{-1}) was considerably higher than under MT (2.47 mg ha^{-1}) as reported by Basamba et al. (2005b). The difference observed in grain yields between the first 2 years after conversion to NT or MT is not surprising. It has been reported that the transition from conventional tillage to no-tillage often creates changes in crop yield during the initial years after conversion presumably as a result of differences

Table 6
Effects of no-till (NT) and minimum tillage (MT) on maize grain yield under different agropastoral treatments

Agropastoral treatment	Grain yield (mg ha^{-1})	
	NT	MT
MMO	3.19	3.59
MRT	3.18	4.01
MGM	4.03	4.35
NSC	2.12	2.49
MAP	2.85	3.58
SED[a]	0.21	0.43

[a] SED: standard error of the difference in means.

in nutrient immobilization/mineralization dynamics (Karlen et al., 1994; Sims et al., 1998; Díaz-Zorita and Grove, 2002). Nevertheless, under both tillage systems, treatments MGM and NSC consistently gave the respective highest and lowest maize grain yields.

Within the NT system treatment MGM produced significantly higher maize grain yield as compared to the other agropastoral treatments. The trend was MGM > MMO = MRT > MAP > NSC. Maize grain yield values ranged from 2.12 mg ha^{-1} (under NSC) to 4.03 mg ha^{-1} (under MGM) (Table 5). Under MT system, again MGM, together with MMO, MRT and MAP, produced significantly higher maize grain yields as compared to treatment NSC. The trend was MGM = MRT > MMO = MAP > NSC, and the values of maize grain yield ranged from 2.49 mg ha^{-1} (under NSC) to 4.35 mg ha^{-1} (under MGM). The higher maize grain yields under MGM may be attributed to the higher nutrient levels, especially soil total N and readily available P, that were observed under this treatment in this study. Also, the soybean may have increased the productivity of this treatment due to increased biologically fixed nitrogen under this cereal legume (CIAT, 1995). Incorporation of legumes at maximum standing biomass productivity under MGM, especially towards the end of the rainy season (Table 1), could have led to release of nutrients from the decomposing green manure (organic matter). This factor may have improved the soil fertility status of plots under treatment MGM, resulting into significantly higher maize grain yields under both tillage systems. Treatment NSC gave the lowest maize grain yields under both tillage systems, possibly due to the problem of aluminum toxicity in these soils. Close to 90% aluminum saturation has been reported for the acid-savanna soils of Colombia (CIAT, 1995). This very high level of aluminum saturation may have a negative impact on maize yield by making major soil nutrients, particularly P, unavailable for crop growth (Pezzarossa et al., 1995; Ernani et al., 2002).

4. Conclusions

Chemical characteristics were, on average, better under no-till as compared to minimum-tilled soils. Phosphorus fractions were also generally higher under no-till treatments. There was no specific trend or dominant treatment as far as the weights and nutrient contents of the SOM fractions are concerned. Seven years after establishment of the long-term ley farming experiment, minimum tillage resulted into slightly higher maize grain yields as compared to no-tillage. Results from this study indicate that the rotational systems (maize–soybean green manure and maize-pastures) improved the soil conditions to implement the no-till or minimum tillage systems on Colombian savanna oxisols. Future research should focus on integrated approaches that combine biophysical and socio-economic parameters to evaluate the sustainable productivity of Colombian savanna oxisols.

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