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Urease activity and its relation to soil organic matter, microbial biomass nitrogen and urea-nitrogen assimilation by maize in a Brazilian Oxisol under no-tillage and tillage systems

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Abstract We studied the relationship between urease activity (UA) and soil organic matter (SOM), microbial biomass N (N_{biom}) content, and urea-N fertilizer assimilation by maize in a Dark Red Latosol (Typic Haplustox) cultivated for 9 years under no-tillage (NT), tillage with a disc plough (DP), and tillage with a moldboard plough (MP). Two soil depths were sampled (0–7.5 cm and 7.5–15 cm) at 4 different times during the crop cycle. Urea was applied at four different rates, ranging from 0 to 240 kg N ha^{-1}. The levels of fertilizer N did not affect the UA, SOM content, and N_{biom} content. No significant difference between the treatments (NT, DP, and MP) was observed for SOM during the experiment, probably because the major part of the SOM was in recalcitrant pools, since the area was previously cultivated (conventional tillage) for 20 years. The N_{biom} content explained 97% and 69% of the variation in UA in the upper and deeper soil layer, respectively. UA and biomass N were significantly higher in the NT system compared to the DP and MP systems. The highest maize productivity and urea-N recovery was also observed for the NT system. We observed that the increase in urea-N losses under NT, possibly as a consequence of a higher UA, was compensated for by the increase in N immobilized in the biomass.

Key words Urease · Microbial biomass nitrogen · Soil organic matter · No-tillage · Maize

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Introduction

Urease catalyzes the hydrolysis of urea to CO_2 and NH_3. Widely distributed in nature, it is present in several animals, plants and micro-organisms. In soils, it can be found as a free enzyme in solution, bound to colloidal particles (mineral or organic) and inside microbial cells (Bremner and Mulvaney 1978; Burns 1982; Nannipieri et al. 1990; Nannipieri 1994; Klose and Tabatabai 1999). Urease activity (UA) is strongly correlated to soil organic matter (SOM) content (Myers and McGarity 1968; Dalal 1975; Bremner and Mulvaney 1978) and microbial biomass (Paulson and Kurtz 1969; Nannipieri et al. 1979; Perucci 1990). Cation exchange capacity (CEC) and pH might also be important in determining the level of enzymatic activity in soils, but the correlation between the latter and CEC or pH is usually low or non-significant (Bremner and Mulvaney 1978). UA usually increases with increasing SOM content and microbial biomass (Bremner and Mulvaney 1978).

Cultivation actually affects SOM dynamic in soils. In temperate climates soils lose up to 50% of their organic matter in about 50–100 years of cultivation. In tropical soils under cultivation the losses of SOM can be significantly higher (Feller and Beare 1997; Shang and Tiessen 1997). Shang and Tiessen (1997), studying a semiarid tropical soil (Oxisol) from Brazil, showed that the manual shifting cultivation of this soil for 6 years led to the loss of 14% of the total C and N, after which the area was abandoned. In a similar soil (Oxisol) in the same region, Tiessen et al. (1992) reported a loss of 30% of the initial total C after only 6 years of mechanized cultivation. Silva et al. (1994), working with 220 Oxisols from the cerrado region of Brazil, found losses of 80%, 76% and 41%, respectively, of total C in 5 years of soybean cultivation on a quartz sand soil (AQ), and a loamy (LVm) and a clayey (LVa) textured Red Yellow Latosol.

In no-tillage (NT) systems, where soils are not ploughed and crop residues lie on the soil surface, decomposition processes slow down and SOM accumu-

lates in the first horizons (Blevins et al. 1977; Juo and Lal 1979; Doran 1980; Dick 1983, 1984). In these systems, residues are incorporated slowly, providing a constant energy supply to soil biota (Doran 1980; Dick 1984).

The accumulation of SOM in surface layers is a characteristic of NT systems; this usually stimulates biological activity and, consequently, increases enzymatic activity (Klein and Koths 1980; Dick 1984). Klein and Koths (1980) observed a significant increase in UA in the soil surface layer (0–10 cm) under a NT system in relation to a conventional tillage system. Dick (1984), working with surface samples (0–7.5 cm) of two soils from the United States, reported UA values 3.0–5.2 times higher in NT compared to tillage systems.

Increases in UA in the first soil layers under NT systems can significantly affect N dynamics and urea-N assimilation by plants. This high UA in NT systems may stimulate quick urea-N hydrolysis and increase NH_3–N volatilization (Dick 1984).

The aim of the present work was to evaluate the influence of 9 years of NT and tillage systems on: (1) SOM content, microbial biomass N (N_{biom}) content and, consequently, UA; and (2) on the interaction between UA and urea-N assimilation by maize.

Materials and methods

The study was carried out at the Maize and Sorghum National Research Centre – Brazilian Institute of Agricultural Research (EMBRAPA-C*N*PMS, Sete Lagoas-MG, Brazil). The area is located at 19°26′S, 44°10′W, and has a mean altitude of 730 m. The mean annual temperature is 22.1 °C, and the mean annual precipitation is 1340 mm, with a wet season from October to March, and a dry season from April to September. The native vegetation is savanna, classified as cerrado sensu stricto (Sans 1986). The soil is a Red Dark Latosol (Typic Haplustox). Table 1 shows the main chemical and physical characteristics of the soil.

The experiment started in 1988, with a maize/beans rotation under irrigation. Three different management systems were used: NT, tillage with a disc plough (DP), and tillage with a moldboard plough (MP). The soil was sampled in 1995 and 1996 during the maize crop. The experimental area was previously cropped for 20 years with a maize/beans rotation and conventional tillage (DP).

The maize (Cargill-805) was sown on 25 November 1995. All the plots were fertilized by 400 kg ha^{-1} NPK (4:20:20). The treatments were delineated in random blocks, arranged in a split-plot design. The main plots received three different management systems: NT, tillage with DP, and tillage with MP. The sub-plots received four N levels as urea fertilizer: 0, 60, 120 and 240 kg ha^{-1} (applied when the plants showed six to eight leaves).

The soil was sampled 4 times during the maize cycle: before planting (*t*1), 45 days (*t*2), 60 days (*t*3) and 100 days (*t*4) after plant emergence. The effect of N levels was analysed only at *t*3 and *t*4. Samples were taken at two depths (0–7.5 cm and 7.5–15 cm). Composite samples (ten random sub-samples) were collected for each sub-plot, at the different depths and sampling times. The samples were kept in plastic bags (field moist soil) and stored at a low temperature (< 0 °C) until analysis.

The N immobilized in the biomass was determined according to the fumigation-extraction method developed by Brookes et al. (1985). In short, triplicate, unfumigated soil samples at field moisture, were extracted for 30 min with 0.5 M K_2SO_4 (1:4 soil:solution ratio). Three further replicates of moist soil samples were fumigated with alcohol-free $CHCl_3$ for 24 h at 25 °C, then extracted with 0.5 M K_2SO_4, similarly to the unfumigated samples. Soil N_{biom} was calculated using Eq. 1:

$$N_{biom} = (N_{fum} - N_{nonfum})/0.54 \quad (1)$$

where: N_{biom} = μg N g^{-1} dry soil; N_{fum} = total N in the K_2SO_4 extract of fumigated soil (μg g^{-1} dry soil); and N_{nonfum} = total N in the K_2SO_4 extract of non-fumigated soil (μg g^{-1} dry soil).

We determined the UA using a buffer method, with toluene as the biological-activity inhibitor, and an incubation time of 3 h (Parcson et al. 1971). The NH_3 released during the incubation time was converted into NH_4^+ and quantified by colorimetry, according to Anderson and Ingram (1992). The other soil analyses were performed in the Laboratory of Soil Science of EMBRAPA-CNPMS according to EMBRAPA (1979).

Table 1 Chemical and physical characteristics of a Dark Red Latosol (Typic Haplustox) from EMBRAPA-CNPMS, Brazil, for two depths (0–7.5 and 7.5–15 cm), under no-tillage (*NT*), tillage with disc plough (*DP*), and tillage with moldboard plough (*MP*); before sowing (*t*1)

Parameters	NT		DP		MP	
	0–7.5	7.5–15	0–7.5	7.5–15	0–7.5	7.5–15
pH (water)	6.40	6.30	6.25	6.33	6.13	6.05
$H^+ + Al^{3+}$ ($cmol_c$ dm^{-3})	2.23	3.48	2.63	2.88	3.00	3.62
Al^{3+} ($cmol_c$ dm^{-3})	–	–	–	–	–	–
Ca^{2+} ($cmol_c$ dm^{-3})	7.75	5.98	7.07	6.95	6.33	5.89
Mg^{2+} ($cmol_c$ dm^{-3})	1.49	0.89	1.06	1.01	1.10	1.02
K^+ (mg dm^{-3})	270.00	154.75	272.50	179.00	234.50	142.75
P (mg dm^{-3})	27.50	28.25	37.00	36.75	32.75	29.50
S ($cmol_c$ dm^{-3})	9.93	7.27	8.83	8.42	8.03	7.28
effective-CEC ($cmol_c$ dm^{-3})	9.93	7.27	8.83	8.42	8.02	7.28
total-CEC ($cmol_c$ dm^{-3})	12.16	10.75	11.46	11.30	11.03	10.90
Moisture content (%)	82	68	77	75	73	67
NH_4^+-N (mg kg^{-1})	1.78	1.89	1.80	1.82	1.88	1.27
NO_3^--N (mg kg^{-1})	43.45	14.65	31.01	17.33	32.08	18.99
total N (g kg^{-1})	0.15	0.14	0.14	0.13	0.13	0.13
Clay (g kg^{-1})	800	800	800	800	800	800
Silt (g kg^{-1})	60	90	70	70	70	70
Sand (g kg^{-1})	140	110	130	130	130	130

Maize was harvested on 5 May 1996, with a 12% moisture content. The apparent urea-N recovery by maize was calculated according to Coelho et al. (1992):

$$\%\ \text{urea-N recovery} = [(TN)F - (TN)C] \times 100/(N)A \quad (2)$$

where: (TN)F = total absorbed N in fertilized plots; (TN)C = total absorbed N in non-fertilized plots; and (N)A = urea-N applied.

Pearson's correlation coefficient (r) was used to study the relationship between UA, SOM, biomass N, pH, effective CEC, and total CEC in the soil.

The influence of pH, organic matter content, total CEC, effective CEC, and biomass N on soil UA was investigated using a stepwise multiple regression model, as follows:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 \quad (3)$$

where: Y = UA (μg NH_4^+ g^{-1} soil h^{-1}); X_1 = biomass N (μg N g^{-1} soil); X_2 = SOM content (g kg^{-1}); X_3 = soil pH_{water}; X_4 = effective CEC at soil natural pH ($cmol_c$ kg^{-1}); and X_5 = total CEC at pH 7.0 ($cmol_c$ kg^{-1}).

Results

The N levels applied did not significantly affect SOM content, N_{biom}, and UA at either $t3$ or $t4$ or for either soils depth (0–7.5 cm and 7.5–15 cm). Therefore, the effect of the management systems (NT, tillage with DP, and tillage with MP) on these parameters was analysed by using mean values of the sampling times. Tables 2, 3 and 4 show the mean values of these parameters for the different sampling times, depths and management systems.

In general, no significant differences were found for the SOM content of the systems during the experiment (Table 2). The SOM varied from 36.0 to 45.9 g kg^{-1} in the topsoil (0–7.5 cm) and from 32.3 to 40.3 g kg^{-1} in the subsoil (7.5–15 cm). Only in the first layer (0–7.5 cm) and for $t1$ was the SOM content higher for NT compared with the other systems (DP and MP). This probably occurred because of the accumulation of easily decomposable organic residues on the soil surface of the NT system during the dry season, which quickly decomposed when the wet season and irrigation started (just after sowing). SOM accumulation under the tillage systems (DP and MP) was minimized and diluted by the distribution of the residues among the harrow layer 1 month before sowing. The contents of SOM followed the same trend with time for all the management systems, at both depths. Between $t1$ and $t2$, with the exception of the topsoil of the NT system, the SOM contents were almost constant. The values increased until a peak in SOM occurred at $t3$ for both depths and all tillage systems, decreasing afterwards to values below the initial levels by $t4$.

Data in Table 3 show that, in general, N_{biom} was significantly higher in NT than in the tillage systems (DP and MP), in both soil layers (0–7.5 and 7.5–15 cm). The values fluctuated in the NT system from 54.7 to 102.7 mg N kg^{-1} soil and from 35.7 to 85.31 mg N kg^{-1} soil in the topsoil and subsoil, respectively. In the other systems (DP and MP), the values ranged from 28.1 to 46.5 mg N kg^{-1}soil, and from 11.4 to 53.4 mg N kg^{-1} soil, respectively. Only at $t2$ and in the second depth (7.5–15 cm) were the levels similar in the NT and MP systems. Indeed, at $t2$ a strong reduction of the N_{biom} values was observed in the NT system (both depths) and in the DP system (7.5–15 cm).

UA (Table 4) showed a pattern similar to that of N_{biom}, and was higher in the NT than in the DP and MP

Table 2 Soil organic matter content (g kg^{-1}) as a function of management system, sampling time and depth. For each soil depth, means followed by the *same letter* do not differ from each other, according to Duncan's multiple range test ($P < 0.05$). $t2$ 45 days, $t3$ 60 days, $t4$ 100 days after plant emergence; *CV* coefficient of variation; for other abbreviations, see Table 1

Depth (cm)	Management system	Sampling time			
		$t1$	$t2$	$t3$	$t4$
0–7.5	NT	45.9 a	39.3 a	45.2 a	36.0 a
	DP	41.1 ab	41.7 a	42.7 a	36.3 a
	MP	38.6 b	36.7 a	42.3 a	36.5 a
CV (%)		7.91	11.21	7.15	9.81
7.5–15	NT	36.5 a	37.2 a	39.2 a	33.8 a
	DP	35.7 a	36.2 a	39.6 a	34.6 a
	MP	39.1 a	36.8 a	40.3 a	32.3 a
CV (%)		4.49	11.40	9.15	17.61

Table 3 Microbial biomass N (N_{biom}; mg kg^{-1}), as a function of management system, sampling time and depth. For each soil depth, means followed by the *same letter* do not differ from each other, according to Duncan's multiple range test ($P < 0.05$). For abbreviations, see Tables 1 and 2

Depth (cm)	Management system	Sampling time			
		$t1$	$t2$	$t3$	$t4$
0–7.5	NT	102.68 a	54.74 a	91.17 a	95.50 a
	DP	35.42 b	29.23 b	40.04 b	43.00 b
	MP	29.85 b	28.07 b	46.50 b	38.00 b
CV (%)		30.31	8.54	8.89	8.76
7.5–15	NT	85.31 a	35.75 a	71.97 a	69.25 a
	DP	51.79 b	11.36 b	45.97 c	33.50 b
	MP	15.37 c	30.46 a	53.40 b	31.75 b
CV (%)		11.92	14.87	11.07	13.95

Table 4 Urease activity (UA; μg NH_4^+ g^{-1} soil h^{-1}), as a function of management system, sampling time and depth. For each soil depth, means followed by the *same letter* do not differ from each other, according to Duncan's multiple range test ($P < 0.05$). For abbreviations, see Tables 1 and 2

Depth (cm)	Management system	Sampling time			
		$t1$	$t2$	$t3$	$t4$
0–7.5	NT	55.00 a	28.80 a	34.33 a	20.74 a
	DP	24.60 b	20.26 b	18.68 b	11.90 b
	MP	29.30 b	20.10 b	11.28 c	10.65 b
CV (%)		9.63	28.33	29.73	39.99
7.5–15	NT	23.60 a	24.80 a	25.75 a	13.88 a
	DP	27.90 a	19.30 a	18.73 b	11.73 a
	MP	29.50 a	19.19 a	13.32 a	10.17 a
CV (%)		12.98	30.39	29.91	40.18

Table 5 Values for correlations between UA, N_{biom}, soil organic matter (*SOM*), pH, effective cation exchange capacity (*E-CEC*), and total cation exchange capacity (*T-CEC*), at depths of 0–7.5 cm and 7.5–15 cm. For other abbreviations, see Tables 3 and 4

	N_{biom}	SOM	pH	E-CEC	T-CEC
	Depth 0–7.5 cm				
UA	0.99**	0.97**	ns	0.99**	ns
N_{biom}	–	0.77**	ns	ns	ns
	Depth 7.5–15 cm				
UA	0.85**	0.87**	0.87**	0.76**	ns
N_{biom}	–	ns	ns	ns	ns

**P<0.01; *ns* not significant (*F*-test)

systems, in the 0–7.5 cm layer. The values for NT varied between 20.7 and 55.0 μg NH_4^+ g^{-1} soil h^{-1} at this depth, and for DP and MP between 10.7 and 29.3 μg NH_4^+ g^{-1} soil h^{-1}. In the deeper soil layer (7.5–15 cm), UA was significantly higher in NT compared to DP and MP systems only at *t*3. At the other sampling times, no differences were observed.

The *r* values (Table 5) showed that the UA was strongly correlated with N_{biom} ($r=0.99$, $P<0.01$), SOM ($r=0.97$, $P<0.01$) and effective CEC ($r=0.99$, $P<0.01$) in the upper soil layer. In the deeper layer (7.5–15 cm) the correlation was significant for N_{biom} ($r=0.85$, $P<0.01$), SOM ($r=0.87$, $P<0.01$), pH ($r=0.87$, $P<0.01$), and effective CEC ($r=0.76$, $P<0.01$).

The influence of SOM, N_{biom}, effective CEC, total CEC and pH on UA was studied using a stepwise multiple regression. For both depths, topsoil (Eq. 3) and subsoil (Eq. 4), only N_{biom} was entered into the model. The other variables did not significantly contribute to the variation of UA. The equations are as follows:

$$UA = 6.78 + 0.32 \times N_{biom}, \text{ coefficient of determination } (R^2) = 0.97,\ P<0.01 \quad (4)$$

$$UA = 15.23 + 0.10 \times N_{biom},\ R^2 = 0.69,\ P<0.01 \quad (5)$$

where: UA = μg NH_4^+ g^{-1} soil h^{-1}; N_{biom} = mg N kg^{-1} soil. N_{biom} by itself explained 97% and 69% of the variation in UA in the upper and deeper layer, respectively. In the deeper layer, 31% of the variation in UA could not be explained by the analysed soil parameters.

In Fig. 1A, UA is plotted as a function of N_{biom}, for all the depths and management systems. The relationship between the variables could be described by a quadratic function. At low values of N_{biom}, the estimated UA slightly decreased to the minimum value of 18.1 μg NH_4^+-N g^{-1} soil h^{-1}. After reaching this minimum value, the activity increased continuously.

We calculated the index UA/N_{biom}, as suggested by Nannipieri (1994). The index showed a strong quadratic relationship with the N_{biom} (Fig. 1B). The index values decreased to a minimum of 0.34 μg NH_4^+-N μg^{-1} N_{biom} h^{-1}, and increased afterwards.

Table 6 shows the UA (average for all the sampling times) in the first 15-cm layer, the maize production ex-

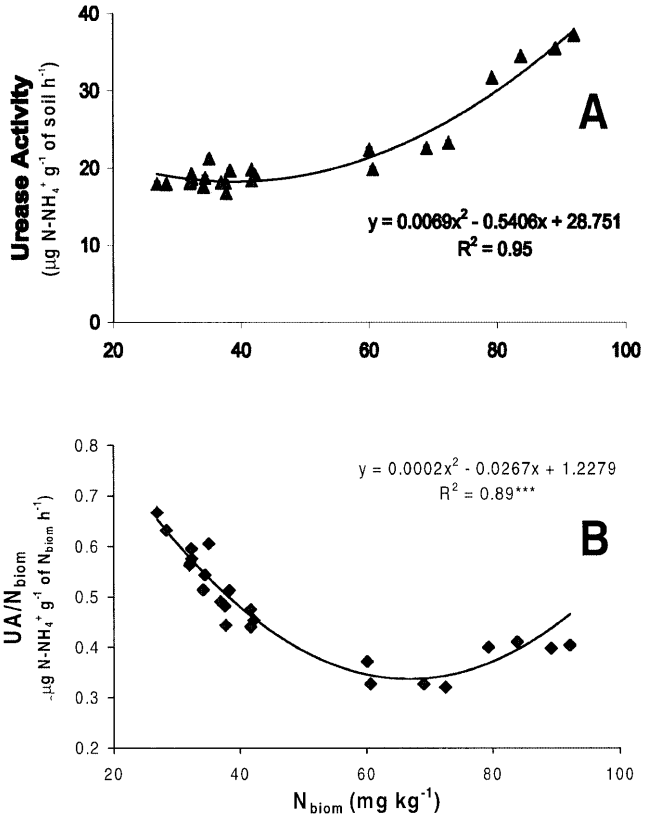

Fig. 1 Urease activity (*UA*; **A**) and UA/microbial biomass N (N_{biom}) (**B**) as a function of N_{biom}

pressed as total dry matter and the recovery of grains, and urea-N fertilizer, as a function of the management system and the level of urea-N applied. In general the UA was always higher in the NT than in the other tillage systems. Following the same trend, the maize pro-

Table 6 UA (μg NH_4^+ g^{-1} soil h^{-1}), maize production as total dry matter (*TDM*; kg ha^{-1}) and grains (kg ha^{-1}), and urea-N recovery (% of urea-N applied recovered) as a function of the level of urea-N fertilizer and management system. For each urea-N level, means followed by the *same letter* did not differ from each other, according to Duncan's multiple range test ($P<0.05$). For other abbreviations, see Tables 1 and 4

Urea-N (kg ha^{-1})	Management system	UA	Production TDM	Urea-N Grains	Recovery (%)
0	NT	25.77 a	7462 a	3781 a	–
	DP	18.33 b	6973 ab	3351 a	–
	MP	17.93 b	6377 b	3298 a	–
60	NT	29.37 a	11217 a	5697 a	52
	DP	20.52 b	8451 b	4423 ab	26
	MP	18.91 b	7608 b	4120 b	23
120	NT	29.88 a	10683 a	5815 a	32
	DP	18.23 b	9156 b	4941 b	28
	MP	17.83 b	8025 b	4509 b	17
240	NT	28.39 a	9701 a	5293 a	12
	DP	19.44 b	8786 b	4561 ab	14
	MP	17.45 b	8065 b	4400 b	10

Table 7 Maximum TDM and grain yield of maize, as a function of the level of urea-N fertilized applied. For other abbreviations, see Tables 1 and 6

Management	Equation	Maximum (kg ha^{-1})		
		R^2	Yield	Fertilizer level
TDM				
NT	$Y=7815.26+52.2044X\text{-}0.1868X^2$	0.82*	11464	140
DP	$Y=6987.70+29.156$ X–$0.09035X^2$	0.99*	9340	162
MP	$Y=6421.20+21.4321$X–$0.0610X^2$	0.99*	8303	233
Grain				
NT	$Y=3899.26+31.0612X\text{-}0.1059X^2$	0.99*	6177	147
DP	$Y=3357.71+21{,}6074X\text{-}0{,}0691X^2$	0.99*	5044.9	156
MP	$Y=3309.24+15{,}8410\ X\text{-}0{,}04734X^2$	0.99*	4640.2	168

*$P<0.05$ (F-test)

duction of total dry matter and grain yields were in general higher in the NT system. The value did not differ significantly only for the grain yields in the treatments without urea-N fertilization. UA correlated positively with total dry matter ($r=0.71$, $P<0.01$) and grain yield ($r=0.65$, $P<0.05$). The recovery of urea-N fertilizer by the maize (Table 6) was higher in NT than in the other systems at fertilization rates of 60 kg ha^{-1} and 120 kg ha^{-1}. For the fertilizer level of 240 kg ha^{-1}, the DP system showed the highest recovery, although the recovery in all the systems was relatively low.

Quadratic equations were fitted to the data for total dry matter and grain production (Table 7). The R^2 varied from 0.82 ($P<0.05$) to 0.99 ($P<0.05$) for total dry matter and was 0.99 ($P<0.05$) for grain yield. With respect to the point at which production was at a maximum, the NT system showed the highest dry matter and grain production, and the lowest urea-N level. The maximum dry matter and grain yields of the MP system were the lowest of all three systems, and they corresponded with the highest levels of urea-N.

Discussion

Results in Table 2 showed that 9 years of NT were not sufficient to increase the SOM contents in the studied soil, even in the upper soil layer. The high mean temperature and the moist soil conditions due to irrigation probably stimulated residue decay and made difficult the accumulation of SOM in this environment. In addition, this area was cropped for 20 years with maize before the current tillage experiment. This period of time was probably sufficient for a drastic reduction of the "active" SOM pool, leaving a more stable ("passive" pool) C fraction (Trumbore and Zheng 1996; Shang and Tessein 1997; Feller and Beare 1997). Using isotopic techniques (^{13}C and ^{14}C) and two-compartment models, the mean residence time of the active SOM pool in tropical soils under cultivation was calculated as ranging from 4 to 45 years (Cerri and Andreux 1990), 2 to 5 years (Veldkamp 1993) and 5 to 8 years (Hsieh 1996). In cultivated soils, a new equilibrium between the SOM pools is reached, and the amount of C in the active pool rather than in the passive pool is more closely related to the new C dynamics of the system (Tiessen et al. 1994). Thus, decreases in total SOM due to cultivation are mostly due to changes in the active pool, and reach a new equilibrium in a period of time similar to the residence time of this active fraction. In this new equilibrium, a larger proportion of the total C is from the passive SOM pool, the level of which is less affected by management practices (Hsieh 1992, 1993, 1996; Harrison et al. 1993).

In general, UA and N_{biom} were higher in the NT than in the tillage systems (Tables 3, 4), especially in the topsoil (0–7.5 cm), indicating that the NT system stimulated microbial growth and enzymatic activity. Klein and Koths (1980) and Dick (1984) also reported increasing soil UA and microbial biomass as a consequence of NT practices with the enrichment of SOM in the topsoil.

Data in Tables 2, 3 and 4 showed that, although total SOM content was not affected by the tillage system, NT practices increased N_{biom} and UA. With soil ploughing, residues are split up and incorporated into the harrow layer, stimulating decay (Shang and Tiessen 1997; Feller and Beare 1997). Under NT systems, residues are not mixed with the soil and the surface area of the crop residues in contact with the soil is much smaller. As a consequence, the decomposition rate tends to decrease (Blevins et al. 1977; Juo and Lal 1979; Doran 1980; Dick 1983, 1984). For this reason, the crop residues accumulate above the soil surface. This residue layer above ground in NT systems appears to be a constant source of labile SOM to soil biota, thus a higher microbial biomass and UA is maintained during the crop cycle.

UA in soils can be intra- and extracellular (Burns 1982; Dilly and Nannipieri 1998). The extracellular enzyme can be free or bound to mineral and/or organic colloidal particles (Bremner and Mulvaney 1978). Therefore, the level of UA depends on soil properties which might influence microbiological activity (e.g. SOM content and microbial biomass) and the adsorption of the enzyme on colloidal particles (e.g. clay content, SOM content, CEC, and pH) (Bremner and Mulvaney 1978; Burns 1982; Nannipieri et al. 1990; Nanni-

pieri 1994; Dilly and Nannipieri 1998; Klose and Tabatabai 1999). Our results showed that UA in the studied soil was strongly correlated to SOM, N_{biom}, and effective CEC in the upper soil layer, and also to pH in the deeper layer (Table 5). However, according to the stepwise multiple regression model used, the variation of UA was explained by only the N_{biom} in the surface (97%) and subsurface (69%) soil. None of the other parameters entered in the model explained the variation in UA, suggesting that all the variation in UA that could be related to these soil parameters (due to their high correlation with UA) was already explained by the N_{biom}. The possible interdependence between the microbial biomass and these parameters (Paul and Clark 1989) would prevent their inclusion in the model. However, in general, N_{biom} did not correlate to the other soil properties at either depth (Table 5), suggesting a weak interdependence between them.

Urease production by soil microorganisms can be constitutive, inducible or repressed (Mobley and Hausinger 1989; McCarty et al. 1992). The non-significant effect of urea-N fertilizer on UA strongly suggested that inducible production of urease was not responsible for the observed differences in the overall activity among the treatments. For the same reason, the repression of microbial urease production by products of microbial assimilation of N (McCarty et al. 1992) was also unlikely, since urea-N was the primary source of N. Therefore, the observed differences in UA among the treatments was probably related to changes in constitutive enzyme production. The high correlation between UA and N_{biom} (Table 5) strongly supported this hypothesis.

Analyzing the relationship between UA and N_{biom} (Fig. 1A) we observed that the two variables were strongly related to each other, even when the data relating to different depths and management systems were plotted together. The shape of the curve suggested that, at low N_{biom} values, small changes in UA would be expected when the N_{biom} increased. Since there was no significant difference in the values of SOM (Table 2) and clay content (Table 1) among the depths and treatments, it was reasonable to assume that the potential of enzyme immobilization by soil colloids would also be similar throughout the curve. Then, in the first part of the curve, the activity of the immobilized enzyme might be more important than that of the free and the intracellular urease. The activity of immobilized urease does not depend on the size and activity of the microbial biomass, and the enzyme can remain active even under conditions of stress (Burns 1982; Nannipieri et al. 1990; Nannipieri 1994; Dilly and Nannipieri 1998). Changes in N_{biom} in the first part of the curve might have been too small to affect the overall enzymatic activity. However, as soils have a maximal capacity of enzyme immobilization (Burns 1982), increasing the N_{biom} would potentially increase the relative importance of the free and intracellular enzyme, whose activities would be similar to the contribution of the immobilized enzyme with respect to the total UA. For this reason, in the last part of the curve, the same unit of increase in N_{biom} had a larger effect on UA than in the initial part.

The index UA/N_{biom} as suggested by Nannipieri (1994) gives the enzymatic activity per unit of N_{biom}. This index can give an idea of the contribution of intracellular and extracellular urease to the overall UA (Nannipieri 1994; Dilly and Nannipieri 1998). The higher the index, the lower the intracellular activity. The non-linearity of the relationship between UA and N_{biom} (Fig. 1A) suggested that the ratio UA/N_{biom} would vary with the size of the N_{biom}. In fact, we observed a quadratic relationship between the UA/N_{biom} and the N_{biom} (Fig. 1B). The shape of the curve allowed two different interpretations of the index. Taking the value of N_{biom} equivalent to the minimum UA/N_{biom} estimated value of the curve (0.34), the graph could be divided into two regions. In the first region (left side), a decreasing trend was observed for UA/N_{biom} as a function of N_{biom}, suggesting that the extracellular enzyme was more important at a low level of N_{biom}. Burns (1982) pointed out that the level of free enzymes in the soil solution is probably negligible due to their short existence. Then, in the initial part of the curve, the activity of the more important extracellular enzyme might be mainly derived from immobilized enzyme. On the other hand, in the second part of the curve, the index tended to increase with increasing values of N_{biom}. This means that the extracellular enzyme activity tended to increase as well. However, it is unlikely that the activity of immobilized urease was higher than that of the intracellular enzyme at high values of N_{biom}. This relative increase in extracellular UA was probably related to an increase in the free extracellular enzymatic activity, contradicting the hypothesis of Burns (1982). The data presented in Fig. 1B suggests that the interpretation of the UA/N_{biom} index demands the careful observation of possible relationships between the index and other variables (i.e. the N_{biom}, SOM, and clay content).

Tables 6 and 7 showed that, although UA significantly increased in the topsoil of the NT system, the highest production of dry matter and grain, and recovery of urea-N fertilizer, was also observed under the NT system. This finding contradicted that reported by Dick (1984), who showed that an increasing UA under NT systems may significantly increase the losses of urea-N fertilizers by volatilization and, consequently, decrease the recovery of the urea-N applied.

Not only UA but also soil pH, buffering capacity, and CEC have an important effect on NH_3–N volatilization, as well as environmental factors such as temperature, soil water content and air exchange (Hargrove 1988). The balance between NH_4^+-N and NH_3–N is strongly affected by the soil pH. A higher hydrogen activity favours the NH_4^+ form, and tends to decrease N loss due to NH_3 volatilization. Our soil showed a slightly acid pH (6.03–6.40) for all the treatments (Table 1), which could have decreased NH_3–N volatilization even

under high UA. However, Singh and Nye (1988) pointed out that even in relatively acid soils, the volatilization of NH_3–N after fertilization with urea can be significantly high. Urea hydrolyzes, forming NH_4^+ and HCO_3^- ions. The latter tends to increase the local soil pH, stimulating the conversion of NH_4^+-N into NH_3–N and, consequently, N losses by volatilization (Singh and Nye 1988). Lara-Cabezas et al. (1997a) reported 41% loss of NH_3–N after the superficial application of 100 kg urea-N fertilizer ha^{-1}, in a clay Oxisol cropped with maize under NT, in spite of its relatively low pH (5.5). The same authors (Lara-Cabezas et al. 1997b), also studying clay Oxisols, reported 78% and 31% losses of N supplied by the urea fertilizer applied on the soil surface in maize fields under NT and conventional tillage, respectively. The soil pH was 6.2 under NT and 5.8 under conventional tillage.

We also noticed that soil pH did not differ among the treatments and did not correlate with maize production or urea-N recovery (data not shown). Thus, the possible decrease in volatilization losses as a consequence of the relatively low pH seemed to be unlikely.

The high N_{biom} values observed for the NT system suggests that a possible excess of urea-N hydrolyzed as a consequence of the high UA in the topsoil was immobilized by the microbial biomass, as hypothesized by Klein and Koths (1980). This temporary immobilization ensured a constant supply of N (via turnover of the microbiota) during the maize cycle, increasing the efficiency of utilization of the urea-N by the plants.

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