DALTON BELCHIOR ABDALA

PRODUTIVIDADE DE MILHO E POTENCIAL DE PERDAS DE FÓSFORO EM ARGISSOLO FERTILIZADO COM CAMA DE FRANGO

Dissertação apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Solos e Nutrição de Plantas, para obtenção do título de *Magister Scientiae*.

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A Deus

A minha mãe, Márcia

Dedico

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BIOGRAFIA

DALTON BELCHIOR ABDALA, filho de David José Franco Abdala e Márcia Rúbia Belchior Abdala, nasceu em Campestre, em sete de Janeiro de 1980.

Iniciou o curso de Agronomia no ano de 2001 na Universidade de Alfenas (Unifenas), transferindo-se, posteriormente, para a ESACMA, em Machado, onde permaneceu no curso de Agronomia desta Escola por um ano e meio.

Em Fevereiro de 2003, foi admitido pela UFV para continuação do curso em Agronomia.

Em Agosto de 2005, recebeu uma bolsa de estudos pela CAPES para participação em um programa de intercâmbio internacional entre a UFV e a University of Florida por um período de um ano acadêmico.

Em outubro de 2006, graduou-se em Agronomia pela Universidade Federal de Viçosa.

Em outubro do mesmo ano, iniciou o Curso de Mestrado na Universidade Federal de Viçosa, concentrando seus estudos na área de fertilidade do solo e nutrição de plantas, concluindo-o em dois de Setembro de 2008.

ÍNDICE

RESUMO

ABDALA, Dalton Belchior, M. Sc., Universidade Federal de Viçosa, Setembro de 2008. **Produtividade de milho e potencial de perdas de fósforo em Argissolo fertilizado com cama de frango** Orientador: Ivo Ribeiro da Silva. Co-orientadores: Roberto Ferreira de Novais e Victor Hugo Alvarez Venegas.

A utilização de resíduos orgânicos na agricultura como fertilizantes ou condicionadores de solo tem ganho importância no Brasil na medida em que a agricultura orgânica tem expandido e os preços de fertilizantes tem aumentado sobremaneira. Contudo, estudos que relacionem as taxas de aplicação de fertilizantes orgânicos, tais como a cama de frango (PL), com o objetivo de aumentar o rendimento de culturas com mínimo risco ao ambiente tem sido escassos. O presente estudo foi conduzido sob condições de campo em um Argisolo Vermelho-Amarelo objetivando-se avaliar o rendimento de grãos de milho, as alterações em algumas caracteristicas químicas do solo, e o potencial de perdas de fósforo (P) como resultado da aplicação consecutiva de doses crescentes de cama de frango em superfície. As doses de PL utilizadas foram 0, 5, 10, 25, 50 e 100 t ha^{-1} e estas foram aplicadas superficialmente por três anos consecutivos e milho foi cultivado. As características químicas apresentadas foram determinadas ao final do terceiro ano de aplicação da PL. Foi observado que a aplicação de PL teve efeitos positivos sobre o rendimento de grãos (CGY), o qual variou entre 4443 kg ha^{-1} no tratamento controle e 12 000 kg ha^{-1} nos tratamentos com aplicação de altas doses de PL. No terceiro ano, o rendimento físico máximo ($\hat{y}$ máx) foi estimado como 12 500 kg ha^{-1}, necessitando, portanto, de uma dose de PL de 74.7 t ha^{-1}. Entretanto, um rendimento mais econômico de 11 207 kg ha^{-1}, representado por 0.9 $\hat{y}$ máx, foi obtido com uma dose de 21.7 t ha^{-1}. A aplicação da dose mais elevada de PL conduziu a um grau de saturação de P de 21% estimado com o extrator Mehlich-3 ($DPS_{M\text{-}3}$) e uma concentração de P pelo mesmo extrator ($P_{M\text{-}3}$, 131 mg kg^{-1}) considerada mais baixa que o valor limite (crítico) que a maioria dos índices ambientais alertam para o potencial risco de perda de P. Contudo, o valor de P soluvel em água (WSP) variou bastante acima do valor preconizado pelos indicadores ambientais, indicando que valores de $DPS_{M\text{-}3}$ acima dos quais perdas de P são acentuadas estão abaixo daqueles encontrados para solos menos intemperizados. Este fato demonstra que medidas isoladas de valores analíticos, como concentração de P ou o $DPS_{M\text{-}3}$, fornecem indicação limitada do real potencial de perda de P e sugerem, pois, a necessidade de se considerar o WSP como medida auxiliar para uma concepção mais realística do potencial de perda de P. Dessa forma, um nível crítico ambiental que também considera os valores críticos de WSP conduziu a uma indicação mais realística da perda de P. Assim, considerando-se valores de WSP, a dose estimada de PL a ser recomendada seria de 5.1 t ha^{-1}. As alterações observadas nos atributos químicos do solo incluiram aumentos nas concentrações de nutrientes (N, P, K^+, Ca^{2+}, Mg^{2+} e Zn), Na^+, pH e Carbono total (CT), e descréscimo em Al^{3+} trocável. Por fim, os resultados obtidos indicam que a dose de cama de frango requerida para a obtenção de rendimento máximo de grãos conduziriam a valores de saturação de P no solo e concentrações de WSP que estão muito acima dos níveis ambientais. Portanto, com vistas a atender recomendações de PL para cultivo de milho com mínimo risco de perdas de P, estas devem incluir análises de WSP complementares as demais medidas de P das análises de rotina ao invés de somente o rendimento de grãos, as concentrações de P_{M-3} e os níveis críticos ambientais referidos pelo DPS_{M-3}.

ABSTRACT

ABDALA, Dalton Belchior, M.S., Universidade Federal de Viçosa, August, 2008. **Corn yield and phosporus loss potential in an Ultisol fertilized with poultry litter.** Adviser: Ivo Ribeiro da Silva. Co-Advisers: Roberto Ferreira de Novais and Víctor Hugo Alvarez V.

The use of organic residues in agriculture as fertilizers or soil amendments has gained importance in Brazil as organic agriculture has expanded and fertilizer prices have increased substantially. However, studies that relate manure rates, especially poultry litter (PL), to maximize crop yield with minimum risk to the environment, are scarce. The present study was carried out under field conditions in an Ultisol to evaluate corn grain yield, the changes in soil chemical characteristics, and the P loss potential as a result of surface application of increasing rates of PL for three consecutive years. The PL rates used were 0, 5, 10, 25, 50 and 100 t ha^{-1} (DW basis) and they were annually broadcast for three consecutive years and corn was cultivated. The reported soil chemical characteristics were determined after the third year of corn cultivation, thus reflecting the cumulative effect of PL application. It was found that the application of PL had positive effects on corn grain yield (CGY), which ranged from 4423 in control plots to about 12 000 kg ha^{-1} in high PL rate treatments. In the third year it was estimated that a maximum physical grain yield (ŷ max) of 12 500 kg ha^{-1} could be achieved with a PL rate of 74.7 t ha^{-1}. However, a more economical grain yield of 11 207 kg ha^{-1}, assigned as 0.9 ŷ max, could be achieved with a PL rate of 21.7 t ha^{-1}. The application of such a high PL rate (74.7 t ha^{-1}) led to a degree of soil P saturation of 21 % estimated with Mehlich-3 (DPS_{M-3}), and a Mehlich-3 P (P_{M-3}) concentration (131 mg kg^{-1}), below the threshold (critical) value, that most environmental indices warn for a potential risk of P loss. Nevertheless, soil water soluble P (WSP) concentration ranged quite above the environmental threshold level, indicating that DPS_{M-3} values above which P losses are accentuated are lower than those found for other less weathered soils. This fact demonstrates that soil test results or the DPS taken solely provides limited indication into P loss potential and suggests the need of taking the WSP into account to relate to P loss potential. As such, an environmental threshold that also considers WSP critical level led to a more realistic indication of P loss potential. If such WSP threshold is taken into account, an estimated PL rate of 5.1 t ha^{-1} would be recommended. The observed changes in soil chemical attributes included increases in soil nutrients concentration (N, P, K, Ca^{2+}, Mg^{2+} and Zn), Na^{+}, pH and total C, and a decrease in exchangeable Al. Finally, the results indicate the PL rate required to maximize CGY would lead to soil P saturation and a WSP concentrations that are well above the environmental threshold. Hence, when recommending PL rate to corn it is suggested that analysis of WSP should be taken into account other than simply grain yield, $P_{M\text{-}3}$ concentrations and the DPS thresholds.

INTRODUCTION

The poultry industry in Brazil has developed remarkably in recent years stimulated by the increase in exports and *per capita* consumption (ANUALPEC, 1999, 2007). The intensive poultry production yields a by-product, the poultry litter (PL), which has been utilized for livestock feeding (AVIZOM, 2003). However, the Normative Instruction N^O 15, of July 17th, 2001, has prohibited the use of all sort of manures or their derivatives for ruminant feeding in Brazil. Despite its excellent characteristics either as nutrient source for plants or soil amendment, PL has been poorly explored as organic fertilizer in commercial corn because there is limited information for recommending it in fertilization schemes. Although it has been widely utilized for horticultural crops such as green onion, sweet corn, carrot and Peruvian carrot (Zarate et al., 2003a,b; Araújo et al., 2004), few studies have been carried out aiming to establish adequate PL rates for corn (Cooperband et al., 2002; Zarate & Vieira, 2003; Motavalli et al., 2003). In Minas Gerais state, for example, the PL rate is recommended based on an equivalent to other types of manures; the ideal application rate should be about ¼ of the recommended dose of beef cattle or dairy manure (CFSEMG, 1999). In an exploratory greenhouse study aimed at evaluating the agronomic potential of PL for corn production in two Oxisols with no previous manure or inorganic fertilizer application, it was found that PL rates from 60 to 70 t ha^{-1} were needed to maximize corn growth over three consecutive cultivations (Souza, 2004). On the other hand, studies carried out in agricultural soils where PL is traditionally applied suggest lower rates (Sistani et al., 2008) and warn for the potential risk of nutrient accumulation, especially P, as its concentration in manures far exceeds plant demand. So, the consecutive application of manures may lead to soil P enrichment and subsequent loss to water bodies (Sharpley et al., 2001).

An adequate dose of manure must be applied so that beneficial effects on soil chemical and physical properties can be achieved without harming the environment. However, overestimated rates of PL can lead to the downward movement and overland flow of P. Since natural water P levels are very low and limiting to growth of organisms, the increase in water P due to non-point agricultural sources contribute to water bodies eutrophication, algal blooms and fish kills (Sharpley et al., 2001).

More recently several analytical methods have been employed to predict and, or monitor P losses from agricultural land to water bodies. Ammonium oxalate was one of the first extractants used with such purpose and it has been used for acidic soils in the Netherlands (van der Zee et al., 1987; Breeuwsma & Silva, 1992), Ireland (Maguire & Sims, 2002a) and in the United States (Paulter & Sims, 2000). Since the utilization of this method is limited by operational difficulties in routine soil fertility laboratories, researchers have been exploring the possibility of using routine analytical protocols with an environmental perspective. Among those methods, Mehlich-1 and Mehlich-3 have received more attention and they have proven good indicator of the potential for P loss from soils to water bodies in temperate regions (Sims et al., 2000; McDowell & Sharpley, 2001a, b). Since then, soil test P has become a popular measure and it has been related to other factors that define water soluble P (WSP), an important indicator for P loss potential. In fact, environmental agencies (USEPA, 2000; CONAMA, 2005;) that regulate water quality established that P levels in natural waters or streams should not exceed 0.1 mg L^{-1} of P.

The environmental thresholds are based on the fact that soils have a finite capacity to adsorb P, then, as they become saturated, the extent of P being subjected to desorption or even not adsorbed is increased. Thus, water soluble P is dependent on soil P sorption capacity (PSC) (McDowell et al., 2001, Bond et al., 2006), and several authors agree on utilizing the content of Fe and Al oxides in soils to represent their PSC (Novais & Kamprath, 1978; Breeuwsma & Silva, 1992; Pautler & Sims, 2000; Maguire and Sims, 2002a,b; Nair et al., 2002; Sims et al., 2002).

Environmental thresholds have been established as the point (soil P concentration or P saturation degree) above which WSP concentrations increases rapidly and, therefore, the risk of P loss is exacerbated. The degree of soil P saturation (DPS), an index that provides an idea of the P status for a determined soil condition, has been used to indicate that P concentrations can exceed a critical concentration well before the soil is completely saturated with P (Breeuwsma & Silva, 1992). According to Breeuwsma & Silva (1992) and Nair et al. (1998), soil ammonium oxalate extractable-Al and -Fe content is suitable for predicting the PSC of an acid soil. However, given the operational difficulties to extract soils with ammonium oxalate, Mehlich-3 or Mehlich-1 extractants have gained importance as routine methods that provide information on both available P and PSC, and may allow estimating the DPS (DPS_{M1} and DPS_{M3}).

The present study was carried out under field conditions in an Ultisol (Argisol) to evaluate corn grain yield, the changes in soil chemical characteristics, and the P loss potential as a result of surface application of increasing rates of poultry litter for three consecutive years.

MATERIAL AND METHODS

A. Experimental Field Characteristics

The experiment was carried out in an Experimental Farm of the Federal University of Viçosa, located in Coimbra County, MG. The altitude is 650 m.a.s.l., latitude 20° 45' S and longitude 45° 51' W with climate classified as CWA (warm and humid summers with a mild and dry winter season) according to Köppen`s. The mean annual air relative humidity is 85 % and the mean annual rainfall is 1350 mm, concentrated from October to March. The soil is a clayey dystrophic Red-Yellow Argisol (Ultisol) with less than 1 % slope and it has been cultivated over thirty years with annual crops such as corn (*Zea mays* L.), common bean (*Phaseolus vulgaris* L.), soybean (*Glycine max* (L.) Merrill) and wheat (*Triticum aestivum*). The area has received regular chemical fertilization and liming during the cultivation period prior to the current experiment installation.

B. Experiment Design and Management

The experiment consisted of six treatments in a completely randomized block design, with four repetitions. Treatments were comprised by six rates of poultry litter (0, 5, 10, 25, 50 and 100 t ha^{-1} on a dry weight basis) over three consecutive cropping years (2004, 2005 and 2006). The plots were 4.0 m long and 5.4 m wide. Poultry litter was broadcast on the soil surface 20 days prior to planting in order to minimize eventual damage towards seedlings germination. Corn was sown in the beginning of the growing season (late October) in rows with 0.9 m spacing, with a stand of 70 000 plants per hectare. Weeds were controlled with pre-planting application of glyphosate (N-(phosphonomethyl)-Glycine) and post-emergence atrazine ((2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine) and nicosulfuron (2-[[(4,6-dimethoxypyrimidin-2-yl)aminocarbonyl]aminosulfonyl]-N,N-dimethyl-3-pyridinecarboxamide) as recommended by the manufacturer. In the winter, the area remained under fallow.

Approximately 150 days after planting the four central corn rows in the plot were hand harvested and the cobs shelled on site. Corn kernel samples were collected and the moisture content was determined (Multigrain moisture meter). This moisture value was used to adjust corn grain yield (CGY) to 13 %.

C. Sampling and chemical analysis of plant material

Corn leaves from 10 plants/plot were randomly collected during tasseling and then combined to obtain a composite sample. In the laboratory, the leaves were washed with deionized water and blotted with paper towel. Leaves were dried in a forced air draft-oven at 70 ºC for 72 h, ground in a Wiley mill to pass through a 1 mm screen, and stored until analysis. The ground leaf tissue was digested with a mixture of nitro-perchloric acid at a 3:1 (*v/v*) ratio and the extracts were analyzed for P, K, Ca, Mg and Zn. The N concentration was determined by the Kjeldahl method.

D. Soil sampling and analysis of soil and poultry litter

Five individual soil samples were collected from the 0 – 10, 10 – 20 and 20 – 40 cm layers at the harvest day using a manual coring device. These five samples were combined to obtain a composite soil sample per plot. They were air-dried, ground to pass through a 2 mm sieve and stored for subsequent analysis. Soil texture was determined by a modification of the pipette method (Ruiz, 2005) (Table 2). Soil samples were analyzed for pH in $CaCl_2$ in a 1:2.5 soil:solution ratio (Table 2). Phosphorus, Fe, Al and Zn were extracted either by Mehlich-1 (M-1) (Mehlich, 1953) or Mehlich-3 (M-3) (Mehlich, 1984) and measured by ICP-OES.

To address the relationship between the two soil P extractants (M-1 and M-3) it was employed a test to check models similarity (Leite & Oliveira, 2002). The relationship between $P_{M\text{-}1}$ and $P_{M\text{-}3}$ had no significant difference ($p > 0.01$); that is the intercept did not differ from zero and the angular coefficient did not differ from the unity (Table 2). In the present study only the $P_{M\text{-}3}$ results are reported.

Table 1. Size class components and pH in three layers of the Ultisol used in the poultry litter fertilization study, before treatment application

Soil layer	**Soil texture**			
	Sand	**Silt**	**Clay**	**pH $CaCl_2$**
cm	-----------------	%	-----------------	
0 -- 10	18	17	65	4.2
10 -- 20	18	17	65	4.1
20 -- 40	12	17	71	4.4

Table 2. Relationship between P_{M-3} and P_{M-1} extractants in the 0-10 and 10-20 cm depths of an Ultisol fertilized with increasing rates of poultry-litter

Soil layer (cm)	**fitted equation**	**R^2**
0 -- 10	$P_{M-3} = 8,64 + 0,98^{**}P_{M-1}$	0,99
10 -- 20	$P_{M-3} = -2,38 + 1,12^{**} P_{M-1}$	0,98

Soil available K was extracted with Mehlich-3 and K in the extract was analyzed by flame photometry. Exchangeable Ca^{2+}, Mg^{2+}, Na^+ and Al^{3+} were extracted with 1 mol L^{-1} KCl and then analyzed by atomic absorption, except Na^+, which was analysed by flame photometry. Total N and C in the soil samples and that in the poultry litter were analyzed by dry combustion in a continuous flow isotope ratio mass spectrometer (20-20 ANCA-GSL, Sercon, Crewe, UK).

Poultry litter (PL) was collected in poultry houses that had used it in one flock cycle in small farms in the vicinity of the experimental field. Poultry litter was analyzed for water soluble P (WSP) and total P. Total P was obtained by ignition-extraction. Shortly, the protocol consisted of igniting one gram of manure at 550 ºC for 2 h. The ignited sample was collected in a 50 mL centrifuge tube containing 40 mL of 1 mol L^{-1} H_2SO_4. Another sample (non-ignited) also was extracted in a similar way. Both samples (ignited and non-ignited) were, then, shaken overnight at 120 opm and, afterwards, filtered through a slow flow rate paper filter and an aliquot of the filtrate was taken for P determination by spectrophotometry following the phospho-molybdenum blue method (Murphy & Riley, 1962). Phosphorus in organic compounds (Po) was estimated as the difference between total P and orthophosphate, reactive P (Pi). WSP was obtained by shaking 0.25 g of PL in a centrifuge tube containing 30 mL of distilled deionized water during 2 h in a rotary set at 120 opm at 4 ºC. Following the centrifugation the tubes were centrifuged at 4 500 *g* for 15 min at 4 ºC and the supernatant was transferred to polyethylene bottles. The filtrates were appropriately diluted and analyzed for P by spectrophotometry. Total concentrations of K, Ca, Mg, Na, Fe, Mn and Zn were determined in aliquots from the ignited sample. Potassium and Na in the extracts were analyzed by flame photometry and the other elements were analyzed by atomic absorption. The chemical characteristics of PL are shown in Table 3.

Table 3. Total concentrations (dry mass basis) of C, Na and other mineral nutrients in the poultry litter

Element	Content
	----- g kg^{-1} -----
C	387
N	58
P*	9
K	170
Ca	20
Mg	3
Na	20
Zn	0,332

* Of the total P, 4 g kg^{-1} were water soluble

E. Reactive and unreactive dissolved phosphorus

Soil samples were analyzed for water dissolved P fractions by shaking soil samples in 50 mL centrifuge tubes with deionized water at a 1:10 soil:water ratio for 2 h in an rotary shaker at 120 opm at 4 ºC. Water dissolved P was determined colorimetrically in the filtrates after passing them through in a 0.45 µm cellulose acetate filter. This fraction is thereafter defined as dissolved reactive P (DRP). Total dissolved P (TDP) was obtained by digesting an aliquot of the filtrate with $K_2S_2O_8$ in acidic media (0.2 g of $K_2S_2O_8$ in 0.5 mol L^{-1} H_2SO_4) in an oven at ≈ 100 ºC overnight. The pH of the digested samples was adjusted to ≈ 4.5 and P was determined colorimetrically. The water dissolved unreactive P (DUP) fraction was obtained by subtracting DRP from TDP.

F. Degree of soil phosphorus saturation

The relative degree of soil P saturation (DPS_{M-3}) was estimated based on concentrations of P (cmol kg^{-1}), and Al plus Fe (cmol kg^{-1}) extracted by Mehlich-3 as follows:

$$\text{DPS (\%)} = \frac{P}{[\alpha\,(Fe + Al)]} \times 100$$

It was adopted an α value of 0.5 because it is most commonly used in studies with temperate region soils (Breeuwsma & Silva, 1992; Maguire et al., 2001; Nair et al., 2004), and it was aimed to compare our findings with those in the literature.

G. Statistical Analysis

Linear regression analysis was performed to each variable dataset. Comparisons between the soil layers were made using general linear regression models for each of the soil layers separately differences in residual variance were observed.

The PL dose that led to the maximum physical efficiency ($\hat{y}$ max) of grain yield was estimated based on equations that relate CGY to PL rates. The maximum economical yield was taken as the PL rate required to obtain a CGY equivalent to 0.9 $\hat{y}$ max. The relationship between P_{M-1} and P_{M-3} was modeled using linear regression according to Leite & Oliveira (2002).

RESULTS AND DISCUSSION

A. Grain yield as influenced by poultry litter rates

Corn grain yield was improved by the increasing PL rates in the three cropping years. Upward shifts in grain yields were also observed over the years (Figure 1). It was also observed that there was a significant residual effect of PL from one year to another because the PL rate required to reach 90 % of the maximum physical grain yield decreased in the second and third years as compared to the first year (Table 4).

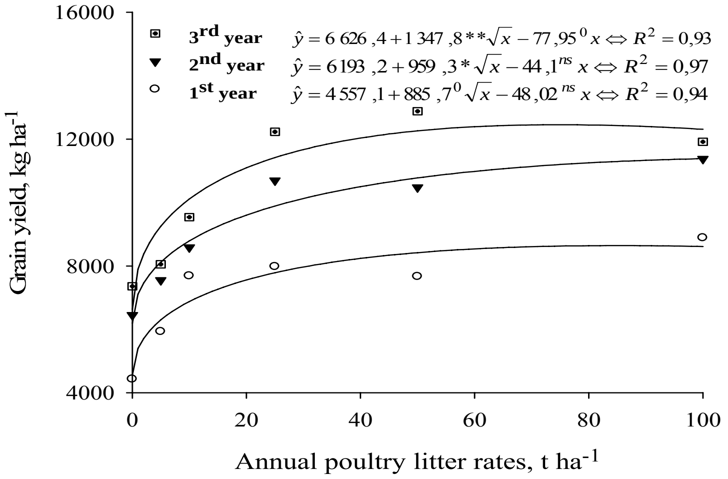


Figure 1. Corn grain yield as a function of annual poultry litter rates surface broadcast during three consecutive cropping years.

Besides the increase in grain yield along the PL rates in the first year, the gains in yield as a result of PL application were proportionally smaller in the second and third years, ranging from 4423 to 8880, 6450 to 11 377 and 7360 to 11914 kg ha^{-1}, representing maximum gains of 100.8, 76.4 and 61.9 % in comparison to the control, respectively, in the first, second and third years.

B. Nutrient concentration in leaves

There was an increase in nutrients concentration in corn leaves along the applied PL rates, except for Ca and Mg. Calcium concentration showed a positive quadratic response up to a PL rate of 25 t ha^{-1}, above which the concentrations decreased slightly with PL rates (Figure 2). When compared to the suggested range of optimum nutrient concentrations in corn leaves (Fancelli & Dourado Neto, 2000), K concentrations were well above the critical level, suggesting luxury consumption. Magnesium concentrations, on the other hand, were below the ideal concentration (Figure 2), even when the soil Mg was increased by high PL applications (Figure 3). Leaf P and N concentrations ranged within their adequate ranges when 5 and 10 t ha^{-1} PL was applied, but reached excessively high values, accumulating at excessive concentrations at higher PL rates. Zinc concentrations varied within its critical concentration. The decrease in nutrient contents at higher PL rates are a result of dilution, thus, indicating that only Mg seemed to have remained below the CL, possibly reflecting the low Mg content in the PL (Table 3). However, the increase in exchangeable Mg^{2+} in the soil along the PL rates (Figure 3) suggests a low efficiency in Mg acquisition by corn plants.

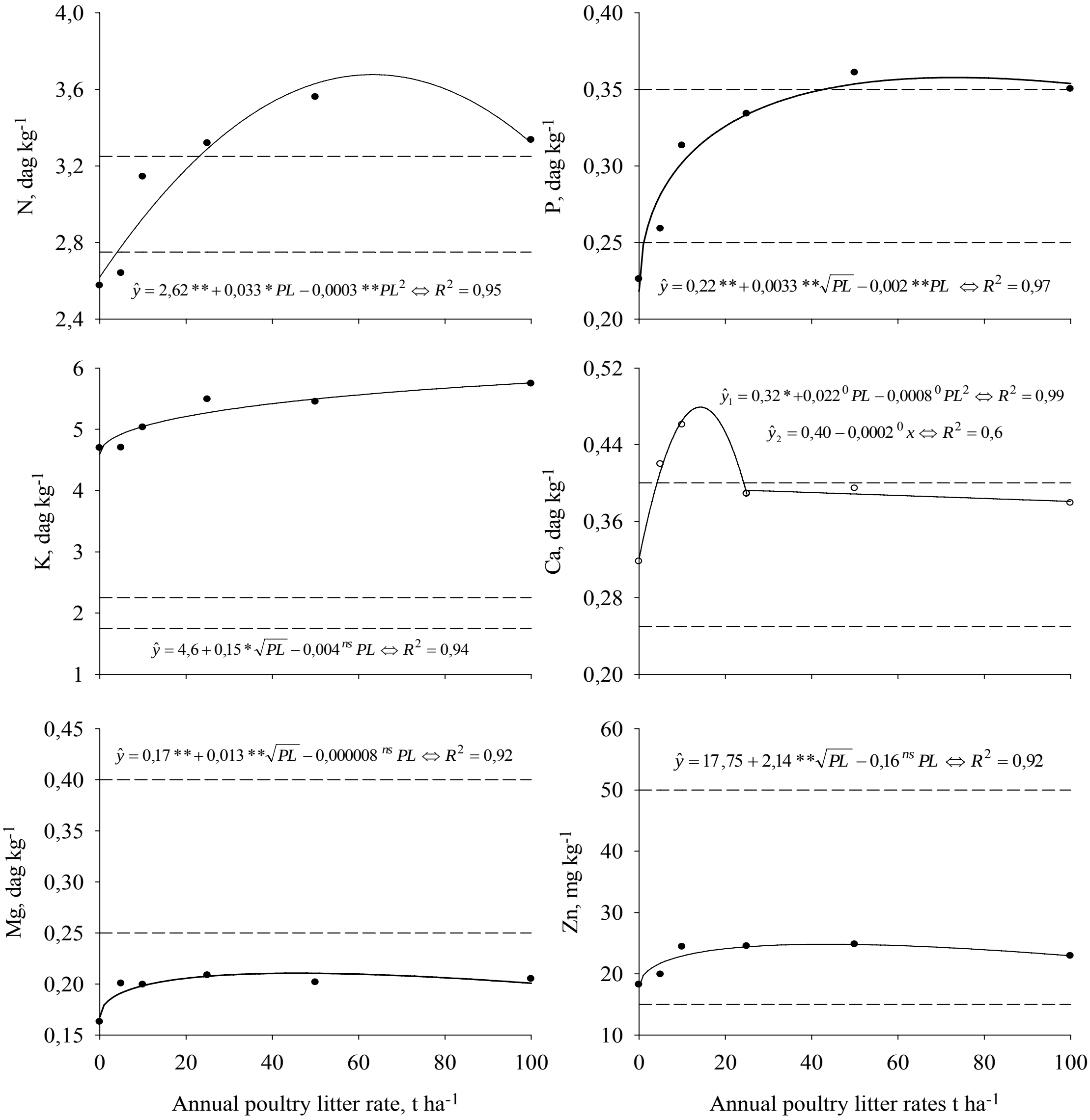


Figure 2. Nutrient concentration in corn leaves as influenced by annual poultry litter rates during three consecutive cropping years. The two parallel dashed lines encompass the range of nutrient concentration considered as ideal for corn plants (Fancelli & Dourado Neto, 2000).

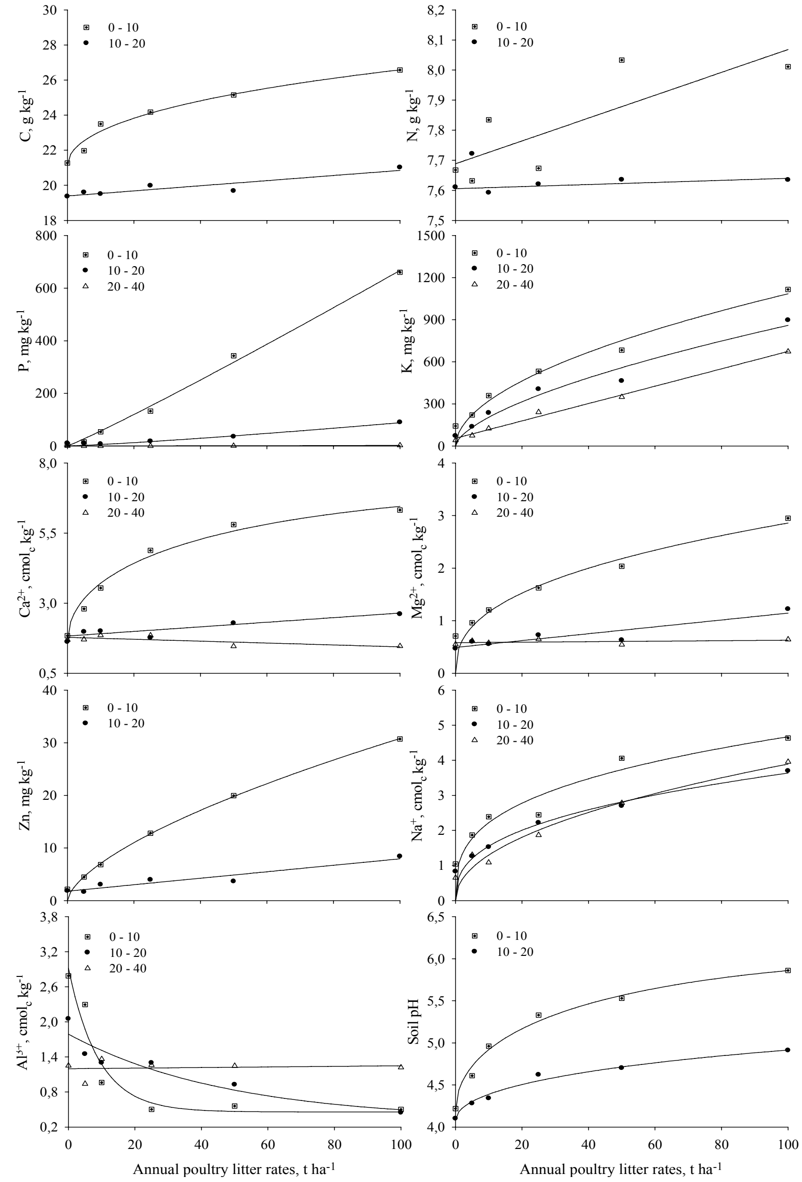
C. Soil chemical characteristics

The increase in PL rates led to greater nutrient concentration in the more superficial (0 to 10 cm) than in the deeper (10 to 20 cm) soil layer (Figure 3). The surface enrichment of nutrients was expected because of the consecutive surface application of PL and the no-tillage cultivation of corn. Mehlich-3 P ($P_{M\text{-}3}$)

concentrations increased up to 134 times in the 0-10 cm soil layer in comparison to the control treatment soil, reaching values over 600 mg kg^{-1}.

Potassium and Na were the mineral elements with the highest mobility along soil depth, followed by Mg^{2+} and Ca^{2+} (Figure 3). Only K and Na^{+} had their concentrations increased in the 20 to 40 cm soil layer. The high levels of exchangeable Na raise some concerns because it may interfere in plant nutrition and perhaps lead to increased soil dispersion and disaggregation (Thoma et al., 2007).

Soil pH also went up along the increments in PL rates and this might be largely credited for the decrease in Al^{3+} and it might have partially contributed for the increase in available and dissolved P concentrations in the soil. Soil pH probably increased due to the presence of $Ca(OH)_2$ in the PL as a consequence of its application on the floor of poultry houses.



Characteristic	0 -- 10	R^2	10 -- 20	R^2	20 --40	R^2
C	$\hat{y} = 21.15 + 0.64^{**}\sqrt{x} - 0.009^{ns}x$	99	$\hat{y} = \bar{y} = 20$	94		
N	$\hat{y} = 7.69 + 0.0038^{*}x$	80	$\hat{y} = 7.61 + 0.003^{*}x$	76		
P	$\hat{y} = 4.87x^{1.07^{**}}$	99	$\hat{y} = 0.34x^{1.21^{**}}$	98	$\hat{y} = \bar{y} = 0.67$	67
K	$\hat{y} = 94.97x^{0.53^{**}}$	98	$\hat{y} = 48.57x^{0.62^{**}}$	98	$\hat{y} = 54.75 + 6.19^{*}x$	99
Ca	$\hat{y} = 1.62 + 0.74^{*}\sqrt{x} - 0.03^{ns}x$	99	$\hat{y} = 1.83 + 0.008^{*}x$	94	$\hat{y} = \bar{y} = 1.67$	
Mg	$\hat{y} = 0.47x^{0.39^{*}}$	92	$\hat{y} = 0.49 + 0.007^{**}x$	94	$\hat{y} = \bar{y} = 0.60$	
Zn	$\hat{y} = 1.62x^{0.64^{**}}$	94	$\hat{y} = 1.78x^{0.06^{**}}$	85		
Na	$\hat{y} = 1.05x^{0.32^{**}}$	91	$\hat{y} = 0.66x^{0.37^{**}}$	94	$\hat{y} = 0.43x^{0.48^{**}}$	96
Al	$\hat{y} = 0.46 + 2.46^{**}e^{(-.011^{**}x)}$	97	$\hat{y} = 1.75e^{(-0.014^{**}x)}$	94	$\hat{y} = \bar{y} = 1.21$	
pH	$\hat{y} = 4.19 + 0.26^{**}\sqrt{x} - 0.009^{o}x$	99	$\hat{y} = 4.08 + 0.11^{**}\sqrt{x} - 0.002^{ns}x$	99		

Figure 3. Total carbon and nitrogen, and other soil chemical characteristics at increasing soil depths (0-10, 10-20, and 20-40 cm) (y) as affected by poultry litter rates (x) broadcast during three consecutive cropping years.

E. Mehlich-3 P, degree of soil P saturation and water soluble P

Available P ($P_{M\text{-}3}$) concentrations ranged from 5 to 660 and 10 to 89 mg kg^{-1}, respectively, in the 0 to 10 and 10 to 20 cm soil layers and they were highly related to the applied PL rates ($p < 0.001$). The degree of P saturation estimated with M3 ($DPS_{M\text{-}3}$) varied from 1 to 112 and 1 to 11 %, respectively, in these same soil layers (Figure 4 and 5b). No increment in $P_{M\text{-}3}$ and $DPS_{M\text{-}3}$ ($p > 0.1$) were observed for the 20 to 40 cm deep soil layer, even under high PL rates. The $P_{M\text{-}3}$ and $DPS_{M\text{-}3}$ values observed under high PL rates in the present study are well above the values considered of low risk to excessive P losses. A $P_{M\text{-}3}$ concentration range from 131 to 489 mg kg^{-1} in the 0 to 10 cm soil layer was achieved at the PL rate at which 0.9 $\hat{y}$ max was reached. This high soil P concentration, however, falls within a range of P concentration that several studies suggest to pose a high potential for P losses and contamination of water bodies (McDowell & Sharpley, 2001a,b; Sims et al., 2002; Abdala et al., 2007). This is supported by the observed increase in $DPS_{M\text{-}3}$ and soil WSP concentrations along the PL rates (Figure 5a). In fact, the increase in WSP concentrations in the surface soil layer were positive and highly related to the PL rates, varying from 0.8 to 50 mg kg^{-1} ($p < 0.001$), while in the 10 to 20 cm soil layer it was not significantly ($p > 0.1$) altered by the PL rates.

The relationship between $P_{M\text{-}3}$ and $DPS_{M\text{-}3}$ was linear with R^2 of 0.99 and 0.98 at the two soil depths, respectively (Figure 5).

Several authors (Breeuwsma & Silva, 1992; Nair et al., 2004) have demonstrated that DPS values up to 25 % were identified as contributing to ground water pollution with leached P. Sims et al. (2002) found that $DPS_{M\text{-}3}$ values ranging from 25 to 40 % and $P_{M\text{-}3}$ of 152 mg kg^{-1} represent an environmental threshold for P losses in a wide variety of less weathered soils of the Mid-Atlantic United States. Gebrim (2006) found that $P_{M\text{-}1}$ values of 150 mg dm^{-3} were an environmental threshold for P losses by leaching in a Brazilian Oxisol with a large P sorption capacity. For a PL rate of 21.7 t ha^{-1}, which is necessary to reach 90 % of maximum grain yield (0.9 $\hat{y}$ max), the $DPS_{M\text{-}3}$ would be only 21 % in the 0 to 10 cm layer because of the high content of pooly crystalline, ammonium oxalate-extractable, Fe and Al (4,550 mg kg^{-1}). In comparison, Sims et al. (2002) suggested a broader range of 25 to 40 % of $DPS_{M\text{-}3}$ for soils with a lower Fe_{ox} + Al_{ox} (1,810 mg kg^{-1}). This fact suggests that soil management and other soil characteristics, as organic matter content play an important role on P sorption other than simply the content of poorly crystalline Fe and Al.

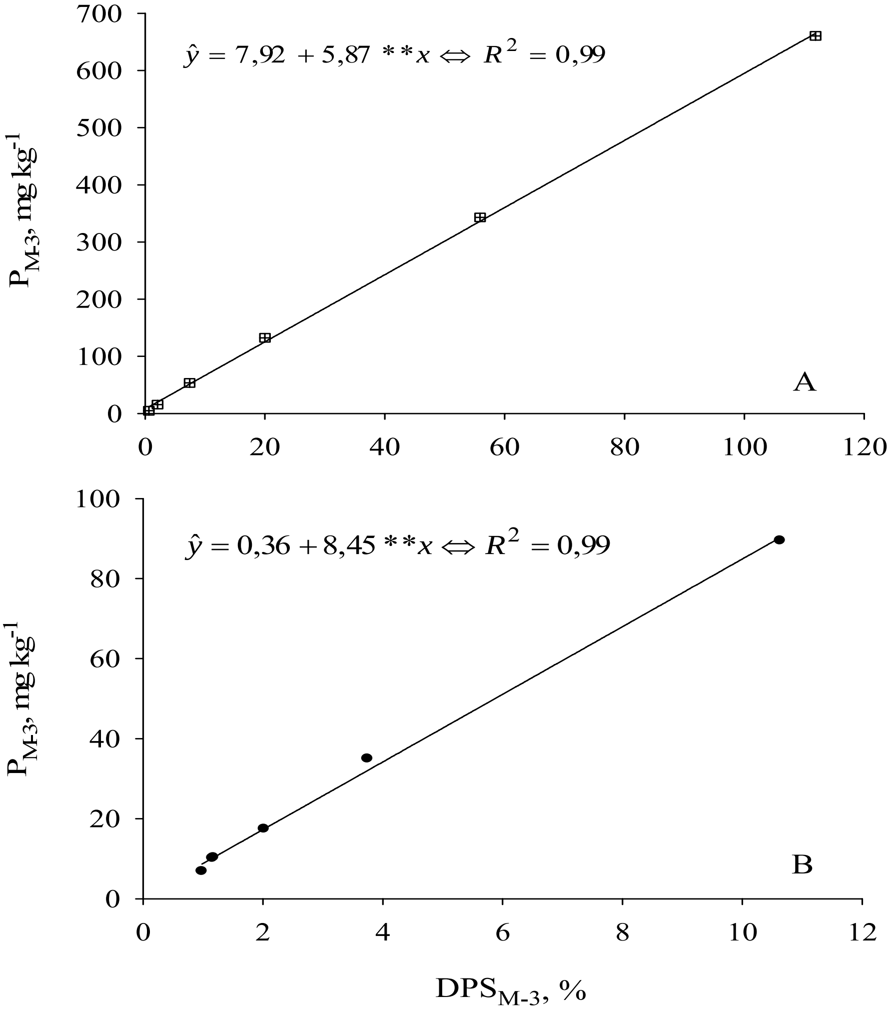


Figure 4. Mehlich-3 extractable phosphorus as a function of the degree of soil phosphorus saturation ($DPS_{M\text{-}3}$) at the 0 to 10 cm (A) and 10 to 20 cm (B) soil layers.

A curvilinear relationship was observed for WSP concentrations with increasing PL rates, possibly as a result of the saturation of P sorption sites, and single slope coefficients were greater for the dissolved reactive-P (DRP) than for dissolved unreactive-P (DUP) (Figure 4A).

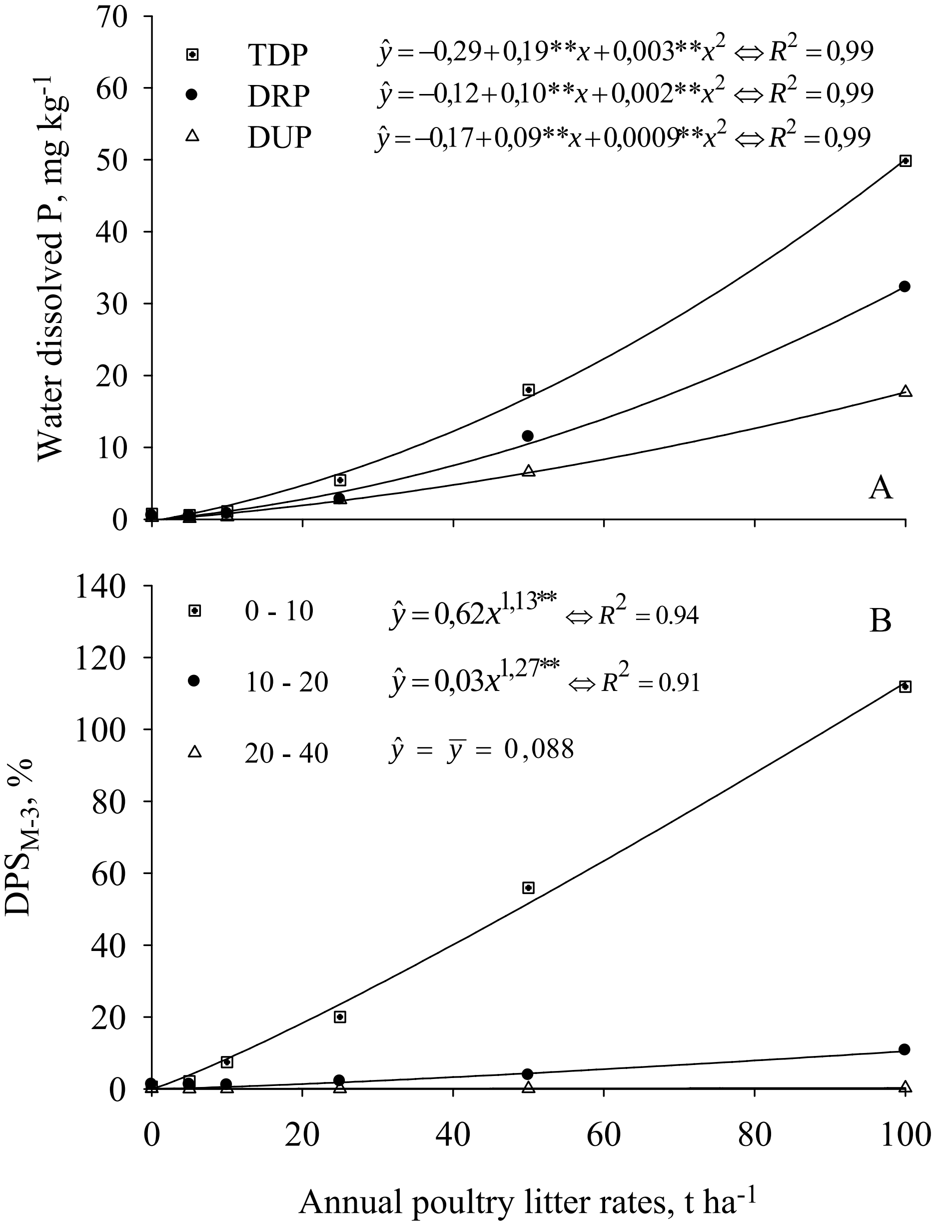


Figure 5. Water dissolved P fractions (TDP: total water dissolved; DRP: water dissolved reactive and DUP: water dissolved unreactive P) (A), and degree of soil P saturation (DPS_{M-3}) (B) as a function of increasing poultry litter rates applied during three consecutive cropping years.

Reactive P was found to be the dominant water dissolved P fraction across the applied PL rates, representing 66 % of TDP, while DUP accounted for only 34 % of TDP. These increases in WSP concentrations did not vary much across the PL rates (10 % st. dev) as more DUP (0.3 to 17.6 mg kg^{-1}) was expected to be more readily desorbable than DRP (0.5 to 32.3 mg kg^{-1}), especially at lower PL rates (Toor et al., 2004; Anderson & Magdoff, 2005; Gebrim, 2006). Soil pH seems to play a key role in this relationship, as its increase leads to a higher pH-dependant CEC in the colloids surface and, therefore, a lower anionic adsorption is expected to take place as pH is raised.

Water soluble P concentrations are usually highly related to increases in P_{M-3} (Bond et al., 2006) and DPS_{M-3} (Sims et al., 2002) in temperate, less weathered soils, and such relationship was also found in the present study (Figure 6) with an oxidic soil. Curvilinear relationships were also observed between WSP fractions across the P_{M-3} and DPS_{M-3} ranges, which does not match fully the concept of changing point or threshold values (split lines) proposed in previous research (Kleinman et al., 2000; Nair et al., 2004). However, it demonstrates that for each unit increase in P_{M-3} concentration or DPS_{M-3} leads to proportionally larger increments in WSP (Figure 6).

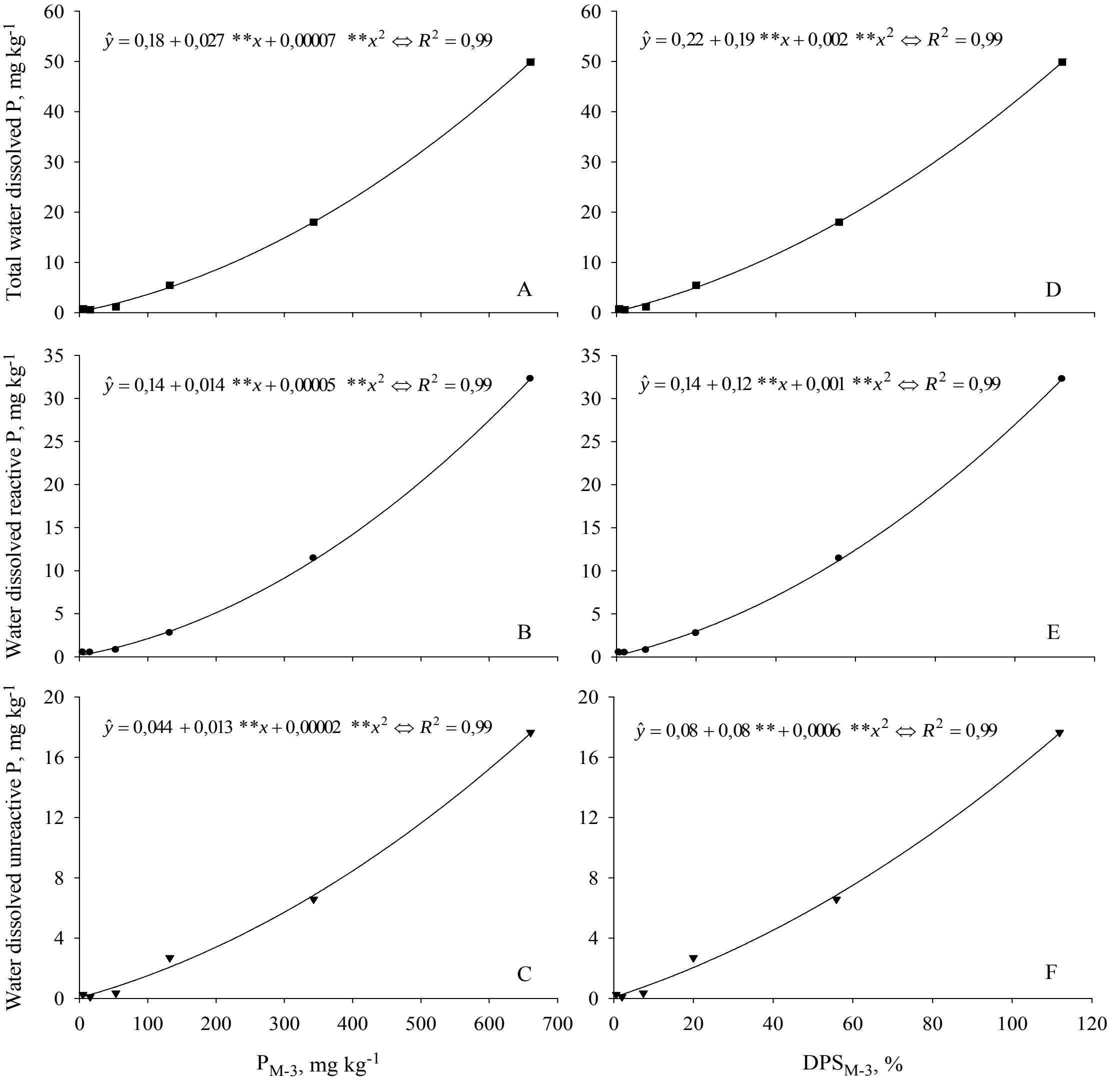


Figure 6. Total water dissolved P (A), water dissolved reactive (B) and unreactive P (C) as a function of Mehlich-3 extractable P ($P_{M\text{-}3}$). Total water dissolved P (D), water dissolved reactive (E) and water dissolved unreactive (F) P as a function of the degree of soil P saturation ($DPS_{M\text{-}3}$).

As the DPS and $P_{M\text{-}3}$ in soils should be ideally monitored in order not to reach excessively high values, it was assessed the relationship between both $P_{M\text{-}3}$ and $DPS_{M\text{-}3}$ with PL rates (Figures 4 and 5b). The equations that describe the above relationships were used to estimate the $DPS_{M\text{-}3,}$ and the $P_{M\text{-}3}$ concentration that would lead to WSP values above the critical value (> 1.0 mg L^{-1}). Thus, it was estimated that $DPS_{M\text{-}3}$ and $P_{M\text{-}3}$ values should not exceed 6.3 % and 28 mg kg^{-1} P, respectively, and the annual PL rate that would not lead to excessive WSP and reduced potential P loss is 5.1 t ha^{-1}, which is significantly lower than the 21.7 t ha^{-1} required to obtain the maximum yield. These results indicate that if PL rates are repeatedly applied using the sole criteria the maximization of corn grain yield, there certainly will be a point in time that P accumulation and risks to be lost to the environment will be exacerbated.

CONCLUSIONS

1. The repeated annual applications of PL improves soil fertility and corn nutrition, which results in greater grain yield and a substantial residual fertilization effect over time.

2. Fertilizing corn through poultry litter application to obtain maximum physical yield implicate in severe consequences towards the environment as the effects of such high PL rates were not only restricted to the topsoil, but also to deeper soil layers, as in the case of available K and exchangeable Na and, at a lesser extent, available P, exchangeable Mg and Ca.

3. An environmental $P_{M\text{-}3}$ threshold of 28 mg kg^{-1} is achieved with a PL rate of approximately 5.1 t ha^{-1}, which allows obtaining less than the maximum grain yield. However, a PL rates (21,7 t ha^{-1}) sufficient to obtain 90 % of the maximum grain yield, if reapplied annually, increases the degree of soil P saturation and total dissolved P, posing a serious risk for P losses to water bodies.

4. The analysis of water soluble P should be taken into account to predict and counteract P losses potential other than simply $P_{M\text{-}3}$ concentrations and the DPS thresholds.

REFERENCES

ABDALA, D. B.; SILVA, I. R; NOVAIS, R. F. & NUNES, F. N. Phosphorus mobility potential in a highly weathered soil fertilized with poultry litter under field conditions. In: XXXI CONGRESSO BRASILEIRO DE CIÊNCIA DO SOLO. Gramado-RS, 2007

ANDERSON, B.H. & MAGDOFF, F. R. Relative movement and soil fixation of soluble organic and inorganic phosphorus. J. Environ. Qual., 34:2228-2233, 2005.

ANUALPEC – Anuário da Pecuária Brasileira, São Paulo, FNP – Consultoria e Comércio. Years: 1999 and 2007.

ARAÚJO, C.; ZARATE, N. A. H. & VIEIRA, M. C. Produção e perda de massa pós-colheita de cenoura 'Brasília' considerando doses de fósforo e de cama de frango semi decomposta. Acta Scientiarum, 26:131-138, 2004.

AVIZOM – Associação dos Avicultores da Zona da Mata (MG) (Informação pessoal – José Davi Ervilha– Presidente), 2003.

BREEUSWMA, A., & S. SILVA. Phosphorus fertilization and environmental effects in the Netherlands and the Po region (Italy). Rep. 57. Agric. Res. Dep. The Winand Staring Centre for Integrated Land, Soil and Water Research. Wageningen, the Netherlands, 1992.

BOND, C. R.; MAGUIRE, R. O.; HAVLIN, J. L. Change in soluble phosphorus in soils following fertilization is dependent on initial Mehlich-3 phosphorus. J. Environ. Qual., 35:1818-1824, 2006.

COMISSÃO DE FERTILIDADE DO SOLO DO ESTADO DE MINAS GERAIS. Adubação Orgânica. *In*: Recomendações para o uso de corretivos e fertilizantes em Minas Gerais – 5ª aproximação. Ribeiro, A.C., Guimarães, P.T.G., Alvarez, V.H. (Eds.) Viçosa, MG, Cap. 12. 1999. p. 87-92.

CONSELHO NACIONAL DO MEIO AMBIENTE-CONAMA. RESOLUÇÃO 357, 2005.

COOPERBAND, L.; BOLLERO, G. & COALE, F. Effect of poultry litter and composts on soil nitrogen and phosphorus availability and corn production. Nutr. Cyc. Agroec., 62:185-194, 2002.

FANCELLI, A. L. & DOURADO NETO, D. Produção de milho. Guaiba-SP, Editora Agropecuária, 2000, 360p.

GEBRIM, F. O. Lixiviação de fósforo, bases, ânions inorgânicos e ácidos orgânicos em solos tratados com camas de aviário. Tese de Mestrado (Solos e Nutrição de Plantas). Universidade Federal de Viçosa, Viçosa, 2006. 95 p.

KLEINMAN, P. J. A.; BRYANT, R. B.; REID, W. S.; SHARPLEY, A. N. & PIMENTEL, D. Using soil phosphorus behavior to identify environmental thresholds. Soil Sci., 165:943-950, 2000.

LEITE, H. G. & OLIVEIRA, F. T. Statistical procedure to test the identity of analytical methods. Commun. Soil Sci. Plant Anal., 33:1105-1118, 2002.

MAGUIRE, R. O.; FOY, R. H.; BAILEY, J. S. & SIMS, T. J. Estimation of the phosphorus sorption capacity of acidic soils in Ireland. Eur. J. Soil Sci., 52:479-487, 2001.

MAGUIRE, R. O. & SIMS, J. T. Measuring agronomic and environmental soil phosphorus saturation and predicting phosphorus leaching with Mehlich-3. Soil Sci. Soc. Am. J., 66:2033–2039, 2002ª.

MAGUIRE, R. O. & SIMS, J. T. Soil testing to predict phosphorus leaching. J. Environ. Qual. 31:1601–1609, 2002b.

MCDOWELL, R. W. & SHARPLEY, A. N. Approximating phosphorus release from soils to surface runoff and subsurface drainage. J. Environ. Qual., 30:508-520, 2001a.

MCDOWELL, R. W. & SHARPLEY, A. N. Phosphorus losses in subsurface flow before and after manure application to intensively farmed land. Sci. Total Environ., 278:113-125, 2001b.

MEHLICH, A. Determination of P, Ca, Mg, K, Na, and NH_4. Soil testing division publication. North Carolina Department of Agriculture, Raleigh, NC. pp. 1–53, 1953.

MEHLICH, A. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal., 15:1409–1416, 1984

MOTAVALLI, P. P.; ANDERSON, S.H. & PENGTHAMKEERATI, P. Surface compaction and poultry litter effects on corn growth, nitrogen availability, and physical properties of a claypan soil. Field Crops Res., 16:303-318, 2003.

MURPHY, J. & J.P. RILEY. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta, 27:31–36, 1962.

NAIR, V.D., GRAETZ, D.A. & REDDY, K.R. Dairy manure influences on phosphorus retention capacity of Spodosols. J. Environ. Qual., **27:**522–527, 1998.

NAIR, V. D. & GRAETZ, D. A. Phosphorus saturation in Spodosols impacted by manure. J. Environ. Qual., 31: 1279–1285, 2002.

NAIR, V. D.; PORTIER K. M.; GRAETZ, D. G. & WALKER, M. L. An Environmental threshold for degree of phosphorus saturation in sandy soils. J. Environ. Qual., 33: 107–113, 2004.

NOVAIS, R. F. & KAMPRATH, E. J. Phosphorus supplying capacities of previously heavily fertilized soils. Soil Sci. Soc. Am. J., 42:931-935, 1978.

PAUTLER, M. C. & SIMS, T. J. Relationships between soil test phosphorus, soluble phosphorus and phosphorus saturation in Delaware soils. Soil Sci. Soc. A. J., 64:765-773, 2000.

RUIZ, H. A. incremento da exatidão da análise granulométrica do solo por meio da coleta da suspensão (silte + argila). R. Bras. Ci. Solo, 29:297-300, 2005

SISTANI, K. R.; SIKORA, F. J. & RASNAKE, M. Poultry litter and tillage influences on corn production and soil nutrients in a Kentucky silt loam soil. Soil Till. Res., 98:130-139, 2008.

SHARPLEY, A. N.; MCDOWELL, R. W. & KLEINMAN, P. J. A. Phosphorus loss from land to water: integrating agricultural to environmental management. Plant and Soil, 237:287-307, 2001

SIMS, J. T.; EDWARDS, A. C.; SCHOUMANS, O. F. & SIMARD, R. R. Integrating soil phosphorus testing into environmentally based agricultural management practices. J. Eviron. Qual., 29:60-72, 2000.

SIMS, J. T.; MAGUIRE, R. O.; LEYTEM A. B.; GARTLEY, K. L. & PAUTLER, M. C. Evaluation of Mehlich-3 as an agri-environmental soil phosphorus test for the Mid-Atlantic United States of America. Soil Sci. Soc. Am. J., 66:2016–2032, 2002.

SOUZA, C.R. Biodisponibilidade e transformações de formas de fósforo em camas de aviário por meio de fracionamento químico e ressonância magnética nuclear do

31P. Tese de mestrado. (Solos e Nutrição de Plantas). Universidade Federal de Viçosa, Viçosa, 2004. 76p.

THOMA, A. P. M.; FERNANDES, R. B. A.; ABDALA, D. B. & SILVA, I. R. Efeito da adição de cama de aviário sobre as características físicas de um Argissolo. In: XXXI CONGRESSO BRASILEIRO DE CIENCIA DO SOLO, Gramado-RS, 2007.

TOOR, G. S.; CONDRON, L. M.; DI, H. J. & CAMERON, K. C. Seasonal fluctuations in phosphorus loss by leaching from a grassland soil. Soil Sci. Soc. Am. J., 68:1429-1436, 2004.

USEPA-UNITED STATES ENVIRONMENTAL PROTECTION AGENCY. The quality of our nation's water. A summary of the national water quality inventory: 1998 Report to Congress. EPA 841-S-00-001, 2000.

VAN DER ZEE, S. E. A. T. M.; FOKKINK, L. G. J. & VAN RIEMSDIJK, W. H. A new technique for assessment of reversibly adsorbed phosphate. Soil Sci. Soc. Am. J., 51: 599–604, 1987.

ZARATE, N. A. H.; VIEIRA, M. C. & BRATTI, R. Efeitos da cama de frangos e da época de colheita sobre a produção e a renda bruta da cebolinha "Todo Ano". Pesq. Agrop. Trop., 33: 73-78, 2003ª.

ZARATE, N. A. H. & VIEIRA, M. C. Produção do milho doce *cv*. Superdoce em sucessão ao plantio de diferentes cultivares de inhame e adição de cama-de-frango. Hortic. Bras., 21:05-09, 2003b.