

Article - Agronomy/Soil Science

# Does Dairy Liquid Manure Complementary to Mineral Fertilization Increase Grain Yield Due to Changes in Soil Fertility?

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## HIGHLIGHTS

- Manure application in agricultural soils is common in livestock production regions.
- Dairy manure application increased the crop grain yield.
- Dairy manure even applied on soil surface provided chemical improvements in deep layers.
- Balance between the soil bases and the acidity is fundamental for maximum yield.

**Abstract:** The main destination of manure is the application to croplands near livestock farms as nutrient source to enhance crop production. The aim of this study was to define the dairy liquid manure (DLM) dose, complementary to the mineral fertilizer, for higher crops yield, in rotation black oat-maize-wheat-soybean, and to identify the soil chemical variables improved by the manure that most affect the yield, in long-term. The experiment was conducted from 2006 to 2015, in no-tillage system, at Paraná State, Brazil. The soil was a Latossolo Bruno Distrófico típico, clayey texture. The treatments consisted by doses of DLM (0, 60, 120 and 180 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>), complementary to the mineral fertilizer (applied in the same amount for all DLM doses). Crops yield and soil chemical variables were evaluated at six depths (0-10; 10-20; 20-30; 30-40; 40-50 and 50-60 cm). The DLM application increased the yield of all crops, but not in all harvests. The DLM even applied at soil surface improved the soil chemical variables in deep layers, resulting in high positive

correlation between yield and exchange bases, P, Zn and Mn contents, and high negative correlation with Ca/Mg ratio and potential acidity at depth 0-10 cm. The DLM dose, complementary to the mineral fertilization, that provided higher soybean and wheat yield was about  $130 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ , while for maize this dose was equal to or greater than  $180 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ . This effect was not attributed to a single chemical variable but the improvement of all chemical variables evaluated.

**Keywords:** organic fertilizer; no-tillage; *Zea mays*; *Glycine max*; *Triticum aestivum*; *Avena strigosa*.

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## INTRODUCTION

The Brazilian livestock sector stands out in the world ranking, presenting the third largest herd of dairy cows (approximately 20 million cows milked in 2016). In relation to the milk production, Brazil occupies the fifth position, and, Paraná state, Southern Brazil, is the second largest national milk producer, with 14.1% of production in 2016 [1]. When the livestock production is based on intensive confinement system, it results in large volumes of manure, which the main destination is the application in croplands. The benefits of applying manure to agriculture are worldwide known. Manure application improves chemical, physical and biological soil properties, and consequently, crop growth and yield, either alone or in association with mineral fertilizers [2-7].

The increasing of the world population requires increases in food production. Thus, in order to preserve the environment and the natural resources, the increases in food production must be accompanied by adequate fertilization management. In intensive milk production systems, most producers apply high rates of manure, associated with mineral fertilization, without considering the amount of nutrients applied [3,8]. The application of manure is usually near to the livestock farm, due to the high transportation cost. It is known that improper use of manure can cause surface and groundwater pollution. Thus, the key to a proper manure management is to balance application rates with crop nutrient needs [9].

In this context, studies should be carried out to help farmers on recommendations of best management practices to reach a sustainable agriculture. In addition, results from long-term experiments are very important to optimize applications, to maximize agricultural production and to minimize environmental impacts such as the water pollution [2,10]. Based on that, this study was conducted in a long-term experiment under no-tillage system with application on the soil surface of dairy liquid manure (DLM) complementary to the mineral fertilizer to define the best DLM dose for higher crops yield, and to identify the soil chemical variables improved by the manure that most affect the yield.

## MATERIAL AND METHODS

The experiment was conducted at experimental station of the ABC Research Foundation, located at Castro ( $24^{\circ}51'50''\text{S}$ ,  $49^{\circ}56'25''\text{W}$ , 1027 m altitude). The soil of the area, clayey texture with 10% slope, was classified as Latossolo Bruno Distrófico típico according to Brazilian Soil Classification System (SiBCS) [11], which corresponding to Oxisol in the American Soil Taxonomy System. The regional climate is classified as Cfb-humid subtropical climate mesothermal (Köppen), with mild summers and an average annual rainfall of 1,554 mm, without a dry season [12].

The installation of the experiment was in May 2006, in an area where no-tillage system had been practiced for more than 15 years. The treatments consisted of four annual rates of DLM (0, 60, 120,  $180 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ ). The experimental design was a randomized complete block design, with four replications, and plots were  $29.8 \text{ m}^2$  (3.5 m by 8.5 m). Each annual DLM rate was applied on the soil surface, without incorporation, and split into two applications: half in the winter crop and half in the summer crop. The soil properties are presented in Table 1 (adapted from [13]).

**Table 1.** Chemical properties and particle size distribution of the soil before the beginning of the experiment (0-10, 10-20 and 20-30 cm).

pH	OC <sup>(1)</sup>	H+Al	Ca	Mg	K	CEC <sup>(2)</sup>	Al	P <sup>(3)</sup>	Clay	Sand	Silt
CaCl <sub>2</sub>	g kg <sup>-1</sup>					cmol <sub>c</sub> kg <sup>-1</sup>		mg kg <sup>-1</sup>		g kg <sup>-1</sup>	
<b>0-10 cm</b>											
5.4	29.3	4.6	5.6	1.7	0.30	12.2	0.0	5.5	691	195	114
<b>10-20 cm</b>											
5.3	22.0	4.6	4.5	1.0	0.16	10.1	0.0	2.5	712	179	109
<b>20-30 cm</b>											
5.4	19.0	4.0	3.9	0.8	0.10	8.8	0.0	1.0	725	99	176

<sup>(1)</sup> OC: organic carbon; <sup>(2)</sup> CEC: cation exchange capacity; <sup>(3)</sup> P- Mehlich-1.

The dry matter and N, P and K content of the DLM applied since the beginning of the experiment (2006–2015) are presented in Table 2 (adapted from [8,14]). The amount of N, P and K (annual average for winter plus summer crops) applied by DLM were: 122, 39 and 169 kg ha<sup>-1</sup> year<sup>-1</sup>; 244, 79 and 338 kg ha<sup>-1</sup> year<sup>-1</sup> and; 367, 118 and 508 kg ha<sup>-1</sup> year<sup>-1</sup> for the doses 60, 120 and 180 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>, respectively. The DLM, a material constituted of feces, urine and water of cleaning, stored in lagoons, came from a farm with the production based on a free stall system of holstein cows. Besides DLM, mineral fertilizers (NPK) were applied (with the exception of black oat crop) in the same amount for all treatments following the soil test and grain crop needs [15]. The amount of N, P and K applied in the different harvests (winter/summer) via mineral fertilization from year 2006-2015 are presented in Table 3 [14]. Mineral fertilization was performed with NPK formulations in-furrow at sowing and with simple fertilizers (urea and KCl) in top-dressing. The average amount for N, P and K, respectively, applied to maize crop was 174, 39 and 70 kg ha<sup>-1</sup>, to soybean crop was 0, 25 and 48 kg ha<sup>-1</sup> and to wheat crop was 122, 30 and 55 kg ha<sup>-1</sup>. In May 2007 and Aug 2013 liming was carried out using 2,500 and 1,900 kg ha<sup>-1</sup> of dolomitic limestone, respectively.

**Table 2.** Chemical properties of the dairy liquid manure (DLM) applied from year 2006-2015 for the experimental area.

Date	Dry matter	N	P	K			
	g L <sup>-1</sup>	g L <sup>-1</sup>	kg m <sup>-3</sup>	g L <sup>-1</sup>	kg m <sup>-3</sup>	g L <sup>-1</sup>	kg m <sup>-3</sup>
May-06	90.5	1.82	0.91	0.77	0.39	3.46	0.39
Oct-06	75.5	1.74	0.87	0.61	0.31	2.35	0.31
May-07	43.3	0.95	0.48	0.41	0.21	1.48	0.21
Nov-07	89.6	2.02	1.01	0.72	0.36	3.04	0.36
Aug-08	87.1	1.75	0.88	0.61	0.31	2.85	0.31
Jan-09	46.7	1.10	0.55	0.32	0.16	1.57	0.16
Aug-09	51.0	0.94	0.47	0.56	0.28	1.20	0.28
Nov-09	44.9	2.60	1.30	0.92	0.46	1.91	0.46
Jul-10	85.5	1.56	0.78	0.70	0.35	3.22	0.35
Jan-11	93.1	1.74	0.87	0.84	0.42	4.14	0.42
Aug-11	113.0	2.29	1.15	0.83	0.42	4.19	0.42
Nov-11	94.0	1.85	0.93	0.69	0.34	3.71	0.34
Aug-12	87.3	2.23	1.11	0.65	0.33	4.09	0.33
Jan-13	73.7	1.56	0.78	0.54	0.27	0.13	0.27
Jun-13	79.1	1.66	0.83	0.61	0.31	3.91	0.31
Nov-13	71.1	1.44	0.72	0.43	0.22	3.27	0.22
Jul-14	94.5	5.20	2.60	0.87	0.44	2.74	0.44
Jan-15	91.4	4.20	2.10	0.70	0.35	3.49	0.35
Average	78.4	2.04	18.33	0.65	5.88	2.82	5.88
Standard <sup>(1)</sup>	69.0	1.56	1.02	0.55	0.33	2.80	0.33

<sup>(1)</sup> The standard is the average was presented of dairy liquid manure collected in Paraná State [14].

**Table 3.** Amount of nitrogen (N), phosphorus (P) and potassium (K) applied in the different harvests (winter/summer) via mineral fertilization from year 2006-2015.

Crop	Harvest	kg ha <sup>-1</sup>		
		N	P	K
Black oat	2006	0	0	0
Maize	2006/07	175	37	93
Black oat	2007	0	0	0
Soybean	2007/08	0	26	50
Wheat	2008	114	39	59
Soybean	2008/09	0	22	42
Black oat	2009	0	0	0
Maize	2009/10	175	41	63
Wheat	2010	134	30	63
Soybean	2010/11	0	26	50
Black oat	2011	0	0	0
Maize	2011/12	165	39	50
Wheat	2012	120	26	50
Soybean	2012/13	0	26	50
Black oat	2013	0	0	0
Maize	2013/14	183	41	75
Wheat	2014	120	26	50
Soybean	2014/15	0	26	50
Total		1,186	405	745

The experiment was carried out in no-tillage system, during nine agricultural years, between 2006 and 2015, with crop rotation constituted of black oat (*Avena strigosa* Schreb.) and wheat (*Triticum aestivum* L.) in the winter and soybean (*Glycine max* (L.) Merr.) and maize (*Zea mays* L.) in the summer. Row spacings were 0.8, 0.4 and 0.17 m for maize, soybean and winter crops (wheat and black oat), respectively. Grain yield and dry matter yield was determined by harvesting 14 rows of 2 m in winter crops and 8 rows of 2 m in summer crops. Grain weight was corrected to 13% humidity and values were converted to kg ha<sup>-1</sup>.

Thus, five black oat, four wheat, four maize and five soybean harvests were evaluated. Data from each harvest and also from the average were analyzed. Besides, accumulated grain yield for maize, soybean and wheat was calculated by adding the subsequent harvest of the each crop, and also it was evaluated the total accumulated grain yield by adding all grain harvests of the period, totaling 13 harvests.

In July 2014, soil samples were collected at six depths (0-10; 10-20; 20-30; 30-40; 40-50; 50-60 cm) with the aid of an auger sampler. Each sample was composed by ten subsamples. All soil samples were air-dried and sieved through a 2-mm mesh sieve. Soil pH was determined in a 0.01 mol L<sup>-1</sup> CaCl<sub>2</sub> suspension (1:2.5 v/v soil/solution); potential acidity (H+Al) was estimated after pH reading with the addition of SMP buffer solution to soil samples, using correlation with SMP index [17]; organic carbon was determined by the colorimetric method and organic matter carbon was calculated multiplying the organic carbon content by 1.724; soil phosphorus was extracted using anion exchange resin; calcium, magnesium and potassium was extracted using cation exchange resin [15]. Based on these results, the calcium/magnesium ratio, base saturation and cation exchange capacity (CEC) were calculated.

The results were submitted to analysis of variance and regression equations. The means of soil chemical variables were compared by the Tukey test at the 5% probability level. Principal component analysis was carried out using accumulated grain yield data (maize, soybean, wheat and total) and soil chemical variables at depth 0-10 cm. The software R was used.

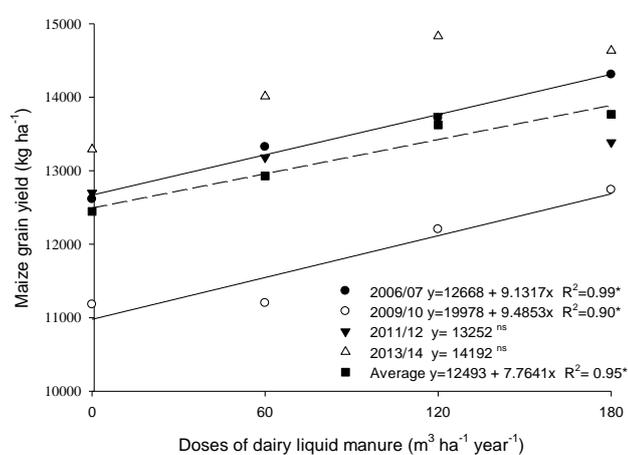
## RESULTS AND DISCUSSION

### Crops yield

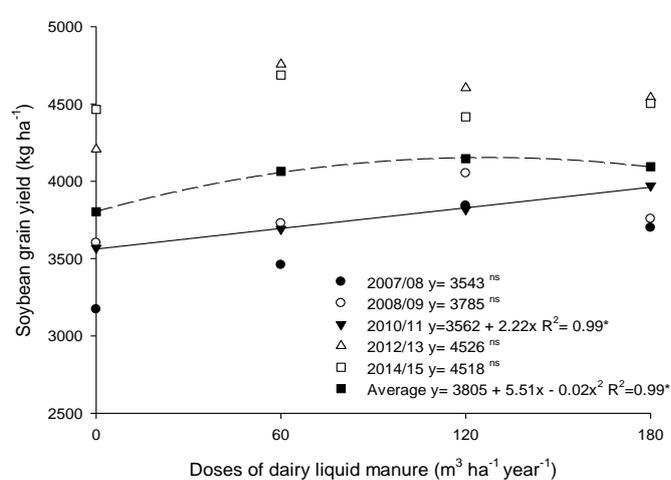
The DLM application linearly increased maize grain yield in the 2006/07, 2009/10 and average harvests (Figure 1a), being 13%, 13% and 10% higher, respectively, with the application of 180 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> compared to the control. On the other hand, the DLM application did not influence the maize yield in the 2011/12 and 2013/14 harvests (Figure 1a). The increase in maize grain yield may be related to the additional N supplied by the manure, suggesting that the added mineral N (175 kg ha<sup>-1</sup> in both harvests) was not enough

to obtain the maximum crop potential. However, in the 2011/12 and 2013/14 harvests, the N supplied by the mineral source may have been enough, reducing the effects of manure [18]. In addition, the higher response of maize at the beginning of the experiment may be due to the low P content in the area before to the installation of the experiment (Table 1) [16], thus, the additional supply of P by DLM may have contributed to the increase of crop yield, evidenced by the strong positive correlation between P content and average maize yield ( $r=0.82$ ). Other papers have found similar results, associating organic fertilizers with mineral fertilizers, attributing increased yield to higher nutrient availability and, consequently, greater extraction by plants [7,19,20].

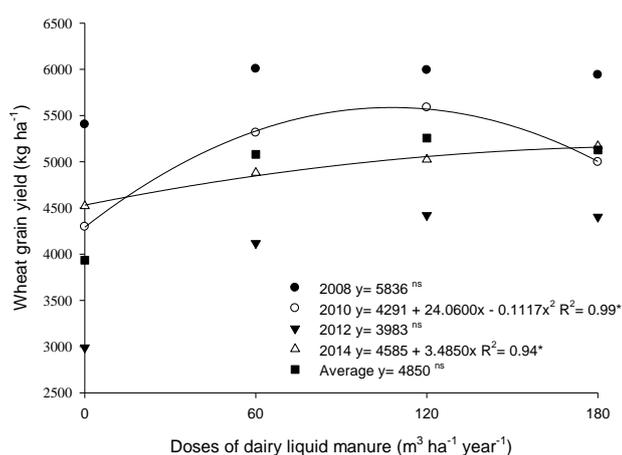
For soybean, in the 2010/11 harvest, the DLM application linearly increased the grain yield (Figure 1b), with 11% increment. On the other hand, for other harvests, the DLM not improved the soybean grain yield. The average of all harvests increased with DLM application, adjusting to a second degree polynomial function (Figure 1b), and the estimated dose for maximum yield was  $126 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  (9% increment). Other studies also found increased soybean yield by combining organic and mineral fertilizer [9,21,22].



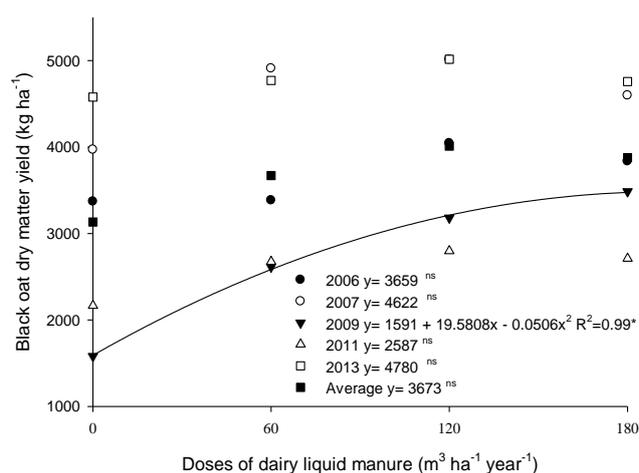
(a)



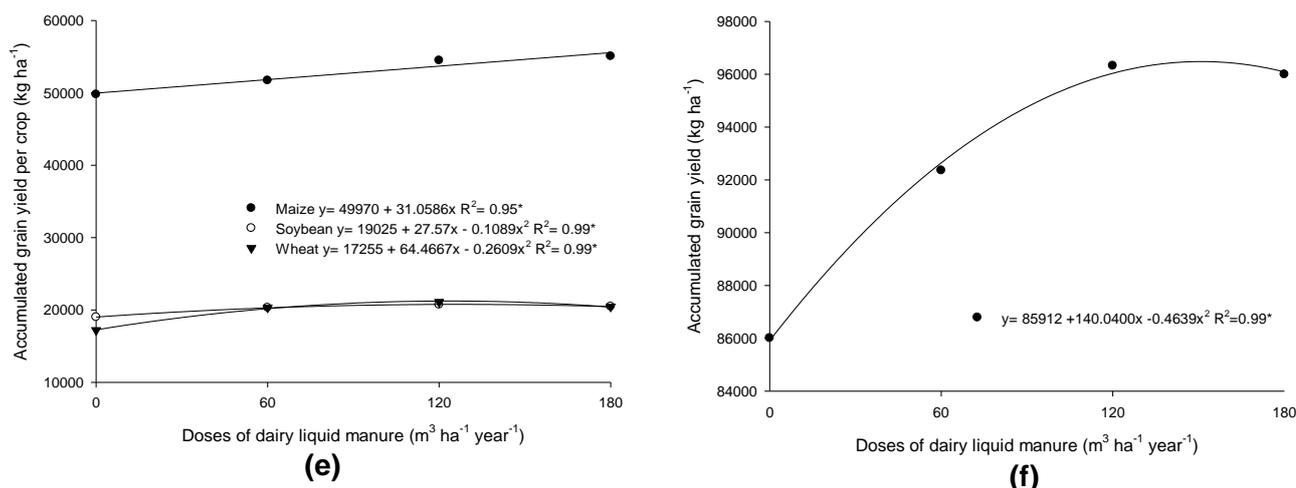
(b)



(c)



(d)



**Figure 1.** Maize (a), soybean (b), wheat (c) and black oat (d) yield per harvest and average of harvests; accumulated grain yield per crop (e) and total accumulated grain yield (maize+soybean+wheat) in the period 2006-2015 (f) as a function of dairy liquid manure (DLM) doses (0, 60, 120 and 180 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>) in no-tillage system, in Castro-Paraná.

Relative to winter crops, the wheat grain yield increased with DLM application in 2010 and 2014 harvests. On the other hand, in the other harvests and in the average of harvests there was no effect of manure application (Figure 1c). In the 2010 harvest, the estimated dose for maximum wheat yield was 108 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>, with 30% increment compared to the control treatment, however in the 2010 and 2014 harvests, the increment was only 14%. In agreement with these data, other authors [20,23] observed that the association of mineral fertilizer with manure increased wheat yield. About the black oat, the DLM application increased the dry matter only in the 2009 harvest, with 120% increment (Figure 1d). The lower response of black oat may be due to N supply from the predecessor crop (soybean) [18]. However, as previously described, in the 2009 harvest, the black oat dry matter yield was improved by DLM application; the dry matter yield in the control treatment in the 2009 harvest was very low (1,581 kg ha<sup>-1</sup>) compared to the average of the control treatment of other harvests (3,521 kg ha<sup>-1</sup>). The lower yield in 2009 probably was associated with factors such as precipitation, temperature, solar radiation and diseases. Thus, the improvement of soil physical, chemical and biological properties with manure application may have compensated this adverse condition, favoring plant development and, consequently, its dry matter yield.

The DLM application in the nine-year period showed great variation on crop yield among the harvests. One reason could be the great variation of the manures applied in the nine-year period in each crop season (Table 2), as well as weather conditions that may vary, influencing the response of the application [24].

Regarding to the accumulated grain yield of each crop, there was a linear increase for maize (10%) and quadratic increase for soybean (9%) and wheat (23%) (Figure 1e). The estimated dose for maximum yield was 127 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> and 123 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>, for soybean and wheat respectively. The linear response of maize, even with low increment (10%) and higher response of wheat with 23% increment, species of the *Poaceae* family, is explained by the additional supply of N with manure application. The higher addition of nitrogen by mineral fertilizer in the maize crop compared to the wheat crop may explain the lower increment of maize with manure application. Also, the lower maize yield increment compared to wheat may be associated with plant lodging by excessive N inputs [25]. The soybean resulted in lower response (9% increment), possibly because in this crop the N is supplied via biological fixation [18]. However, the other benefits by manure application improved the soybean grain yield up to 127 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> DLM. The higher response of maize and wheat in relation to soybean has been observed with application of swine manure doses [21].

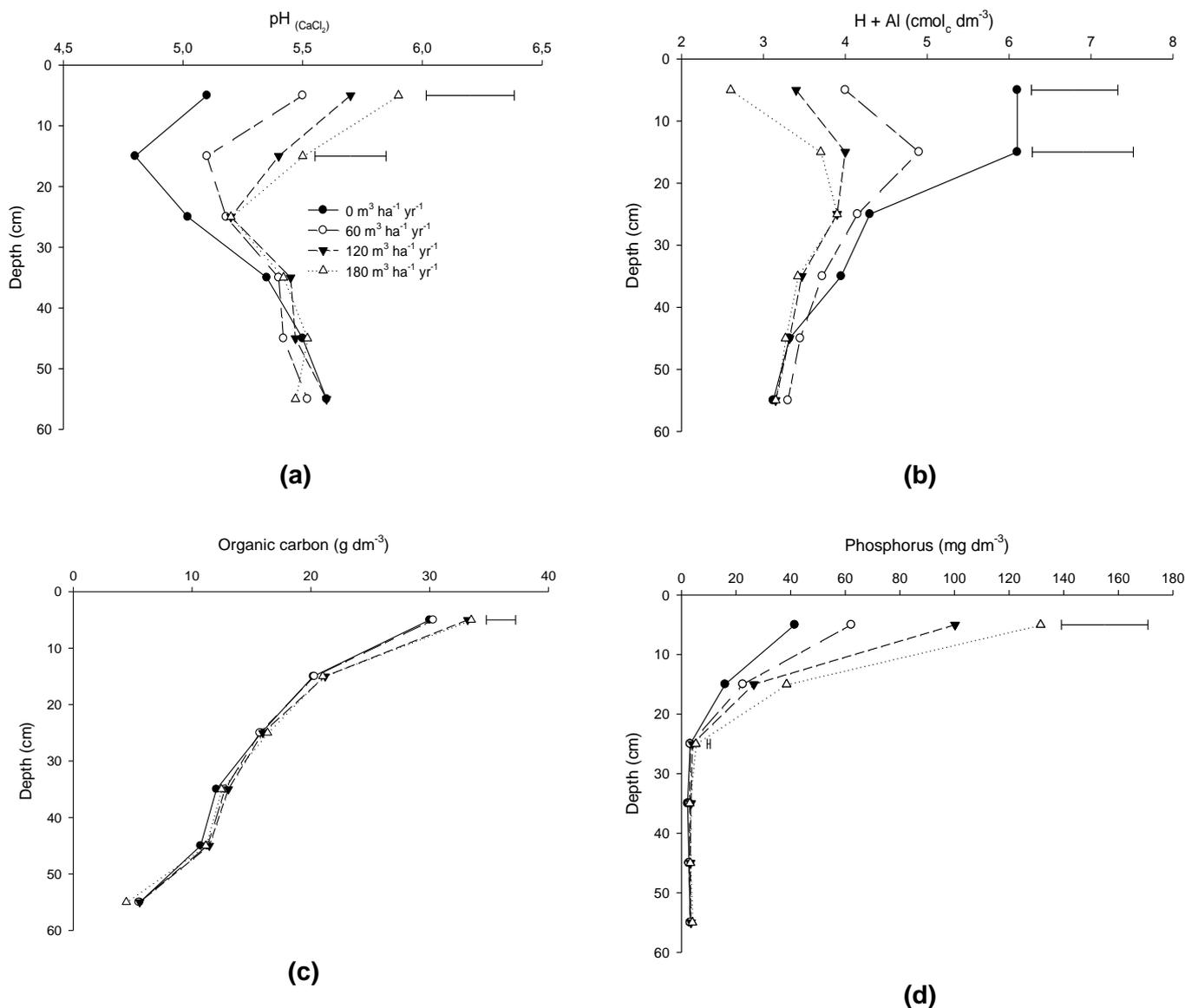
The total accumulated grain yield (all crops) in the nine-year period (2006-2015) increased up to 151 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> DLM dose (Figure 1f), resulting in 12% increment compared to the control treatment (without DLM application). Combining mineral and organic fertilizers, the nutrients are slowly but continuously supplied reaching the need for crops. Also, there is the supply of readily available macro and micronutrients, resulting in better growth and grain yield [23]. Beyond the chemical aspect, the better crop yield with the balanced application of organic and mineral fertilizer can be attributed to improvements in soil physical and biological properties [5,6,19,26]. The integrated use of manure with mineral fertilizers increased soybean and wheat

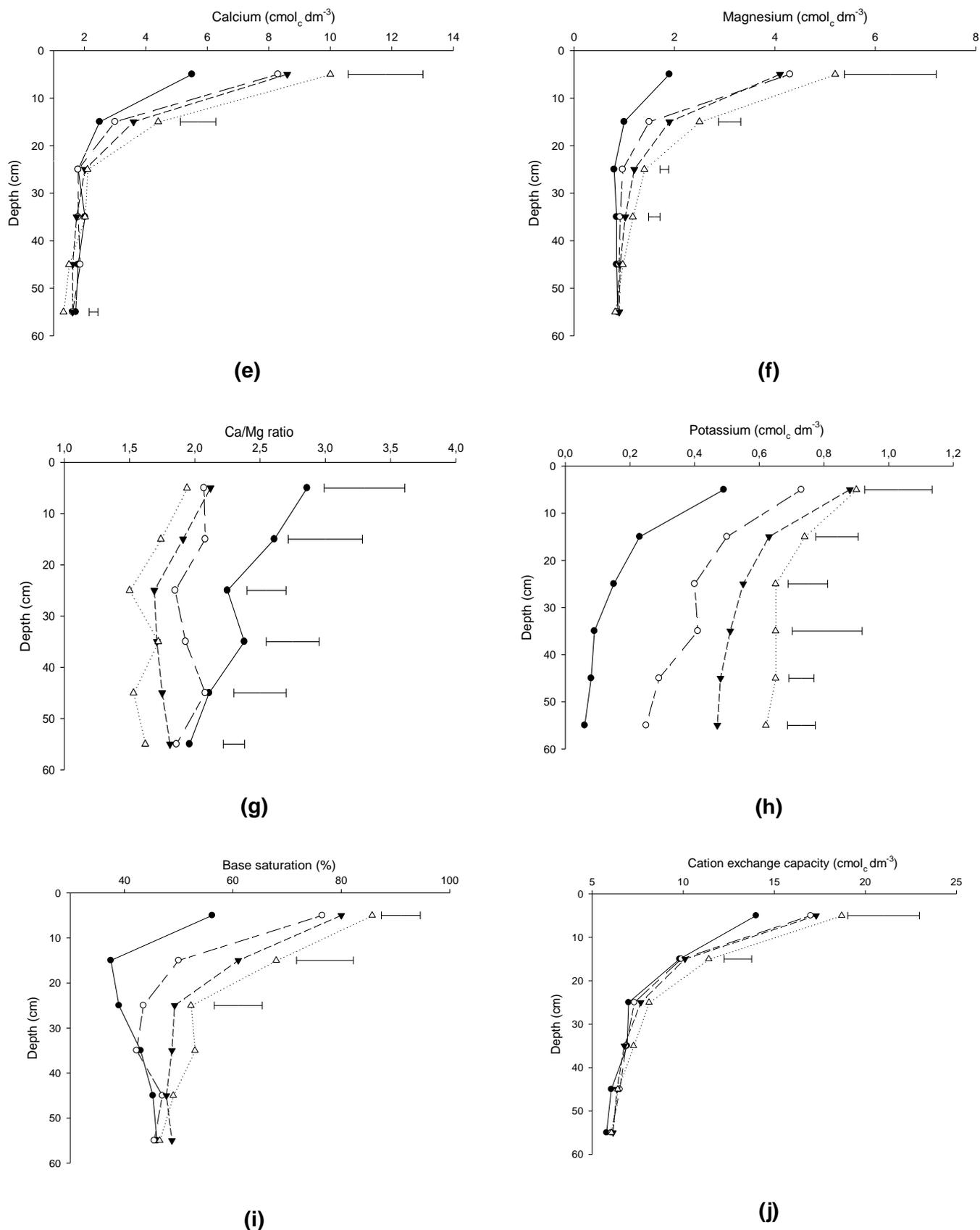
yield, which provided stability in production compared to the use of only mineral fertilizer [26]. The same authors highlighted that the beneficial effect of integrated use of mineral fertilizer with manure was more pronounced and effective in increasing yield as the cultivation year progressed.

### Soil fertility

After nine-year period of fertilization, the DLM application influenced all soil chemical variables evaluated (Figure 2). The DLM application increased the soil active acidity (pH) and reduced the potential acidity (H+Al) up to 20 cm depth, evidencing the alkalizing effect of this product (Figure 2a,b) possibly due to the presence of carbonates and bicarbonates, that are added to animal feed and excreted in manure. In addition, other compounds such as organic acids from the carboxyl and phenolic hydroxyl groups also have an important role in buffering soil acidity and increasing soil pH [27].

For each  $m^3$  of manure applied annually, there was an average increase of 0.0043 and 0.0040 units in the pH scale after nine years of application, at depths 0-10 and 10-20 cm, respectively (Table 4). At depth 0-5 cm, [28] observed for each  $m^3$  of bovine manure applied annually, average linear increase of 0.0047 units in pH after six years of application. The effect of DLM application on the depth acidity correction was also observed with the successive application of swine manure doses [29,30].





**Figure 2.** pH in CaCl<sub>2</sub> (a), potential acidity (H+Al) (b), contents of organic carbon (c), phosphorus (resin) (d), calcium (e), magnesium (f), calcium/magnesium ratio (g), potassium (h), base saturation (i), cation exchange capacity (j) at six depths of a Latossolo Bruno Distrófico típico, after nine years of dairy liquid manure (DLM) application at doses of 0, 60, 120 and 180 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>, in black oat-maize-soybean-wheat crop rotation under no-tillage system. DLM applied in each crop season since May 2006. Soil sampled in July 2014. (Tukey DMS, p < 0.05).

**Table 4.** Regression equations for pH in CaCl<sub>2</sub>, phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K) and base saturation (V%) in soil depth after nine years of dairy liquid manure (DLM) application at doses of 0, 60, 120 and 180 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>, in a Latossolo Bruno Distrófico típico under no-tillage system, in black oat-maize-wheat-soybean crop rotation. DLM applied in each crop season since May 2006. Soil sampled in July 2014.

Variable	Regression equations			
	0-10 cm	R <sup>2</sup>	10-20 cm	R <sup>2</sup>
pH	y= 5.160 + 0.0043x	0.95*	y= 4.840 + 0.0040x	0.94*
P	y= 37.650 + 0.5133x	0.98*	y= 15.150 + 0.1192x	0.95*
Ca	y= 6.030 + 0.0230x	0.84*	y= 2.430 + 0.0105x	0.98*
Mg	ns		y=0.935 + 0.0085x	0.99*
K	y= 0.543 + 0.0023x	0.88*	y= 0.276 + 0.0028x	0.95*
V (%)	ns		y= 38.750 + 0.1708x	0.98*
	20-30 cm	R <sup>2</sup>	30-40 cm	R <sup>2</sup>
pH	ns		ns	
P	ns		ns	
Ca	ns		ns	
Mg	y= 0.788 + 0.0034x	0.99*	y= 0.831 + 0.0018x	0.97*
K	y= 0.190 + 0.0028x	0.96*	y= 0.148 + 0.0030x	0.93*
V (%)	y= 39.17 + 0.00758x	0.99*	ns	
	40-50 cm	R <sup>2</sup>	50-60 cm	R <sup>2</sup>
pH	ns		ns	
P	ns		ns	
Ca	ns		ns	
Mg	y= 0.853 + 0.0006x	0.97*	ns	
K	y= 0.090 + 0.0032x	0.99*	y= 0.065 + 0.0032x	0.99*
V (%)	y= 45.45 + 0.0200x	0.98*	ns	

\* significant at 5 %; ns: not significant at 5 %.

As expected, the DLM application reduced soil potential acidity (H+Al) up to 10-20 cm, especially at doses 120 and 180 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> [28]. The pH increase resulted on insoluble Al species, reducing the soil H+Al content. Also, the exchangeable bases increase, which compete for exchange sites, can decrease H+Al content [15]. The soil pH reduction in the 0-10 and 10-20 cm layer in the treatment without manure application increased the potential acidity (Figure 2b) by 1.5 cmol<sub>c</sub> dm<sup>-3</sup> for both depths.

The organic carbon (OC) content increased with DLM doses only in the depth 0-10 cm (Figure 2c). In this layer the 120 and 180 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> resulted in 11% and 12% higher OC compared to the control, respectively. This effect only in the 0-10 cm depth is due to the DLM application on the soil surface without revolving. The positive effect on OC with DLM application may be due to a direct action of carbon addition via manure or indirectly by increasing the C addition via root and aerial biomass. Generally, greater increase occurs with increasing dose and years of application [5,31,32].

The phosphorus (P) content increased with DLM application up to 20-30 cm (Figure 2d), with linear increment to 20 cm (Table 4). This P increment in depth (20-30 cm) may be related to the presence of preferential channels, common in no-till fields. Other authors also observed P increase with use of bovine manure, in superficial layers (5 cm) [31], as well as in deeper layers (30 cm) [32].

At 0-10 cm depth, the application of 120 and 180 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> increased 141% and 217%, respectively, the P content compared to the control. On the other hand, at 10-20 cm depth, this increase was 18% and 45% for the same doses. The effect of manure application was more evident in the surface layer (0-10 cm), what can be explained by the predominance of kaolinite, gibbsite, goethite and hematite mineral clays in the studied soil, and so, a high degree of P specific adsorption [34] decreasing the P mobility in depth. In addition, the soil management contributed to this, considering that in the no-tillage system the application of manure is on the soil surface without incorporation, and the mineral fertilizer is applied in-furrow at sowing with minimal soil disturbance. Furthermore, the increment in organic matter content increases negative charges, contributing to the reduction of P adsorption by repulsion [33]. Thus, in addition to the P additional supply to the soil by manure, another factor that may have contributed to the increase of available this nutrient content in the soil is the reduction in the fixation/adsorption of the applied P due to the organic matter increase (OC) in the 0-10 cm layer. It is noted that although the application of the highest DLM doses increases the P content above the high interpreted level (41-80 mg kg<sup>-1</sup>) [15], the content is below the critical level (188 mg kg<sup>-1</sup> P for a Latossolo with sandy texture) [8]. If considered only the P supply from the organic source, the

estimated average dose to be added would be  $98 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ , being 124, 84 and  $87 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ , for maize, soybean and wheat, respectively. Therefore, an estimated manure dose for maximum yield would be approximately  $300 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  for maize,  $220 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  for soybean and wheat, and  $250 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  considering the crops average. Thus, it would be possible to reduce the need for mineral P application, maintaining the fertilization with the manure and reducing the production costs.

The DLM fertilization also increased the calcium (Ca) content up to 20 cm depth (Figure 2e), due to the supply of this element by the manure (average content 2.24 of CaO). This effect was adjusted by regression to the linear function in both layers (Table 4), showing that for each  $\text{m}^3$  of manure added annually to the soil for nine years, there was an increase in exchangeable Ca of 0.023 and  $0.010 \text{ cmol}_c \text{ dm}^{-3}$  at layers 0-10 and 10-20 cm, respectively (Table 4). Other authors observed that each  $\text{m}^3$  of bovine manure added annually to the soil increased by  $0.0113 \text{ cmol}_c \text{ dm}^{-3}$  Ca after a period of six years in the 0-5 cm layer [28]. In general, there is a greater increase of Ca in the superficial layer due to the high binding energy of Ca ions to negative colloid charges, especially in systems without revolving and with the application of fertilizers and acidity correctives on the soil surface. Probably, the high initial Ca content ( $5.6 \text{ cmol}_c \text{ dm}^{-3}$  in the 0-10 cm layer) [16] contributed to the vertical displacement of the nutrient, which is important to increase the deep root growth and, consequently, the nutrient and water supply to plants. Ca is essential in cell division and is absorbed practically all over the root hood and is considered immobile in the plant [35], so depth supply favors root growth.

Magnesium (Mg) content increased with DLM application up to 40 cm depth (Figure 2f); in the depths 10-20, 20-30, 30-40 and 40-50 cm the increment was linear (Table 4). Similarly to Ca, the increase of Mg is due to the addition by nine consecutive years of DLM (average content of  $1.46 \text{ g L}^{-1} \text{ MgO}$ ). Mg ions tend to move more easily in depth relative to Ca due to lower colloid binding energy. As in this study, others have verified that with the manure application occurs greater displacement of Mg in depth than Ca [28,30].

DLM application reduced the Ca/Mg ratio up to 60 cm (Figure 2g). The manure increased the Ca and Mg contents, but the key element that determined the reduction of this relationship was the Mg, which had the largest increase in proportion, as well as had effect in deeper layers. Similarly, other authors verified reduction of Ca/Mg ratio in layer 0-5 cm and 5-10 cm after six years of bovine manure application [36].

Potassium (K) contents increased linearly with the DLM application, and this effect was verified in all evaluated layers (Figure 2h and Table 4). This effect was also verified by other authors after 25 years of bovine manure application [3]. The increment is due to the supply of this nutrient by DLM and mineral fertilizer, associated with the high initial K content ( $0.3 \text{ cmol}_c \text{ dm}^{-3}$  in the 0-10 layer) [16] and the lower adsorption energy of this ion in relation to Ca and Mg. Other authors observed increase in K content up to 80 cm after six years of liquid manure application [31,36].

Base saturation (V%) was affected by DLM application up to 30 cm depth (Figure 2i), adjusting for regression to the linear function in the 10-20, 20-30 and 40-50 cm layers (Table 4). These data were consistent with the increase in Ca, Mg and K content provided by the DLM application, in addition to the reduction in potential acidity and the OC increase, which contributes to soil cation adsorption [28,30,36]. Other authors verified increase in V% up to 10 cm [28], 12 cm [29] and 30 cm [37] after six, eight and eight years of bovine and swine application, respectively. During this experiment, two liming were carried out (in 2007 and 2013) and in the control treatment (without DLM application), the V% reduced (Figure 2i), showing the acidification effect of mineral fertilization and base exportation. The application of DLM even in the lowest dose provided an increase of V% and so, the acidification effect of the mineral fertilizers was neutralized, reducing the need for liming.

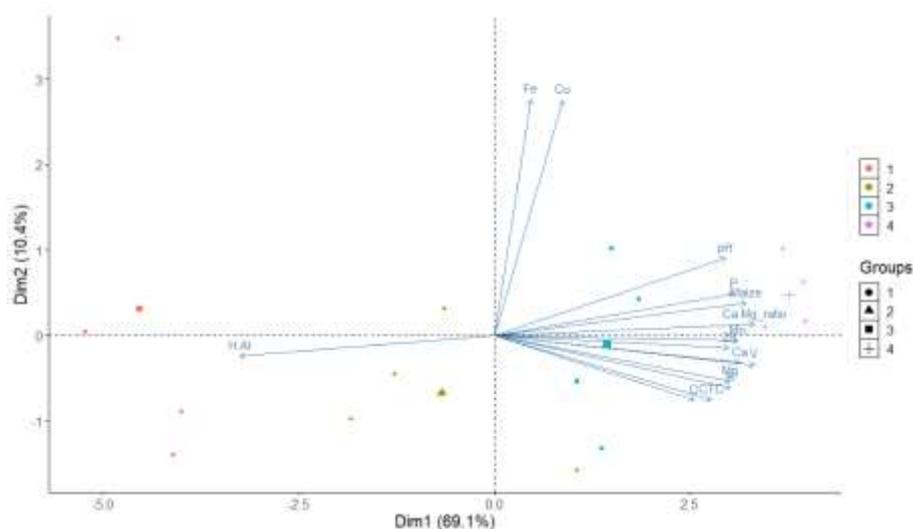
DLM application increased soil cation exchange capacity (CEC) up to 20 cm (Figure 2j), changing from medium to high in the 0-10 cm layer [16]. The increased OC content (Figure 2c) contributed to this DLM effect being verified moderate correlation ( $r = 0.58$ ) between soil OC and CEC contents in the 0-10 cm layer. The increase in soil CEC favors the adsorption of cations added to the soil by manure and mineral fertilizers, such as K, Ca and Mg [37].

### Main soil chemical variables that influenced grain yield

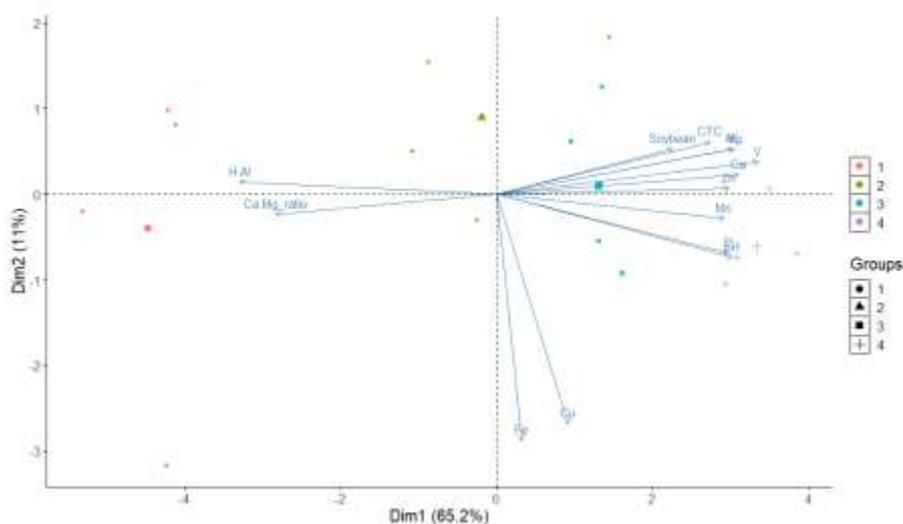
The principal component analysis (PCA) was carried out between accumulated grain yield and soil chemical variables in the 0-10 cm layer, considering that in this layer there was a greater change in the soil chemical variables as a function of DLM application. The increase in accumulated yield was due to the improvement in all evaluated chemical variables, and components 1 and 2 represented approximately 80%,

77%, 78% and 78% of the ability to explain the covariance of the variables for maize, soybean, wheat and total, respectively (Figure 3).

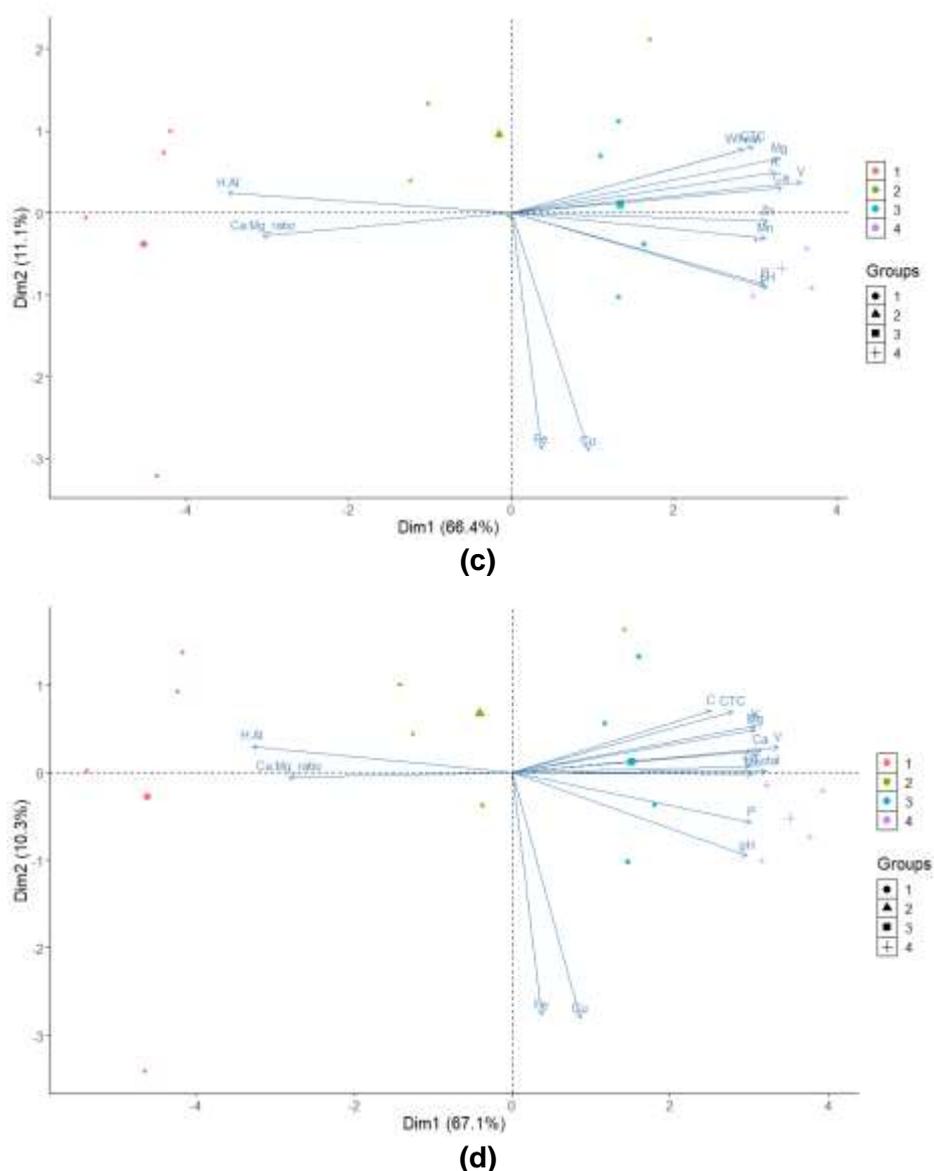
For maize, there was a high positive correlation between accumulated yield and P (Figure 3a), while for soybean and wheat, the base complex was mainly responsible for high yield (Figure 3b and Figure c). In PCA carried out for accumulated total grain yield it was observed that, besides the bases, the micronutrients Zn and Mn were highly associated with higher yield (Figure 3d). Except for maize, in all PCA, Ca/Mg ratio and potential acidity (H+Al) were negatively correlated with accumulated yield. In generally, the dispersion of the observations followed the treatment standard.



(a)



(b)



**Figure 3.** Principal component analysis (PCA) of soil chemical attributes and maize yield (a); soybean (b); wheat (c); and total (maize + soybean + wheat) (d), in the 0-10 cm depth, after nine years of application of 0, 60, 120 and 180 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> of dairy liquid manure under no-tillage, in Latossolo Bruno Distrófico típico.

## CONCLUSION

The DLM application complementary the mineral fertilization increase soybean, wheat and maize grain yield under no-tillage, with a best average dose for all crops of 150 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>. Among the crops, maize has a linear response, since soybean and wheat has a maximum dose recommended.

The DLM improve all soil chemical variables, and even applied on the soil surface it improve the soil chemical variables in deep layers.

The crop yield increment is not attributed to a single variable, but the improvement of all soil chemical variables, however, the results suggest that the balance between the exchangeable bases and the acidity of the soil exchange complex is fundamental for maximum expression of the productive potential.

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