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Phosphorus Fractions in Soil with Organic and Mineral Fertilization in Integrated Crop-Livestock System

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ABSTRACT: Use of organic fertilizers in integrated crop-livestock (iCL) systems may affect soil phosphorus fractions. This study aimed to determine phosphorus fractions in the soil under the iCL system after six years of application of organic or mineral fertilizers. The experiment was conducted on a Rhodic Kandiudox (*Nitossolo Vermelho Distroférrico*) in a randomized block design, using a 5 × 3 + 1 factorial scheme, with four replicates. The treatments consisted of three organic fertilizers (poultry litter, pig slurry, and compost) and two mineral fertilizers (M1, equivalent to pig slurry; and M2, equivalent to poultry litter) in interaction with three application rates, corresponding to 75, 100, and 150 % of the fertilizer recommendation for the crop of interest and a control (with no fertilizer). Soil sampling was performed in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers for determination of the phosphorus fractions. Successive use of organic or mineral fertilizers for six years in the iCL system considerably raises the labile and moderately labile P fractions up to the 0.20 m depth and, with less intensity, raises the non-labile fractions up to the 0.10 m depth. The soil P increase associated with fertilizer input raises soybean and corn yields, and it does not exceed the critical P limit according to local environmental legislation.

Keywords: manure, P fractionation, P sorption, soil fertility.

INTRODUCTION

To meet the high demand for food production in Brazil, crops must be fertilized with phosphorus, since more than 80 % of Brazilian soils are poor in this nutrient. However, it is estimated that the total P surplus in the soil represents about 70 % of the P fertilizers used per year, which indicates the inefficiency of P use in Brazil (Withers et al., 2018).

Strategies must be created to increase the efficiency of P availability in the soil and reduce strong dependence on imported phosphate fertilizers. One noteworthy alternative is reuse of P from livestock residues associated with conservationist systems, such as the integrated crop-livestock (iCL) system, which can further enhance the efficiency of P availability in the soil (Crusciol et al., 2015; Andrade et al., 2017; Prochnow et al., 2018).

Effective use of organic fertilizers in an iCL system may result in positive economic and environmental effects because of the greater diversity of the integrated system, which may therefore favor nutrient cycling and availability (Anghinoni et al., 2011; Hentz et al., 2016).

In regions of high swine and poultry concentration, as in southern Brazil, rational use of animal waste as fertilizer mainly considers the phosphorus (P) level, and this level guides the agronomic recommendations (Gatiboni et al., 2015; CQFS-RS/SC, 2016). In addition, in the state of Santa Catarina, the nutrient limits foreseen in environmental legislation must be observed. This legislation establishes the maximum amount of P to be applied (Fatma, 2016).

In areas managed with no tillage or pastures, organic fertilizers are normally applied on the soil surface without incorporation, but there are few studies on organic fertilization for iCL. Therefore, we have been observed an increase in P content in the soil surface layers over the past years, when organic fertilizers are used in conservation systems (De Conti et al., 2015; Grohskopf et al., 2016).

Soil management systems can change P dynamics, especially those that promote addition of organic matter on the soil, thus contributing to a decrease in adsorption and a consequent increase in P availability to plants (Pereira et al., 2010; Bezerra et al., 2015). Moreover, additional carbon from organic fertilization contributes to an increase in higher lability P (Guardini et al., 2012).

Many methodologies have been tested in Brazil to quantify P fractions in the soil, but the method developed by Hedley et al. (1982) allows an understanding of the P dynamics in soils under different uses, fertilization sources, and cultivation systems (Schmitt et al., 2017). Phosphorus fractioning consists of sequential extraction in a soil sample with a series of reagents or extraction solutions that selectively dissolve different forms of P in the soil based on the nature of the phosphate compound and the energy bonds, which enables an explanation of P dynamics (Gatiboni et al., 2013).

Knowledge of P chemical fractionation may help to understand P availability in its recognized forms between labile P and total P in the soil as a result of the type and rate of fertilizers applied in the iCL system. Based on this scenario, the aim of this paper was to determine the levels of phosphorus fractions after six years of increasing application rates of organic or mineral fertilizers in the iCL system to contribute to efforts to increase crop yield and environmental quality.

MATERIALS AND METHODS

The experiment was set up in 2011 in Concórdia, Santa Catarina State, Brazil, at 27° 12’ 0.08” S, 52° 4’ 58.22” W, and 569 m a.s.l. The system of production adopted was the integrated crop-livestock (iCL) system with corn (*Zea mays* L.) and soybean (*Glycine* max) crops during the summer and black oat (*Avena strigosa* Schreb) in the winter.

The weather is humid subtropical (Cfa), according to the Köppen classification system. The coldest months (June and July) have average temperatures around 15 °C and the annual mean temperature is 23 °C. Mean annual rainfall is 1,500 mm. The predominant landform is sloped surfaces.

Daily data regarding the maximum and minimum temperatures and rainfall during the two years of the experiment (2015-2017) were collected at the weather station at the Embrapa Swine and Poultry Research Center; the monthly values are shown in figure 1. It should be noted that rainfall and temperature conditions were proper for crop development.

The soil of the experimental area is a Rhodic Kandiudox (*Nitossolo Vermelho Distroférrico*). The chemical and physical properties of the soil are shown in table 1. In the period between 1994 until 2011, the area of the experiment was managed with corn in the summer and black oat and fodder radish cover in the winter. Two applications of 5 Mg ha^{-1} of dolomitic limestone were made during this period, as well as organic fertilization with pig slurry of 50 m^3 ha^{-1} yr^{-1}, in accordance with the guidelines of the Santa Catarina environmental agency (IMA), as well as mineral fertilization defined by soil analysis and expected crop yield.

When the experiment was set up, the oat cover crop was chemically desiccated with the use of glyphosate herbicide (2,160 g ha^{-1} de i.a.). This agriculture practice was always repeated 14 days before sowing the winter and summer crops.

The experiment was carried out in field condition using a randomized block design with four replicates in a 5 × 3 + 1 factorial scheme, which included five fertilizers, three application rates, and a control treatment without fertilization. Fertilizer treatments comprised three organic fertilizers [poultry litter, liquid pig slurry (slurry), and compost], two mineral fertilizers [M1 and M2], and the control (with no fertilization). They interacted

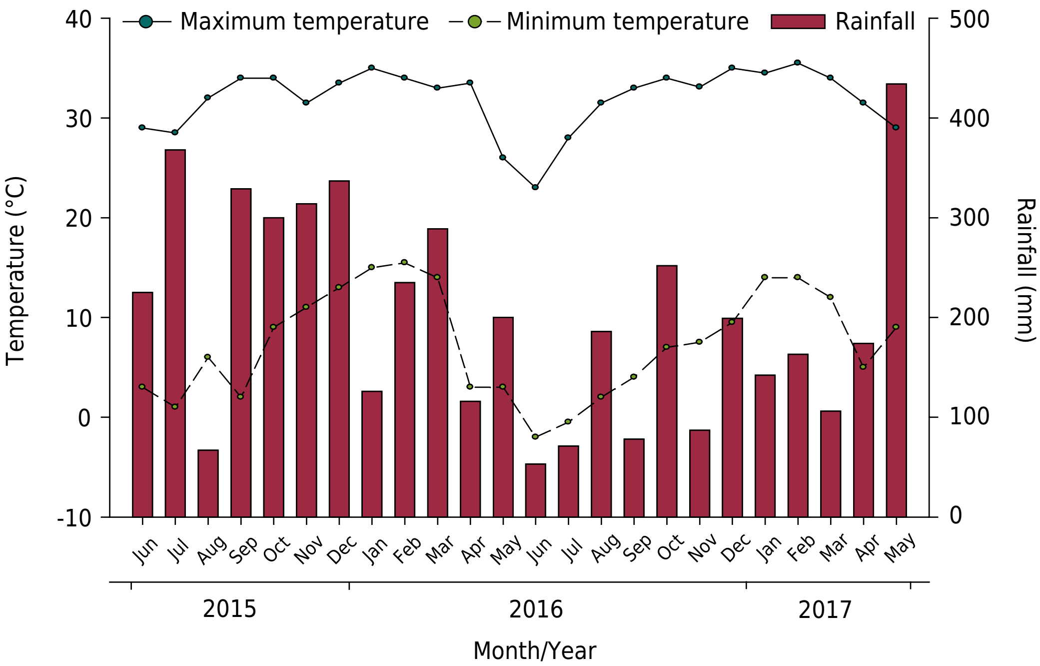

Figure 1. Rainfall and maximum and minimum temperatures registered during the experiment in the 2015-2017 crop seasons, Concórdia, Santa Catarina, Brazil.

Table 1. Initial characterization of the Rhodic Kandiudox (*Nitossolo Vermelho Distroférrico*) in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers. Concórdia, Santa Catarina, Brazil

Property	Layer		
	0.00-0.05 m	0.05-0.10 m	0.10-0.20 m
Clay (g kg^{-1})	680	680	700
$pH(H_2O)$	5.8	5.6	5.5
H+Al ($cmol_c$ kg^{-1})	5.7	6.0	5.8
OC (g kg^{-1})	18	17	17
N (g kg^{-1})	1.9	1.7	1.5
P (mg kg^{-1})	100	80	70
K^+ (mg kg^{-1})	590	406	346
Ca^{2+} ($cmol_c$ kg^{-1})	8.4	6.7	9.5
Mg^{2+} ($cmol_c$ kg^{-1})	4.8	4.0	4.2
CEC ($cmol_c$ kg^{-1})	20.5	17.8	20.5
V (%)	72	66	72
Cu (mg kg^{-1})	4.7	5.5	4.4
Zn (mg kg^{-1})	5.1	4.4	3.6

Soil analysis was determined according to Tedesco et al. (1995). $pH(H_2O)$ at a ratio of 1:5 v/v; TOC = total organic carbon; TN = total nitrogen; P = available phosphorus; K^+ = exchangeable potassium; Ca^{2+} = exchangeable calcium; Mg^{2+} = exchangeable magnesium; CEC = cation exchange capacity; V = base saturation. The clay content was determined according to Claessen (1997).

with three application rates, corresponding to 75, 100, and 150 % of that recommended for the crop of interest, based on the element with the highest demand for the crop in order to achieve estimated yields of ≥8 Mg ha^{-1} in corn and ≥4 Mg ha^{-1} in soybean. The experimental units consisted of 5 × 5 m plots, with a 2.5 m distance between blocks.

Fertilizers were applied on the surface beside the plant row for both the winter and summer crops. The slurry and poultry litter came from the animal production system of the Instituto *Federal Catarinense*, *Campus* Concórdia, in Santa Catarina, Brazil. The chemical properties of each organic fertilizer for each summer crop are shown in table 2. The fertilizers were analyzed according to the official methodology (APHA, 1992; AOAC, 2000) for determining N, P, and K.

According to the N, P, and K contents in the organic fertilizers, we established the mineral formulations from the following sources: urea for N, triple superphosphate for P, and potassium chloride for K. The same amounts of these nutrients were added in the M1 treatment (corresponding to pig slurry) and the M2 treatment (corresponding to poultry litter).

The compost fertilizer was produced from pig slurry (which has a dry matter content of 40 to 60 g kg^{-1}), using 8 to 12 liters of pig slurry per kilogram of the substrate, divided in different periods, formed of a mixture of wood shavings and sawdust. This mixture was arranged in a pile 1 m high, 3 m wide, and 20 m long. This liquid material was applied weekly, and the compost mass was stirred if the internal temperature exceeded 60 °C. After the temperature stabilized, the mature compost was ready for use.

The winter pasture was formed with black oat (*Avena strigosa* Schreb) at a sowing rate of 50 kg ha^{-1} of seeds, with 80 seeds per linear meter, and a 0.20 m spacing between rows. This pasture was used by sheep, managed within an electric fence. The grazing pattern and stocking rate considered the forage production, and the animals were removed when the stubble height was 0.10 m.

Table 2. Contribution of nutrients in the organic fertilizers applied in the iCL system

Treatment	Content of nutrients in the fertilizer			100 % rate	% of recommendation		
	N	P	K		75	100	150
					P contribution		
	g kg^{-1}			kg or L ha^{-1}	kg ha^{-1}		
2011/12 Corn crop							
Poultry litter	20.7	13.4	12.8	4800	48	64	96
Pig slurry	3.7	1.4	1.5	26880	28	38	57
2012/13 Corn crop							
Poultry Litter	21.8	13.3	13.4	4600	46	61	91
Pig slurry	3.8	1.0	4.2	25974	19	25	37
Compost	5.9	5.5	5.2	16949	70	93	139
2013/2014 Soybean crop							
Poultry Litter	20.3	11.6	19.5	2463	22	29	43
Pig slurry	4.2	0.8	1.4	11905	7.5	10	15
Compost	6.5	6.5	5.4	15384	75	100	150
2014/2015 Corn crop							
Poultry Litter	24.2	12.6	29.1	4132	39	52	78
Pig slurry	2.7	0.9	1.8	37037	25	33	49
Compost	5.8	4.7	6.9	17241	61	81	121
2015/2016 Soybean crop							
Poultry Litter	22.1	10.6	20.3	2262	18	24	36
Pig slurry	3.4	0.9	2.0	14706	10	13	19
Compost	8.5	7.9	4.5	5882	34	46	69
2016/2017 Corn crop							
Poultry Litter	25.5	15.3	18.7	3921	45	60	90
Pig slurry	2.5	0.3	0.3	40000	10	14	21
Compost	6.8	7.6	4.6	14706	84	112	168
Sum of the contribution during the system conduction							
Poultry Litter					218	290	434
Pig slurry					99.5	133	198
Compost					324	432	647

Chemical analyses were performed according to the Methodology of American Public Health Association – APHA (2012).

In the 2015/16 summer crop, soybean (*Glycine max*) was sown with 18 seeds per linear meter and a 0.45 m spacing between rows, and in the 2014/15 and 2016/17 crop seasons, the corn single hybrid Celeron TL of Syngenta was grown at a spacing of 0.80 m between rows and eight seeds per linear meter.

Stratified soil sampling was performed at the end of the summer crop in the 2016 season in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers. Three simple samples were randomly collected, one in the row and two between crop rows, to constitute a combined sample, using a cutting shovel up to 0.20 m. The combined samples underwent P fractionation through successive extractions following the methodology developed by Hedley et al. (1982) with modifications proposed by Condron and Goh (1989) and adaptations described by Gatiboni et al. (2013).

The results were analyzed for homogeneity and normality of variance. The treatments were compared through the Tukey test at the 5 % level of error probability, protected by the overall significance of the F test. In addition, regressions were calculated to determine the response of variables to the use of organic and mineral fertilizer rates.

RESULTS AND DISCUSSION

The phosphorus (P) contribution to the iCL system from increasing rates of organic or mineral fertilizers throughout several summer crop seasons reached 434, 198, and 647 kg ha^{-1} of P for poultry litter, pig slurry, and compost, respectively, at the highest recommended rate and similar amounts in the mineral fertilizers for M1 (corresponding to pig slurry nutrient levels) and M2 (corresponding to poultry litter nutrient levels) (Table 3). Thus, fertilizers with higher levels of P (litter and compost) showed higher contents of labile P forms, extracted by resin. All of the fertilizers had a linear increase in this P form to the 0.20 m depth, with the exception of poultry litter in the 0.10-0.20 m layer, which exhibited a quadratic increase (Table 3).

The ratio of the P content extracted through resin from the poultry litter and slurry fertilizers was higher than 2:1, which are similar to their peers with mineral fertilizers M1/thicken manure and M2/pig slurry (Table 3). Thus, in the surface, both the poultry litter and M2 shown superior P content extracted by resin than the pig slurry in the 75 % rate and the M1 from 100 % of fertilization recommendation; in the 0.05-0.10 m layer, the poultry litter superiority and M2 to the slurry, compost, and M1 occurs from 100 %; in the layer of 0.10-0.20 m, the poultry litter is higher than the slurry and the compost from 75 % and similar to M1 from 100 % (Table 3).

The use of organic fertilizers (pig slurry, cattle, and pig litter) and mineral fertilizers (NPK) after eight years increased P content extracted by resin in the surface layer in an Ultisol (*Argissolo típico*), with decreases to the depth of 0.04 m (Couto et al., 2017). These are the same results observed in a study in different soil classes (Santos, 2000). The decrease in P content at greater depth is explained by the fact that the residues

Table 3. Labile soil phosphorus fraction extracted by ionic exchange resin in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers after six years use of organic and mineral fertilizers in a Rhodic Kandiudox

Fertilizer	Fertilization recommendation				Equation
	0 %	75 %	100 %	150 %	
	Labile P				
	mg kg^{-1}				
	0.00-0.05 m				
Poultry Litter	48.6	102.9 A	162.1 AB	175.8 A	$\hat{y} = 49.5 + 0.893^{**}x$ $R^2 = 0.92$
Pig slurry	48.6	61.8 B	66.7 C	86.9 B	$\hat{y} = 45.9 + 0.247^{**}x$ $R^2 = 0.94$
M1	48.6	81.7 AB	88.2 C	114.5 B	$\hat{y} = 48.1 + 0.432^{*}x$ $R^2 = 0.99$
M2	48.6	102.2 A	172.7 A	174.1 A	$\hat{y} = 50.7 + 0.906^{**}x$ $R^2 = 0.87$
Compost	48.6	94.2 AB	127.6 B	168.9 A	$\hat{y} = 44.2 + 0.808^{**}x$ $R^2 = 0.98$
	0.05-0.10 m				
Poultry Litter	19.2	43.5 AB	101.1 A	97.6 A	$\hat{y} = 18.4 + 0.578^{**}x$ $R^2 = 0.79$
Pig slurry	19.2	37.1 AB	44.8 B	57.2 B	$\hat{y} = 18.9 + 0.254^{**}x$ $R^2 = 0.99$
M1	19.2	18.6 B	38.5 B	58.1 B	$\hat{y} = 12.6 + 0.259^{**}x$ $R^2 = 0.75$
M2	19.2	38.8 AB	107.8 A	103.6 A	$\hat{y} = 16.5 + 0.626^{**}x$ $R^2 = 0.76$
Compost	19.2	57.2 A	66.9 B	90.9 A	$\hat{y} = 19.9 + 0.476^{**}x$ $R^2 = 0.99$
	0.10-0.20 m				
Poultry Litter	13.0	42.5 A	50.3 A	54.2 A	$\hat{y} = 12.9 + 0.537^{**}x - 0.002^{**}x^2$ $R^2 = 0.99$
Pig slurry	13.0	18.9 B	20.6 C	21.9 B	$\hat{y} = 13.6 + 0.061^{**}x$ $R^2 = 0.95$
M1	13.0	18.0 B	38.5 AB	40.7 A	$\hat{y} = 11.3 + 0.200^{**}x$ $R^2 = 0.79$
M2	13.0	31.0 AB	52.7 A	55.6 A	$\hat{y} = 13.5 + 0.303^{**}x$ $R^2 = 0.90$
Compost	13.0	18.4 B	27.6 BC	27.7 B	$\hat{y} = 13.0 + 0.106^{**}x$ $R^2 = 0.85$

Mean values followed by different letters in the column are different through the Tukey test ($p \leq 0.05$). * = $p \leq 0.05$; ** = $p \leq 0.01$). M1 = mineral fertilizer 1, equivalent to pig slurry; M2 = mineral fertilizer 2, equivalent to poultry litter.

are added to the soil surface in no tillage systems without incorporation (Cassol et al., 2012; Grohskopf et al., 2016).

Other factors that might have contributed to greater availability of labile P in the litter, slurry, and compost fertilizers (Table 3) are related to stimulation of microbial activity (De Brouwere et al., 2003; McDowell and Stewart, 2006) and long-term successive use of these fertilizers (Gatiboni et al., 2008). However, Caione et al. (2015) found similar P fractions after two years of use of different phosphate fertilizers (mineral and organic fertilizers) in an Ultisol (*Argissolo Vermelho Eutrófico*) with a sugarcane crop.

It is noteworthy that the association of clay content from this Rhodic Kandiudox (680-700 g kg^{-1}), the pH, and the organic carbon values in the surface (Table 1) affect the sorption capacity and rates of release of intrinsic soil orthophosphate ions. This agrees with Gatiboni et al. (2013), who argued that pH, soluble Al contents, Fe, Ca, OM, and clay content may be related to the dissolution, adsorption, and desorption of P in the soil system.

The $NaHCO_3$, as well as ion exchange resin, extracts the labile P of the soil, and these two extractants showed a similar pattern of P extraction. All the fertilizers led to a linear increase in all the layers, except for the 0.05-0.10 m layer for M2, which exhibited a quadratic increase, and the 0.10-0.20 m layer for M1, which showed no effect (Table 4).

In extraction with $NaHCO_3$, it is noteworthy that the largest values of labile P were found in M2, especially at the rate of 150 % in the 0.00-0.05 m layer, which were similar to the values from poultry litter and compost at the rate of 100 % in the 0.05-0.10 m layer (Table 4). This result confirms the greater sensitivity of this extraction method in detecting labile P when large amounts of P are applied to the system, especially in an inorganic form.

Table 4. Labile soil phosphorus fraction extracted by $NaHCO_3$ 0.5 mol L^{-1} in the 0.00-0.05, 0.05-0.10 and 0.10-0.20 m layers after six years use of organic and mineral fertilizers in a Rhodic Kandiudox

Fertilizer	Fertilization recommendation				Equation
	0 %	75 %	100 %	150 %	
	Labile P				
	mg kg^{-1}				
	0.00-0.05 m				
Poultry Litter	62.6	99.6	119.1 A	128.7 B	$\hat{y} = 62.1 + 0.665^{**}x - 0.0014^{**}x^2$ $R^2 = 0.93$
Pig slurry	62.6	88.6	88.5 AB	111.0 B	$\hat{y} = 62.4 + 0.312^{**}x$ $R^2 = 0.97$
M1	62.6	87.2	82.4 B	117.8 B	$\hat{y} = 59.7 + 0.342^{**}x$ $R^2 = 0.88$
M2	62.6	91.5	116.8 A	186.6 A	$\hat{y} = 62.5 - 0.043^{**}x + 0.0058^{**}x^2$ $R^2 = 0.95$
Compost	62.6	96.8	99.5 AB	128.5 B	$\hat{y} = 62.1 + 0.428^{**}x$ $R^2 = 0.98$
	0.05-0.10 m				
Poultry Litter	57.5	71.7	98.2 A	105.6	$\hat{y} = 55.6 + 0.339^{**}x$ $R^2 = 0.89$
Pig slurry	57.5	66.6	73.9 B	83.7	$\hat{y} = 56.2 + 0.175^{**}x$ $R^2 = 0.97$
M1	57.5	76.8	96.6 A	91.4	$\hat{y} = 60.2 + 0.251^{**}x$ $R^2 = 0.80$
M2	57.5	83.1	101.5 A	99.9	$\hat{y} = 56.8 + 0.555^{**}x - 0.002^{*}x^2$ $R^2 = 0.94$
Compost	57.5	78.5	80.2 AB	90.2	$\hat{y} = 59.0 + 0.217^{**}x$ $R^2 = 0.97$
	0.10-0.20 m				
Poultry Litter	50.8	57.5	61.4 B	71.7 B	$\hat{y} = 49.3 + 0.136^{**}x$ $R^2 = 0.94$
Pig slurry	50.8	54.5	60.8 B	67.1 B	$\hat{y} = 50.6 + 0.029^{*}x + 0.0006^{**}x^2$ $R^2 = 0.88$
M1	50.8	49.1	40.0 C	56.7 B	$\hat{y} = 60.8$
M2	50.8	60.8	77.8 A	89.6 A	$\hat{y} = 48.2 + 0.265^{**}x$ $R^2 = 0.92$
Compost	50.8	57.5	61.5 B	66.6 B	$\hat{y} = 50.5 + 0.106^{**}x$ $R^2 = 0.99$

Mean values followed by different letters in the column are different through the Tukey test ($p \leq 0.05$). * = $p \leq 0.05$; ** = $p \leq 0.01$). M1 = mineral fertilizer 1, equivalent to pig slurry; M2 = mineral fertilizer 2, equivalent to poultry litter.

The $NaHCO_3$ P fraction in the surface was related to the organic or mineral fertilizers used, as reported by Guardini et al. (2012) and Lourenzi et al. (2013), who studied the no tillage system in Ultisols (*Argissolo Amarelo* and *Argissolo Vermelho*). The greater concentration on the surface occurred because the P from the fertilizers applied may be adsorbed with high binding energy to the surface of the soil mineral colloids.

However, the use of high P application rates in the soil reduces the availability of these sites of high adsorption capacity for the phosphate ion, and therefore this element is adsorbed in sites of lower binding energy. Thus, there is accumulation of P in labile and moderately labile fractions in the surface layers of the soil (Gatiboni et al., 2008; Guardini et al., 2012). In addition, an increase in environmental contamination potential may be associated with this, which is indicated by calculation of the critical limit of environmental P (Gatiboni et al., 2015).

The largest contribution to the increase in the P extracted by P-NaOH 0.1 mol L^{-1} in the iCL system up to the 0.20 m depth was because of the increase of the doses, with an intrinsic linear or quadratic adjustment of each fertilizer for each layer analyzed. Only M1 maintained a linear increase in the three layers (Table 5). This fraction is related to moderately labile P, that is, the P bonded to Fe or Al sesquioxides (Hedley et al., 1982; Gatiboni et al., 2013).

The high concentration of P extracted by P-NaOH 0.1 mol L^{-1} (Table 5) is related to the clayey texture (Table 1) and high iron content of the soil, within the range 180 and 360 g kg^{-1}, which creates many adsorption sites and causes temporary mobilization of available P. This consequently reduces the efficiency of the P applied in the soil-plant system.

The high capacity of P adsorption in this soil class may be because of the specific differences between the fertilizers for the extraction with P-NaOH 0.1 mol L^{-1} extraction;

Table 5. Moderately labile soil phosphorus fraction extracted by NaOH 0.1 mol L^{-1} in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers after six years use of organic and mineral fertilizers in a Rhodic Kandiudox

Fertilizer	Fertilization recommendation				Equation
	0 %	75 %	100 %	150 %	
	Moderately labile P				
	mg kg^{-1}				
	0.00-0.05 m				
Poultry Litter	393	515 B	578 AB	608	$\hat{y} = 402 + 1.491^{**}x$ $R^2= 0.96$
Pig slurry	393	530 B	511 B	561	$\hat{y} = 405 + 1.215^{**}x$ $R^2= 0.88$
M1	393	486 B	563 AB	685	$\hat{y} = 375 + 1.934^{**}x$ $R^2= 0.96$
M2	393	771 A	771 A	775	$\hat{y} = 396 + 6.972^{**}x - 0.03^{**}x^2$ $R^2= 0.99$
Compost	393	564 AB	612 AB	633	$\hat{y} = 392 + 4.072^{**}x - 0.02^{**}x^2$ $R^2= 0.99$
	0.05-0.10 m				
Poultry Litter	339	571	549	565	$\hat{y} = 342 + 4.072^{**}x - 0.002^{**}x^2$ $R^2= 0.97$
Pig slurry	339	442	454	577	$\hat{y} = 329 + 1.523^{**}x$ $R^2= 0.96$
M1	339	411	433	502	$\hat{y} = 335 + 1.065^{**}x$ $R^2= 0.99$
M2	339	470	604	603	$\hat{y} = 350 + 1.900^{**}x$ $R^2= 0.88$
Compost	339	537	555	599	$\hat{y} = 365 + 1.763^{**}x$ $R^2= 0.91$
	0.10-0.20 m				
Poultry Litter	148	274 AB	274	280	$\hat{y} = 149 + 2.286^{**}x - 0.09^{**}x^2$ $R^2= 0.99$
Pig slurry	148	257 AB	266	263	$\hat{y} = 148 + 2.103^{**}x - 0.009^{**}x^2$ $R^2= 0.99$
M1	148	199 B	293	300	$\hat{y} = 146 + 1.101^{**}x$ $R^2= 0.86$
M2	148	250 AB	257	357	$\hat{y} = 143 + 1.348^{**}x$ $R^2= 0.97$
Compost	148	318 A	334	341	$\hat{y} = 148 + 3.140^{**}x - 0.012^{**}x^2$ $R^2= 0.99$

Mean values followed by different letters in the column are different through the Tukey test ($p \leq 0.05$). * = $p \leq 0.05$; ** = $p \leq 0.01$). M1 = mineral fertilizer 1, equivalent to pig slurry; M2 = mineral fertilizer 2, equivalent to poultry litter.

which explains the similarity between the mineral and organic forms of P that contributed to the system (Table 5). In this P fraction, there were significance only at the rate of 75 % of fertilization recommendation, being the M2 treatment higher than the others, except for the compost; at the rate of 100 % with slurry lower than M2 in the 0.00-0.05 m layer; and in the rate of 75 % with M1 lower than the compost in the 0.10-0.20 m layer (Table 5).

Comparing poultry litter to M2 and slurry to M1, we observed that organic fertilizers had lower P-NaOH concentrations (Table 5). This result can be explained by the presence of organic compounds, especially those with high carboxylic and phenolic groups, which block the adsorption sites of Fe and Al oxides (Andrade et al., 2003) and reduce P adsorption (Gatiboni et al., 2013).

Increasing application rates of organic and mineral fertilizers in the iCL system raised the moderately labile P contents corresponding to the P-NaOH 0.5 mol L^{-1} fraction, with the effect of fertilizers only in the 75 % rate at the 0.00-0.05 m layer, where compost had a higher content of P-NaOH 0.5 mol L^{-1} than poultry litter (Table 6). Among the fertilizers, it is noteworthy that the mineral form M2 exhibits the highest P-NaOH 0.5 mol L^{-1} contents in the 150 % rate in the 0.00-0.05 and 0.10-0.20 layers and in the 100 % rate in the 0.05-0.10 m layer, a result that may be explained by the greater contribution of this element to the soil. This fraction is related to the moderately labile form of P that is physically and chemically protected in the internal surfaces of soil micro-aggregates (Cross and Schlesinger, 1995).

As in the P-NaOH 0.1 mol L^{-1} fraction, mineral fertilizers showed higher P-NaOH 0.5 mol L^{-1} (moderately labile P fraction) contents than organic sources, considering the same nutrient input in the system, which is demonstrated by higher angular coefficients in the minerals in relation to their organic pairs in the layers evaluated (Table 6).

Table 6. Moderately labile soil phosphorus fraction extracted by NaOH 0.5 mol L^{-1} in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers after six years use of organic and mineral fertilizers in a Rhodic Kandiudox

Fertilizer	Fertilization recommendation				Equation
	0 %	75 %	100 %	150 %	
	Moderately labile P				
	mg kg^{-1}				
	0.00-0.05 m				
Poultry Litter	256	306 B	360	420	$\hat{y} = 246 + 1.101^{**}x$ $R^2 = 0.95$
Pig slurry	256	338 AB	392	385	$\hat{y} = 267 + 0.931^{**}x$ $R^2 = 0.87$
M1	256	351 AB	360	409	$\hat{y} = 262 + 1.011^{**}x$ $R^2 = 0.98$
M2	256	425 AB	468	493	$\hat{y} = 278 + 1.640^{*}x$ $R^2 = 0.92$
Compost	256	467 A	476	483	$\hat{y} = 257 + 3.883^{**}x - 0.020^{**}x^2$ $R^2 = 0.99$
	0.05-0.10 m				
Poultry Litter	147	407	390	430	$\hat{y} = 150 + 4.362^{**}x - 0.017^{**}x^2$ $R^2 = 0.97$
Pig slurry	147	417	428	489	$\hat{y} = 149 + 4.440^{**}x - 0.015^{**}x^2$ $R^2 = 0.99$
M1	147	411	367	435	$\hat{y} = 186 + 1.898^{**}x$ $R^2 = 0.81$
M2	147	471	503	472	$\hat{y} = 147 + 6.419^{**}x - 0.030^{**}x^2$ $R^2 = 0.99$
Compost	147	427	497	480	$\hat{y} = 146 + 5.598^{**}x - 0.020^{**}x^2$ $R^2 = 0.99$
	0.10-0.20 m				
Poultry Litter	123	173	170	174	$\hat{y} = 172$
Pig slurry	123	147	189	183	$\hat{y} = 124 + 0.446^{*}x$ $R^2 = 0.80$
M1	123	146	171	195	$\hat{y} = 119 + 0.492^{*}x$ $R^2 = 0.96$
M2	123	171	160	273	$\hat{y} = 107 + 0.917^{**}x$ $R^2 = 0.79$
Compost	123	234	224	234	$\hat{y} = 124 + 1.933^{**}x - 0.008^{*}x^2$ $R^2 = 0.97$

Mean values followed by different letters in the column are different through the Tukey test ($p \leq 0.05$). * = $p \leq 0.05$; ** = $p \leq 0.01$). M1 = mineral fertilizer 1, equivalent to pig slurry; M2 = mineral fertilizer 2, equivalent to poultry litter.

Among the main fertilizers that contributed to an increase in non-labile phosphorus extracted by HCl, poultry litter, M2, compost, and M1 stand out, with a linear increase in the 0.00-0.05 m layer; poultry litter, M2, and compost stand out in the 0.05-0.10 m layer; and M2 stands out up to the 0.10-0.20 m layer. There were also no differences between the fertilizers at the same rate (Table 7). These results indicate that the presence of the inorganic form of P and higher rates of organic and mineral fertilizers can create chemical bonds with calcium carbonate, and this P will not be available to plants, due to the strong binding force of the inorganic compound formed.

Even with contents lower than those shown in the previous fractions, in the fraction of P extracted by HCl 1 mol L^{-1}, the application of rates up to 150 % increase from the content of 10.8 mg kg^{-1} of non-labile P in the control treatment (zero rate) to 33.8, 30.1, 28.2, and 21.0 mg kg^{-1} in the poultry litter, M2, compost, and M1 respectively, in the surface layer, and are nearly double the concentration from poultry litter, M2, and compost in the 0.05-0.10 m layer (Table 7).

The increase in fertilizer rates, regardless of the form of fertilizer, favors the formation of covalent bonds between P and the clay colloids. This condition explains the increase in residual P content, which shows a linear increase for all fertilizers up to the 0.10 m layer, except for M1 in the surface layer and effective contributions for pig slurry and M2. The same response was maintained in the 0.10-0.20 m layer (Table 8).

Among fertilizers, M2 shows a more intense increase in the residual P fraction in response to fertilizer rates, with the highest angular coefficient in all layers. At the 150 % rate, there was an increase of 164, 184, and 154 % in the 0.00-0.05, 0.05-0.10,

Table 7. Non-labile soil phosphorus fraction extracted through the HCl 1 mol L^{-1} in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers after six years use of organic and mineral fertilizers in a Rhodic Kandiudox

Fertilizer	Fertilization recommendation				Equation
	0 %	75 %	100 %	150 %	
	Non-labile P				
	mg kg^{-1}				
	0.00-0.05 m				
Poultry Litter	10.8	18.2	33.7	33.8	$\hat{y} = 10.5 + 0.167^{**}x$ $R^2 = 0.83$
Pig slurry	10.8	10.2	17.7	16.5	$\hat{y} = 14.8$
M1	10.8	11.6	15.6	21.0	$\hat{y} = 9.3 + 0.068^{*}x$ $R^2 = 0.81$
M2	10.8	13.8	23.8	30.1	$\hat{y} = 8.9 + 0.133^{**}x$ $R^2 = 0.86$
Compost	10.8	21.8	23.7	28.2	$\hat{y} = 11.6 + 0.117^{*}x$ $R^2 = 0.98$
	0.05-0.10 m				
Poultry Litter	7.6	11.9	12.8	14.0	$\hat{y} = 8.0 + 0.044^{**}x$ $R^2 = 0.95$
Pig slurry	7.6	9.7	8.7	10.5	$\hat{y} = 9.6$
M1	7.6	6.7	10.0	9.7	$\hat{y} = 8.8$
M2	7.6	9.6	11.4	13.2	$\hat{y} = 7.4 + 0.038^{**}x$ $R^2 = 0.97$
Compost	7.6	12.5	12.3	14.1	$\hat{y} = 8.1 + 0.043^{**}x$ $R^2 = 0.92$
	0.10-0.20 m				
Poultry Litter	6.9	9.8	11.5	10.2	$\hat{y} = 10.5$
Pig slurry	6.9	9.2	8.5	10.5	$\hat{y} = 9.4$
M1	6.9	5.7	9.0	8.3	$\hat{y} = 7.7$
M2	6.9	9.4	9.1	12.7	$\hat{y} = 6.6 + 0.036^{**}x$ $R^2 = 0.90$
Compost	6.9	9.4	9.4	8.8	$\hat{y} = 9.2$

Mean values are not different through the Tukey test ($p \leq 0.05$). * = $p \leq 0.05$; ** = $p \leq 0.01$. M1 = mineral fertilizer 1, equivalent to pig slurry; M2 = mineral fertilizer 2, equivalent to poultry litter.

and 0.10- 0.20 m layers, respectively, in relation to the treatment without fertilization (zero rate) (Table 8).

An increase in the recommended rates of both organic and mineral fertilizer rates in the iCL system led to an increase in corn yields in the 2015 and 2017 crop seasons and in soybeans in the 2016 crop season (Figure 2). The corn yield in 2015 showed a quadratic increase for poultry litter and a linear response for the other treatments. In 2016, the soybean yield in iCL showed a linear increase for all the fertilizers used and was most intense for compost. In 2017, corn yield showed a linear increase for all treatments, with the highest yield observed in M2. The corn yield in 2015 was higher than that observed in 2017, which can be explained by the amount of rainfall (Figure 1).

These results were also reported by Hentz et al. (2016), who showed an increase in corn yield due to increasing rates of organic fertilizers such as poultry litter and pig slurry, with similar efficiency between their mineral pairs. Novakowiski et al. (2013) reported a direct response between poultry litter and pig slurry fertilization and corn yield. Hanisch et al. (2009) also reported a positive effect of fertilization with poultry litter and other organic sources in increasing corn yield. An increase in corn yield as an effect of fertilization with organic manures has been previously reported in traditional crop sequences in southern Brazil (Scherer et al., 2010; Sartor et al., 2012).

The positive results of corn and soybean yields in the three crop seasons in the iCL production system suggest that using 150 % of fertilization recommendations in both crops for all fertilizers can achieve high yields, and this rate will not exceed the critical limit for P defined by Santa Catarina environmental legislation, considering previous use of these fertilizer in accordance with efficient practices (Figure 2).

Table 8. Residual soil phosphorus in the 0.00-0.05, 0.05-0.10, and 0.10-0.20 m layers after six years use of organic and mineral fertilizers in a Rhodic Kandiudox

Fertilizer	Fertilization recommendation				Equation
	0 %	75 %	100 %	150 %	
	Residual P				
	mg kg^{-1}				
	0.00-0.05 m				
Poultry Litter	524	536	612	824	$\hat{y} = 416 + 1.935^{**}x$ $R^2 = 0.72$
Pig slurry	524	695	780	747	$\hat{y} = 555 + 1.626^{*}x$ $R^2 = 0.80$
M1	524	550	720	731	$\hat{y} = 667$
M2	524	661	667	862	$\hat{y} = 505 + 2.135^{**}x$ $R^2 = 0.92$
Compost	524	569	800	813	$\hat{y} = 505 + 2.109^{**}x$ $R^2 = 0.76$
	0.05-0.10 m				
Poultry Litter	459	486	596	754	$\hat{y} = 417 + 1.935^{**}x$ $R^2 = 0.82$
Pig slurry	459	598	590	679	$\hat{y} = 465 + 1.426^{**}x$ $R^2 = 0.96$
M1	459	544	624	691	$\hat{y} = 451 + 1.582^{*}x$ $R^2 = 0.97$
M2	459	614	622	844	$\hat{y} = 437 + 2.435^{**}x$ $R^2 = 0.92$
Compost	459	568	698	709	$\hat{y} = 463 + 1.794^{**}x$ $R^2 = 0.89$
	0.10-0.20 m				
Poultry Litter	306	371	377	397	$\hat{y} = 381$
Pig slurry	306	290	311	465	$\hat{y} = 266 + 0.950^{*}x$ $R^2 = 0.72$
M1	306	329	354	359	$\hat{y} = 347$
M2	306	417	467	471	$\hat{y} = 321 + 1.166^{**}x$ $R^2 = 0.90$
Compost	306	363	380	452	$\hat{y} = 398$

Mean values are not different through the Tukey test ($p \leq 0.05$). * = $p \leq 0.05$; ** = $p \leq 0.01$). M1 = mineral fertilizer 1, equivalent to pig slurry; M2 = mineral fertilizer 2, equivalent to poultry litter.

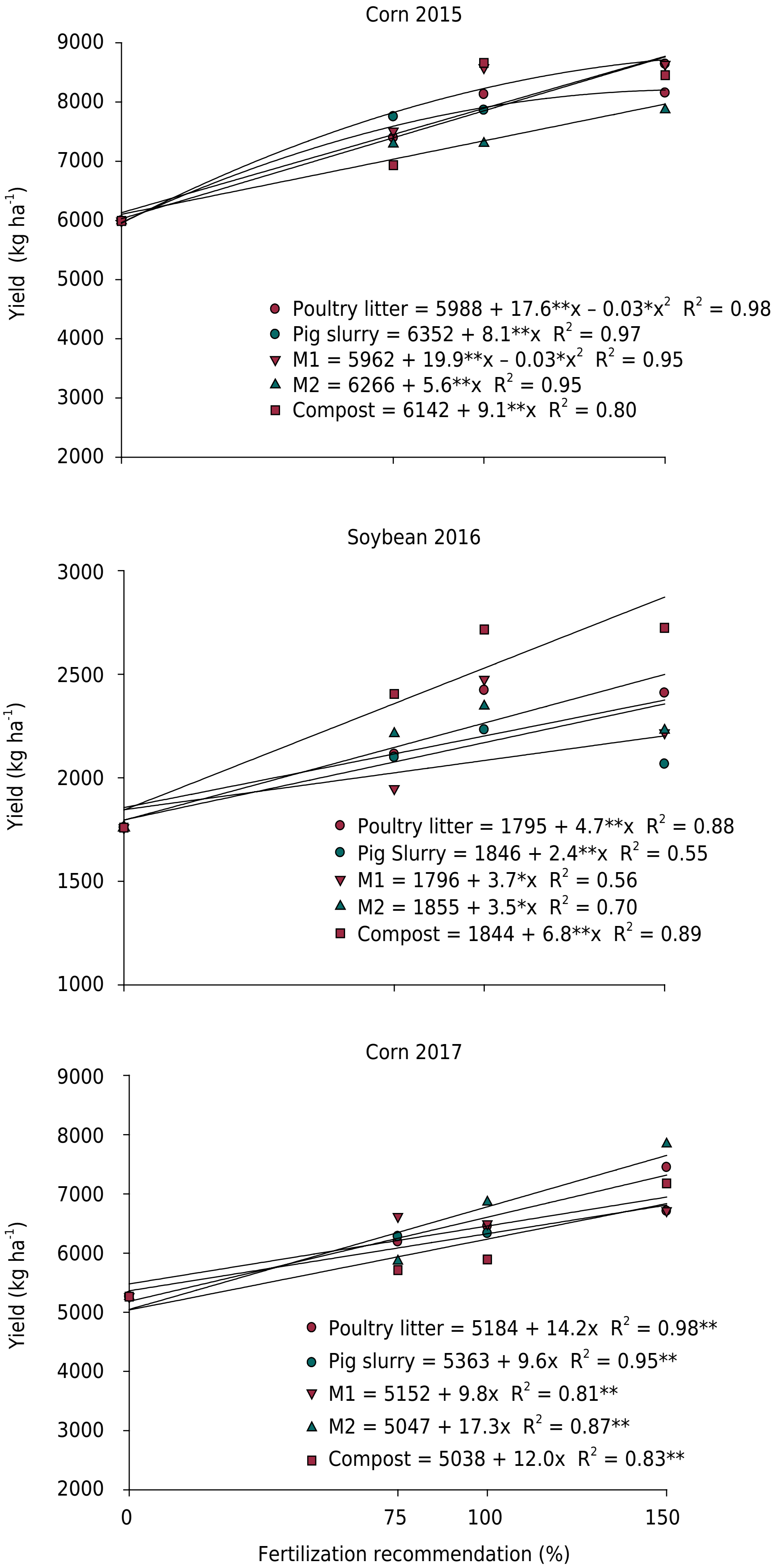

Figure 2. Soybean and corn yield (kg ha^{-1}) in response to the use of increasing rates of organic and mineral fertilizers in a Rhodic Kandiudox.

CONCLUSIONS

Successive use of organic or mineral fertilizers over six years in an iCL system intensely increases the labile and moderately labile P fractions up to the 0.20 m depth, and it has a less intense and positive effect on the non-labile fractions up to 0.10 m.

The higher contribution of P in the poultry litter, M2 (poultry litter), and compost fertilizers leads to higher contents of P (labile, moderately labile, and non-labile) in the three forms of availability, and the mineral form leads to higher levels in the moderately labile form compared to poultry litter/M2 and pig slurry/M1.

The increase in soil P contents is positively related to soybean and corn yields and suggests that 150 % of fertilization recommendation can improve P availability necessary for high crop yields, and it will not exceed the critical limit for P according to local environmental legislation.

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