The Journal of Agricultural Science

cambridge.org/ags

Integrated Crop–Livestock Systems Research Paper

Cite this article: Moreira SG, Hoogenboom G, Nunes MR, Sanchez PA (2023). Circular agriculture practices enhance phosphorus recovery for large-scale commercial farms under tropical conditions. *The Journal of Agricultural Science* **161**, 763–777. https://doi.org/10.1017/S0021859624000042

Received: 19 July 2023
Revised: 15 December 2023
Accepted: 31 December 2023
First published online: 8 January 2024

Keywords:
beef cattle; circular agronomy; circular bioeconomy; crop rotation; no-till

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Circular agriculture practices enhance phosphorus recovery for large-scale commercial farms under tropical conditions

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Abstract

The objective of this research was to assess the adoption of circular agricultural practices as a tool to improve the recovery use efficiency of phosphorus (P) applied to tropical soils. Two Brazilian farms (1 and 2) that are under long-term no-till and cropped year-round with cover and/or cash crops were used in this study. Soybean, maize and common bean were grown during the summer season (October–February), followed by wheat, common bean and maize during the winter season (February–August). *Brachiaria ruziziensis* was intercropped with off-season maize. Farm 1 also grew sweet potatoes in rotation with grains. In the integrated crop–livestock system, the leftovers from the silos and crop residues were used to feed beef cattle, while the residues not used in the confinement were turned into compost and applied in the production fields. During the last 3 years, 80 (farm 1) and 71 (farm 2) kg/ha/year of P-fertilizer was applied to meet the demand of the different crops and 56% (farm 1) and 58% (farm 2) of P-fertilizer was exported through the crops and livestock. P-recovery represented more than 50% on both farms. Around 60% of the P consumed by animals was excreted in the form of faeces and urine and the animal manure was used to produce organic compost. Therefore, most of the P consumed by the livestock was returned back to the field to serve as organic fertilizer. This study showed that circular agricultural practices can enhance P-recovery.

Introduction

Over the past 50 years Brazil has changed from a food importer to one of the world's largest food producers due to an increase in agricultural efficiency. This change was based on new technologies for tropical agriculture that transformed the acidic and nutrient-poor tropical soils into the current built-up fertility areas with a high crop yield (Resende *et al.*, 2016; Moreira, 2019). From 1976/77 to 2022/23, food production in Brazil increased by 700%, while the cultivated area only increased by 90% (Companhia Nacional de Abastecimento – CONAB, 2023). If Brazil had maintained the yield rates of 1976/77, i.e. 1270 kg/ha, the current cultivated area would have been 246 million ha, instead of the current 78 million ha.

Even with all the gains in yield and production, there is still a need for change. Currently, many agricultural systems in the world have become very specialized with a low crop diversity that depends mainly on chemical inputs (Basso *et al.*, 2021). Therefore, the circular agricultural approach was created to improve issues associated with the current agricultural practices (De Boer and Van Ittersum, 2018). The use of no-till (NT), crop rotation, maize intercropped with grasses, such as *Brachiaria ruziziensis*, cover crops to keep the soil covered all year round, use of inoculants for biological nitrogen fixation, as well as organic compost to reduce the use of chemical fertilizers are key circular practices to reduce the use of natural resources and promote the reuse and recycling of nutrients (Muscat *et al.*, 2021; Moreira *et al.*, 2023).

Most of the tropical soils found in Brazil are originally acidic, with low pH values (4.5–5.5), high aluminium contents and low fertility, including low contents of calcium, magnesium, P and potassium (Lopes and Guilherme, 2016; Volf and Rosolem, 2021). P use efficiency in these highly weathered soils is low, primarily due to the P adsorption onto the surface of iron (Fe)- and aluminium (Al)-(hydr)oxide colloids (Heuer *et al.*, 2017; Matos *et al.*, 2017; Nascimento *et al.*, 2018; Vásconez and Pinochet, 2018; Zavaschi *et al.*, 2020). Under acidic conditions, the presence of Fe^{2+} and Al^{3+} ions in the soil solution favours the formation of iron and aluminium phosphates, thus leading to even lower plant-available P (Urrutia *et al.*, 2014; Lopes and Guilherme, 2016; Sanchez, 2019).

To meet the growing global food demand and to decrease the agricultural negative impact on the environment, e.g. biodiversity, ecosystem health and climate change, crop yield must increase without increasing the use of natural resources such as land, water and mineral fertilizers (Basso *et al.*, 2021). The degraded pasturelands with a low nutrient rate in Brazil have been incorporated into the agricultural production areas, requiring the application of high doses of amendments, especially P-fertilizers. Nevertheless, P-fertilizer is finite (Withers *et al.*, 2018) and, according to the circular agriculture principles, its use must be minimized (Muscat *et al.*, 2021). Currently, soybean alone is being grown in Brazil at a rate of 1.5 million ha/year, which has caused a tremendous increase in the use of P-fertilizer (Companhia Nacional de Abastecimento – CONAB, 2023).

Adopting soil and crop management practices such as NT combined with cropping system diversification contributes to the sustainability of production systems (Moreira *et al.*, 2023). However, currently, just about 50% of the total cropland in Brazil is being cultivated under NT (Moreira, 2019). This fact highlights an opportunity to improve the sustainable production system by improving the adoption of these practices. When NT is combined with other conservation practices, such as soil protection through cover crops and cash crops, as well as diversification of cropping systems with crop rotations, the agricultural system becomes more sustainable. For instance, NT can promote soil health by decreasing soil erosion and runoff, increasing soil nutrient cycling, biological activity, carbon and nutrient contents, microbial activity and the formation and preservation of stable soil aggregates, in addition to the retention and movement of water and air in the soil system (Nunes *et al.*, 2018, 2020a; Moreira *et al.*, 2020).

The adoption of circular agriculture principles could promote crop yield and minimize the depletion of natural resources and, thus, avoid unnecessary losses (Muscat *et al.*, 2021). However, this hypothesis has never been tested under tropical conditions. The outcome of this study can serve as an example for other farmers in countries that have a high agricultural intensification, i.e. with two or three seasons in the same cropping year. The conditions of these two large farmers will provide us with the opportunity to validate the concept of circular agriculture for large-scale grain production in tropical environments. In this study, our main objective was to evaluate the efficiency of P recovery in production systems that adopt circular agricultural practices.

Materials and methods

Farm history and management

The two large commercial farms (3W Agronegócios [farm 1] and Santa Helena Farms [farm 2]) that were evaluated in this study have been described by Moreira *et al.* (2023). Briefly, the farms are in Minas Gerais, Brazil, in Itutinga county 21°23′S; 44°39′W (farm 1) and Nazareno county 21°15′S; 44°31′W (farm 2). The main soils on both farms are oxisols and classified as Typic Hapludox in the US Soil Taxonomy (Soil Survey Staff, 2014). The climate in the region is classified as Cwa (Köppen climatic classification). Thus, the winter is cold and dry, and the summer is hot and humid.

The two farms started their operations approximately two decades ago and have been expanding since then, incorporating areas previously under degraded pastures while adopting circular agricultural practices. Herein, degraded pastures are native or cultivated pastures that have suffered a sharp drop in carrying capacity, due to the reduction in biomass production. In Brazil, the poor yield of degraded pastures is due to inadequate soil management, overgrazing, insufficient control of weeds and pests and lack of fertilization (Feltran-Barbieri and Féres, 2021). Lack of adequate fertilization is the main factor in Brazilian conditions leading to degradation since the majority of the soils exhibit a high acidity and a limited nutrient content, particularly in terms of P (Lopes and Guilherme, 2016), and most pastures are planted without a soil fertility correction such as the application of limestone and P-fertilizer.

The total cropland of both farms is under NT and the cropping system is diversified. The soil is covered with mulch from both the cash and cover crops for the entire year, with maize intercropped with a tropical grass. As described by Moreira *et al.* (2023), since 2020 the farms have implemented an integrated crop–livestock system in beef cattle confinement using agricultural products and by-products that are produced on each farm. The study considered data collected during the 2018/19, 2019/20 and 2020/21 cropping years with two growing seasons per cropping year, i.e. summer season (October–February) and winter season (February–August).

The cultivated area of farm 1 was 1559 ha in 2018/19, 1675 ha in 2019/20 and 1848 ha in 2020/21 during the summer season, and 1299 ha in 2018/19, 1437 ha in 2019/20 and 1787 ha in 2020/21 during the winter season. The cultivated land in farm 2 was 903 ha in 2018/19, 1025 ha in 2019/20 and 1116 ha in 2020/21 in the summer season, and 739 ha in 2018/19, 1025 ha in 2019/20 and 1021 ha in 2020/21 in the winter season.

Soil management, crop yield and estimates of P uptake

Details of crop management and fertilizer practices during the 3 years were presented by Moreira *et al.* (2023). During the first year, deep tillage was required to incorporate limestone and gypsum up to 0–0.40 m; during the remaining years the soil was managed under NT. In addition, millet (*Pennisetum glaucum*) was grown as a cover crop during the first year of cultivation prior to the first crop to protect the soil against erosion following incorporation of lime and gypsum. Millet was grown from September to December and was followed by common bean (*Phaseolus vulgaris*), the first cash crop.

The procedures that were used for grain and sweet potato harvest, cleaning, drying, weighing and storage are provided in detail by Moreira *et al.* (2023). The estimation of the dry matter (DM) yield (kg/ha) of crop residues produced in each of the production fields was based on the harvest index for each of the crops as published in the Brazilian literature (Table 1). P content of both the grain and residue was also sourced from the Brazilian literature, with a few exceptions. Analysis of the grain and residue intended for livestock feed was conducted at a regional laboratory, utilizing samples collected directly from each farm. The DM yield of the cover crops (millet, oat and *B. ruziziensis*), and the P content of DM were also estimated based on the average P concentration from the literature for Brazilian Cerrado conditions (Table 2).

The average amount of P applied to each field (kg/ha/year) as P-fertilizer, crop residue or compost, as well as the average amount of P exported by crops and in the bodies of beef cattle (kg/ha/year) were calculated using the same procedures described by Moreira *et al.* (2023) for nitrogen. As the most of the crop root system is concentrated in the upper soil layers, total P mineralization of the organic phosphorus stock was estimated for the top 0.60 m soil for both farms. Organic P values were calculated using the average organic carbon content in

Table 1. P content in DM (kg/t) of grains and residues and the harvest index according to the Brazilian literature

Crop	Part of the plant	Value	Source of data
Soybean	Grain	4.9	Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA (2020)
	Residue	1.2	Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA (2020)
	Harvest index	0.544	Average number according to Pierri *et al.* (2016) and Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA (2020)
Wheat	Grain	3.2	Pauletti and Motta (2019)
	Residue	2.0	Average value of analysis of samples from farms
	Harvest index	0.445	Average according to Pierri *et al.* (2016)
	Broken grain	3.4	Average value of analysis of samples from farms
Maize	Grain	4.2	Silva *et al.* (2018)
	Residue	1.4	Silva *et al.* (2018)
	Harvest index	0.462	Average according to Pierri *et al.* (2016) and Silva *et al.* (2018)
	Silage	1.7	Average value of analysis of samples from farms
	Snaplage[a]	2.2	Average value of analysis of samples from farms
Sorghum	Grain	5.7	Borges *et al.* (2018)
	Residue	2.0	Borges *et al.* (2018)
	Harvest index	0.483	Borges *et al.* (2018)
Common bean	Grain	7.9	Silva and Moreira (2022)
	Residue	2.5	Silva and Moreira (2022)
	Harvest index	0.497	Silva and Moreira (2022)
	Broken common bean/soybean	3.0	Average value of analysis of samples from farms
Oat	Grain	3.0	Average value of analysis of samples from farms
	Residue	1.0	Van Raij *et al.* (1996)
	Harvest index	0.250	Pierri *et al.* (2016)
Sweet potato	Root	2.0	Average value of analysis of samples from farms
	Residue	0.1	Van Raij *et al.* (1996)
	Harvest index	0.230	Ariana Lemes da Costa from Universidade Federal de Lavras (personal information)

aOnly ear silage (cob, grain and straw maize).

each layer of the soil, i.e. 1.9% (0–0.20 m), 1.4% (0.20–0.40 m) and 1.2% (0.40–0.60 m) for farm 1, and 1.9% (0–0.20 m), 1.3% (0.20–0.40 m) and 0.9% (0.40–0.60 m) for farm 2. The C/P ratio was assumed to be 71.3, calculated for the 0–0.20 m soil depth based on Balota *et al.* (2014), and the averaged soil bulk density (1.2 kg/dm^3) for oxisols in the same region of our study (Rocha *et al.*, 2002).

The total quantities of organic phosphorus stock for both farms were the sum of the values obtained for the top three soil layers (0.0–0.20, 0.20–0.40 and 0.40–0.60 m). An average rate of 7.0% per year was used as the average mineralization value for the topsoil layer (Camargo *et al.*, 2002), considering soils under NT with constant inputs of mineralizable residues for the surface layer. Because there was no increase in soil organic matter (SOM) below the top 0.20 m of soil profile under NT (Moreira *et al.*, 2020), only mineralized P from the 0–0.20 m layer was considered in the present study.

The P recovery from fertilizer is usually calculated by the difference in P uptake between the fertilized and unfertilized crop (control), divided by the P-fertilizer rate that was applied (Sanchez, 2019). However, we could not calculate fertilizer P recovery using common procedures because there were no control plots. Instead, P recovery was calculated as the ratio between all P extracted by the crops and all P input for the soil:

$$\text{P recovery} = \frac{(\text{P Crop})}{(\text{PFertilizer} + \text{P Compost} + \text{P Residue} \ + \text{P SOM})} \tag{1}$$

where P Crop is the average amount of P exported by crops (kg/ha/year) during the three cropping years; P Fertilizer is the average amount of P from all chemical fertilizers (kg/ha/year) applied during the three cropping years; P Compost is the average amount of P of the compost applied (kg/ha/year) during the three cropping years; P Residue is the average amount of P residue (kg/ha/year) produced during the three cropping years and P SOM is the average amount of mineralized P in the 0–0.20 m layer (kg/ha/year) during the three cropping years.

The amount of P (kg/ha/year) used in compost piles was estimated based on the difference between the sum of the total amount of P in the by-product and forage produced for feed minus the amount not used by the animals or stored.

Table 2. Cover crop yield and P content in the DM for each crop under Brazilian Cerrado conditions

Literature	Millet		*B. ruziziensis*		Oat	
	DM t/ha	P content kg/t of DM	DM t/ha	P content kg/t of DM	DM t/ha	P content kg/t of DM
Bressan *et al.* (2013)	5.0	–	4.0	–		–
Camargo and Piza (2007)	–	–	–	–	3.4	–
Carvalho *et al.* (2015)	4.0	–	2.1	–	–	–
Castro *et al.* (2017)	8.2	0.5	4.3	1.3	–	–
Correia *et al.* (2013)	–	–	4.4	–	–	–
Gonçalves and Ceretta (1999)	–	–	–	–	3.3	–
Guimarães (2000)	7.9	–	–	–	–	–
Leite *et al.* (2010)	7.0	1.0	–	–	–	–
Moreira *et al.* (2014)	8.6	2.3	3.7	2.9	2.8	3.3
Pariz *et al.* (2011)	–	–	5.5	–	–	–
Pacheco *et al.* (2011)	3.4	3.0	4.5	1.9	–	–
Pacheco *et al.* (2013a)	1.9	3.0	–	–	–	–
Pacheco *et al.* (2013b)	0	3.0	–	–	–	–
Pacheco *et al.* (2017)	4.6	–	–	–	–	–
Pauletti and Motta (2019)	–	2.3	–	–	–	2.6
Richart *et al.* (2010)	–	–	3.6	–	–	–
Salume *et al.* (2020)	–	–	–	–	–	8.0
Silva *et al.* (2016)	7.4	–	–	–	–	–
Teixeira *et al.* (2005)	2.9	2.3	–	–	–	–
Torres *et al.* (2005); Torres *et al.* (2008) and Torres and Pereira (2008)	7	2.0	–	–	2.9	4.6
Van Raij *et al.* (1996)	–	–	–	–	–	4.0
Average number	5.7	2.1	4.0	2.2	3.1	4.5

– data not provided by the author(s).

Integration of agricultural production with animals in confinement

As described by Moreira *et al.* (2023), grain production was integrated into the beef cattle production system, in confinement in 2020, using animals of the Nellore breed (*Bos indicus*). During the first year, the integration started with only a few animals on both farms and the number of animals has slowly increased. For farm 1, the number of confined animals increased from 686 animals in the growing phase prior to the fattening confinement and 774 animals during the fattening phase in 2020 to 1214 animals in the growing phase and 1030 animals in the fattening phase in 2021. In 2020, farm 2 had 148 animals in the growing phase and 88 animals in the fattening phase and expanded to 492 animals in the growing phase and 509 animals in the fattening phase in 2021.

The diet of the animals in confinement was determined by nutritionist veterinarians and varied according to the group of animals. Therefore, the diet offered to growing animals was different from that of fattening animals (Table S1). During the confinement period, maize silage and snaplage (silage rich in starch in which only the ears and grains are ensiled), grains and silo leftovers, i.e. broken grains, leftover sweet potatoes, produced on the farms were used. However, other products were purchased in the marketplace, such as sorghum grain, soybean meal and cottonseed, dried distillers grain, among others when economically advantageous (Table S2). Part of the straw from wheat was also used to feed confined animals, as well for composting. Thus, only part of wheat residues returned to the cultivated soils. In turn, leftovers from animal feed, as well as straw from the pre-cleaning system of grain silos that were not used in animal feed, were added in the composting. Periodically, the manure from the confinement was gathered and transported to the compost piles to be combined with all by-products.

The amounts of P exported in the live weight of the animals during the average confinement period (85 days for farm 1 and 76 days for farm 2) were calculated according to the average P composition of the animals as determined by Valadares Filho *et al.* (2016). The average amount of P exported in the live weight of the animals and the P input in the diet and P output via urine + faeces (kg/ha/year) were estimated by dividing the total amounts of P by the total cropland for the two cropping years (2019/20 and 2020/21) for farm 1 (3523 ha) and farm 2 (2141 ha). The total amount of P in excreta (faeces and urine) was estimated by subtracting the P ingested in the diets from the P exported in the animals' live weight.

Results

Phosphorus content in grains, residues, forages and live weight of animals

The total amount of P accumulated in the grain, forages and residues by crop, growing season and farm is presented in Tables 3 and 4. The agricultural practices, cultivated areas and crop yield are presented by Moreira *et al.* (2023). Thus, for this study, we focused on the P inputs and outputs in the system. This includes the amount of P consumed in the DM by the animals, exported during the confinement period and in the crop residues (Table 5). The animals from farms 1 and 2 ingested 2795 and 1376 t of DM, equivalent to 10.5 and 3.1 t of P, respectively (Table S2). In total, 4.4 t of P for farm 1 and 1.1 t of P for farm 2 were exported during the confinement period (Table 5).

Soil P and organic P

During the three cropping years from 2018/19 to 2020/21, the P content based on Mehlich-1 averaged of all production fields increased from 3.5 to 5.4 for the 0–0.20 m soil depth, from 1 to 1.3 for the 0.20–0.40 m soil depth and from 0.5 to 1.9 mg/dm^3 for the 0.40–0.60 m soil depth for farm 1. For farm 2, the P content for the 0–0.20 and 0.20–0.40 m soil depths ranged from 6.4 to 6.0 and 2.5 to 1.5 mg/dm^3, respectively during the five cropping years from 2016/17 to 2020/21.

The total quantities of 1051 kg of organic phosphorus stock for farm 1 and 958 kg for farm 2 were the sum of the values obtained for the top three soil layers from 0.0 to 0.20 m (444 kg for both farms), from 0.20 to 0.40 m (327 for farm 1 and 304 kg for farm 2) and from 0.40 to 0.60 m (280 for farm 1 and 210 kg for farm 2) (Figs 1 and 2). Assuming an average SOM mineralization rate of 7% per year in the 0–0.20 m layer (Camargo *et al.*, 2002), nearly 31 kg/ha/year of P was mineralized per year for each farm (Figs 1 and 2).

P inputs and outputs

About 405 t of P was applied on farm 1 and 215 t of P on farm 2 as P-fertilizers during the three years of this study (Tables 6 and 7) to meet the demand of the different crops. These values represent the average rates of 79.7 kg/ha/year for farm 1 and 70.7 kg/ha/year for farm 2 (Figs 1 and 2 and S1 and S2). About 219 t of P was exported by grains, sweet potatoes and animal bodies on farm 1. This number considers the 2.6 t of P from the grains consumed by the animals on farm 1 (Table S2) and the 4.4 t of P exported by the animals (Table 5). The total P extraction in DM on farm 1, including P from grains, forage and leftovers, was 10.5 t (Tables S4). Thus, 43.7 kg/ha/year of P in grains and sweet potatoes were exported, or 45.0 kg/ha/year when considering the amount exported by the animals (Figs 1 and S1).

For farm 2, 125 t of P was exported as grains and by animals. About 126 t of P was exported by the grains initially (Table 7), but 1.9 t of P in the grains was consumed as animal feed (Table S2), and 1.1 t of P in the live animal weight was exported by the animals that were sold (Table 5). The total P consumption in DM for farm 1, including P from grains, forage and leftovers was 3.1 t (Table S4). Thus, on average, 41.3 kg/ha/year of P was exported (Figs 2 and S2).

Regarding the total amount of P in the residues of each crop, 86 t of P for farm 1 and 47 t of P for farm 2 were returned directly to the soil during the three years of the study (Tables 6 and 7). Nearly 10 t for farm 1 and 4 t of P for farm 2 were returned to the soil in 2021/22, which resulted in a total of 18.8 kg/ha/year for farm 1 and 16.9 kg/ha/year for farm 2 that was added to the soil (Figs 1 and 2 and S1 and S2).

Most of the animal feed used in the animals' diet was produced on both farms, while the remainder was purchased on the market when it was most economically advantageous. The food produced for animal feed on farm 1 had 11.5 t of P in its composition, part of which was in the form of maize silage (2.1 t), snaplage silage (1.3 t), leftover sweet potatoes (4.1 t) and wheat straw (4.0 t) (Table 6). Leftover and maize snaplage made available as forage (Table 6), 6 t of P (1.7 kg/ha/year) were consumed by the livestock on farm 1. When including the feed purchased from the market (Table S2), the total P intake on farm 1 amounted to 3 kg/ha/year (Fig. 1). Based on the records for farm 1, at the end of the study period there was currently 500 t of DM of wheat straw (0.9 t of P) and 496 t of DM of maize silage (0.8 t of P) stored on the farm, resulting in a total of 0.35 kg/ha/year stored as forage (Fig. 1).

The maize silage (0.5 t of P) and wheat straw (2.0 t of P) used for animal feed on farm 2 totalled 2.5 t of P in its composition (Table 7). In addition, it used broken grains and other grains that were ground for animal feed. Of the total forage and leftovers made available as forage (Table 7), 2.4 t of P (1.14 kg/ha/year) were used by the animals on farm 2 for a total of 1.5 kg/ha/year (Fig. 2) when considering the feed from the market that was provided to the animals (Table S2). The estimated amount of P excreted in faeces and urine was 6.1 t for farm 1 (1.7 kg/ha/year) and 2.0 t for farm 2 (0.9 kg/ha/year).

Using leftover grain silage, wheat straw and animal manure, farm 1 produced 5000 t of organic compost being equivalent to 7 t of P (1.4 kg/ha/year) and farm 2 produced 3360 t of organic compost (equivalent to 4.7 t of P or 1.4 kg/ha/year) to be applied in the production fields. The compost piles received 3.5 kg/ha/year on farm 1 and 1.9 kg/ha/year of P on farm 2, accounting for 1.7 kg/ha/year of P for farm 1 and 0.9 kg/ha/year of P for farm 2 from animal manure, and about 1.8 kg/ha/year of P for farm 1 and 1 kg/ha/year of P for farm 2 from leftovers not consumed by animals or stored.

P recovery efficiency

Phosphorus recovery for farms 1 and 2 was calculated according to Equation (1). For farm 1, P recovery was 50.3% and P recovery for farm 2 was almost the same as for farm 1, i.e. 50.5%. It should also be noted that farm 1 applied only 79.7 kg/ha/year as P-fertilizer and P extracted by crops was 65.8 kg/ha/year (Fig. 1). On the other hand, the P accumulated by crops in farm 2 was 60.7 kg/ha/year and 70.7 kg/ha/year was applied as P-fertilizer (Fig. 2).

Discussion

Soil phosphorus and organic phosphorus

Most of the total P in tropical soils, e.g. oxisols, is not available to plants due to the P adsorption on the surface of Fe- and Al-(hydr) oxides (Urrutia *et al.*, 2014; Lopes and Guilherme, 2016; Sanchez, 2019; Volf and Rosolem, 2021), as well as losses due to

Table 3. Cultivated area, forage, grain and sweet potato yield based on DM and the total amount of phosphorus accumulated in the grain, forages and residues by each crop grown during each growing season for farm 1

Crop		Cropping 2018/19						Cropping 2019/20						Cropping 2020/21					
		Summer season			Winter season			Summer season			Winter season			Summer season			Winter season		
		Area ha	Yield t/ha	P t	Area ha	Yield t/ha	P t	Area ha	Yield t/ha	P t	Area ha	Yield t/ha	P t	Area ha	Yield t/ha	P t	Area ha	Yield t/ha	P t
Maize snaplage	DM residue							40	17.4	1.0									
	DM forage								15.0	1.3									
Maize silage	DM forage										15	13	0.3				65	15.7	1.7
Maize	Grain	288	12.6	15.2	202	8.4	7.2	385	12.5	20.1	574	7.3	17.7	584	12.6	30.8	201	5.7	4.8
	DM residue		14.6	6.0		9.8	2.8		14.5	6.8	0	8.5	7.0		14.6	12.2		6.6	1.9
Common bean	Grain	469	3.0	11.0	355	1.9	5.3	439	2.5	8.6	309	1.7	4.1	375	1.9	7.1	449	2.1	5.8
	DM residue		3.0	3.5		1.9	1.7		2.5	2.7		1.7	1.3		1.9	2.3		2.1	1.8
Soybean	Grain	605	5.2	15.5				574	4.5	12.6				776	5.9	17.4			
	DM residue		6.3	4.7					5.4	3.8					7.0	5.2			
Wheat grain	Grain				646	3.8	7.8				299	3.0	2.9				612	2.0	4.1
	DM residue					4.7	5.6					3.8	2.1					2.5	3.0
Wheat grain[a]	Grain				96	4.4	1.4				210	4.1	2.8				175	4.7	1.4
	DM Harvest					5.5	1.0					5.1	2.0					5.9	1.0
Sorghum	Grain																154	1.9	1.6
	DM residue																	2.2	0.7
Millet[b]	DM residue	469	5.7	2.9										249	5.7	3.0			
Brachiaria[c]	DM residue				202	4	1.8				610	4	5.4				201	4	1.8
Oat	DM residue										30	3	0.4						
Sweet potato	Nature mass roots	197	72					237	72					113	72		131	66	
	DM roots		18	7.1					18	8.6					18	4.1		16	4.3
	DM residue			1.2						1.4						0.7			0.7
Cover crop area		469			202			0			640			249			201		
Cash crop area		1559			1299			1675			1437			1848			1787		
Total area		2028			1501			1675			2047			2097			1988		

[a] Wheat straw harvest after wheat grain.

[b] Millet grown before summer season common bean (same fields).

[c] *B. ruziziensis* intercropped with maize (same fields).

Table 4. Cultivated area, forage, grain and sweet potato yield based on DM and the total amount of phosphorus accumulated in the grain, forages and residues by each crop grown during each growing season for farm 2

Crop		Cropping 2018/19						Cropping 2019/20						Cropping 2020/21					
		Summer season			Winter season			Summer season			Winter season			Summer season			Winter season		
		Area	Yield	P	Area	Yield	P	Area	Yield	P	Area	Yield	P	Area	Yield	P	Area	Yield	P
		ha	t/ha	t	ha	t/ha	t	ha	t/ha	t	ha	t/ha	t	ha	t/ha	t	ha	t/ha	t
Maize silage	DM forage										13	12.3	0.3				25	11.2	0.5
Maize	Grain	274	12.6	14.5	150	7.3	4.6	323	12.3	16.6	247	7.4	7.7	300	11.6	14.6	70	4.8	1.4
	DM residue		14.6	5.7		8.5	1.8		14.3	6.6		8.6	3.0		13.5	5.8		5.6	0.6
Common bean	Grain	236	2.7	5.1	196	2.3	3.6	385	2.2	6.6	294	2.0	4.6	161	2.5	3.2	300	1.0	2.5
	DM residue		2.8	1.6		2.3	1.1		2.2	2.1		2.0	1.5		2.5	1.0		1.0	0.8
Soybean	Grain	393	4.5	8.6				317	4.7	7.2				655	4.5	14.5			
	DM residue		5.4	2.6					5.6	2.2					5.4	4.4			
Wheat grain	Grain				227	3.1	2.3				232	2.7	2.0				462	0.8	1.2
	DM residue					3.9	1.6					3.3	1.4					1.1	0.9
Wheat grain[a]	Grain				166	2.6	1.4				154	2.8	1.4						
	DM harvest					3.2	1.0					3.5	1.0						
Sorghum	Grain																164	2.5	2.3
	DM residue																	2.9	0.9
Oat	Grain										30	0.4	0.04						
	DM residue											1.2	0.04						
Millet[b]	DM residue	86	5.7	1.0				151	5.7	1.7				84	5.7	1.0			
Brachiaria[c]	DM residue										36	4	0.3				95	4	0.8
Oat residue[d]	DM residue										55	3.1	0.8						
Cover crop area		86			0			151			91			84			95		
Cash crop area		903			739			1025			970			1116			1021		
Total area		989			739			1176			1061			1200			1116		

[a] Wheat straw harvest after wheat grain.

[b] Millet grown before summer season common bean (same fields).

[c] *B. ruziziensis* intercropped with maize (same fields).

[d] Oat for mulch in winter season.

Table 5. Number of animals in confinement per year for each animal category, i.e. growing and fattening phase, initial and final live weight, live weight gain per animal and total per farm and P exported by animals during the two years of confinement on farms 1 and 2

	Farm 1						Farm 2					
		Live weight (kg/animal)			Gain/farm	P exported[a]		Live weight (kg/animal)			Gain/farm	P exported[a]
Confinement type	Number of animals	Initial	Final	Gain	kg	kg	Number of animals	Initial	Final	Gain	kg	kg
	January–December 2020											
Growing phase	686	335	415	80	54 857	466	148	344	393	48	7148	61
Fattening phase	774	410	518	108	83 882	712	88	385	509	124	10 930	93
Total for 2020	1460				138 739	1178	236				18 078	154
	January–December 2021											
Growing phase 1	585	320	410	90	52 686	447	274	374	422	49	13 361	112
Growing phase 2	629	275	352	77	48 742	414	218	270	376	106	23 159	198
Fattening phase 1	688	410	540	130	89 114	757	400	435	553	118	47 244	402
Fattening phase 2	342	424	573	150	51 130	434	109	415	551	136	14 776	125
Total for 2021	2244				241 672	2052	1001				98 539	837
Total	3704					3231	1237					990

[a] Quantities of P exported in the animal's live weight during the confinement period on each farm, calculated based on the composition of the animals (Valadares Filho *et al*., 2016).

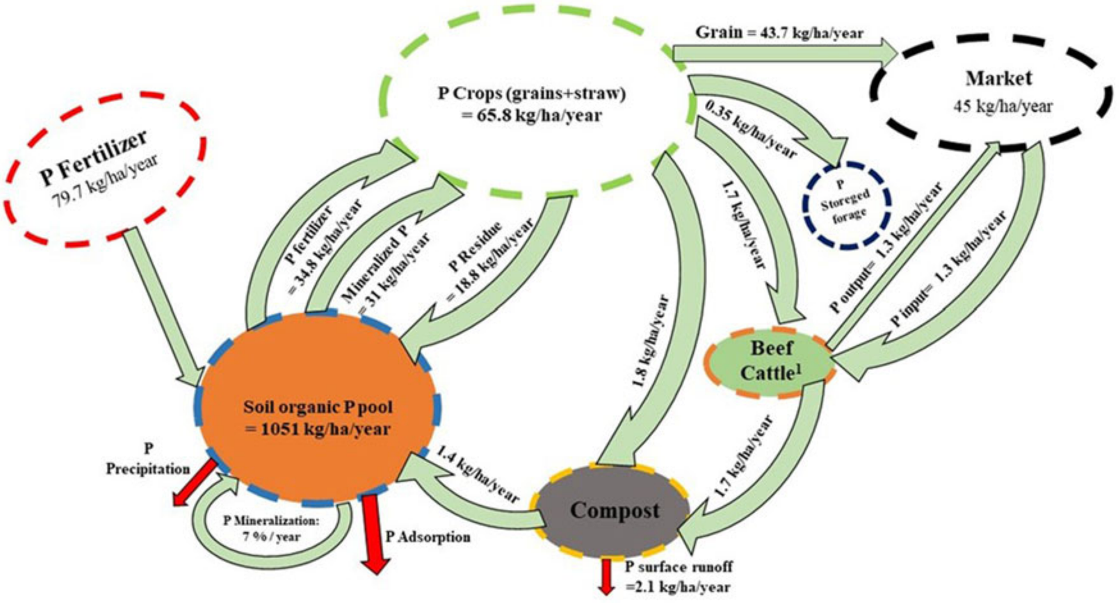

Figure 1. Summary of average P inputs and outputs (kg/ha/year) in the production system of farm 1 based on the data obtained for the 2018/19, 2019/20 and 2020/21 cropping years and beef cattle production from 2020 to 2021. The stocking rate on the farm was 1 animal/ha.

precipitation of the orthophosphate ion ($H_2PO_4^-$) from P-fertilizer, with the Al^{3+} and Fe^{2+} ions present in acidic soils (Lopes and Guilherme, 2016). In fact, the initial pH (H_2O) of soil prior to the study ranged from 4.9 to 5.2 and available P (Mehlich-1) was extremely low, ranging from 0.1 to 3.8 mg/dm^3 (Moreira *et al*., 2023). However, the P content (Mehlich-1) for the 0–0.20, 0.20–0.40 and 0.40–0.60 m soil layers increased in farm 1 after the three cropping years (2018/19 to 2020/21). Within the top layer, i.e. 0–0.20 m, where most of the root system is concentrated under NT (Nunes *et al*., 2019), the P content improved from very low, i.e. <4.0 mg/dm^3 to low rates, i.e. 4.0–8.0 mg/dm^3, according to the soil fertility interpretation classes in the region (Ribeiro *et al*., 1999). In the surface soil layers of farm 2, the P content was classified as low (Ribeiro *et al*., 1999).

Organic P is particularly important in NT systems, especially in the topsoil layers where the crop root systems predominate. The release of P from crop residues to the soil via organic matter mineralization is relatively fast compared to the release of organic N by microorganisms. More than half of the organic P in the soil consists of monoesters, in which P is bound to oxygen. This P–O bond can be easily broken by the phosphatase enzyme produced by plant roots, mycorrhizal fungi and other microorganisms

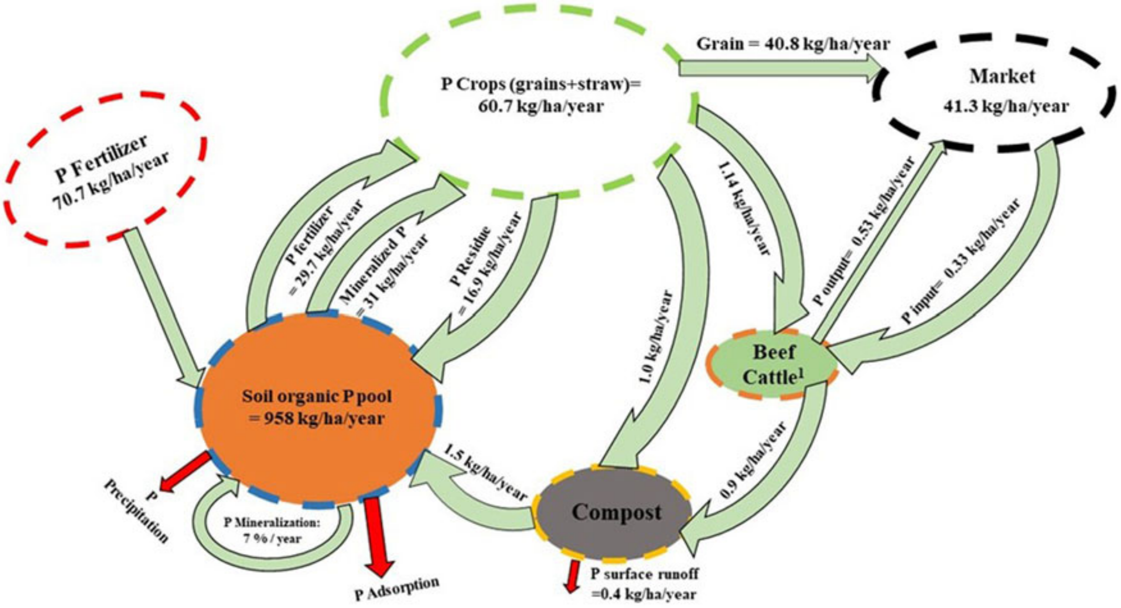

Figure 2. Summary of average P inputs and outputs (kg/ha/year) in the production system of farm 2 based on data obtained for the 2018/19, 2019/20 and 2020/21 cropping years and beef cattle production from 2020 to 2021. The stocking rate on the farm was 0.6 animals/ha.

Table 6. Phosphorus inputs and outputs in the grains, sweet potatoes, forage and straw to confinement for each growing season during the three cropping years for farm 1

	Cropping 2018/19			Cropping 2019/20			Cropping 2020/21			Total
Item	Summer season	Winter season	Total P	Summer season	Winter season	Total P	Summer season	Winter season	Total P	Three Cropping years
	kg/farm			kg/farm			kg/farm			t
Phosphorus input										
Fertilizer	97 498	52 882	150 381	72 905	47 165	120 070	87 759	46 965	134 724	405.2
Compost									7006	7.0
Total crop residue	2934	15 397	18 331	11 926	15 799	27 725	19 176	20 391	39 567	85.6
Maize residue		6013	6013	2832	7834	10 666	6996	12 195	19 191	35.9
Common bean residue		3535	3535	1684	2744	4429	1320	2280	3599	11.6
Soybean residue		4686	4686		3823	3823		5249	5249	13.8
Wheat residue			0	5631		5631	2093		2093	7.7
Sorghum residue			0			0			0	0.0
Oat residue			0			0	419		419	0.4
Brachiaria residue			0	1778		1778	5368		5368	7.1
Sweet potato residue		1162	1162		1398	1398		667	667	3.2
Millet residue	2934		2934	0		0	2981		2981	5.9
Input soil total			168 711			147 795			181 296	497.8
Input soil 2021/22									9875	9.9
Phosphorus output in the crops										
Maize grain	15 197	7159	22 356	20 132	17 683	37 814	30 822	4799	35 622	95.8
Common beans grain	11 038	5259	16 297	8569	4120	12 689	7118	5766	12 884	41.9
Soybean grain	15 494		15 494	12 639		12 639	17 356		17 356	45.5
Wheat grain		9118	9118		5650	5650		5586	5586	20.4
Sorghum grain			0			0		1637	1637	1.6
Sweet potato (83%)	5908		5908	7108		7108	3389	3564	6953	20.0
Total			69 174			75 900			73 084	218.2
Total phosphorus in forage and leftover to confinement										
Maize silage					337	337			1739	2.1
Maize snaplage				1316	0	1316				1.3
Wheat straw[a]		979	979		2002	2002		1048	1048	4.0
Sweet potato (17%)[b]	1210		1210	1456		1456	694	730	1424	4.1
Total			2189			5110			4211	11.5

[a] Wheat straw harvest after wheat grain.

[b] Based on the farm's data, 83% of sweet potatoes are as eligible for sale, while the remaining 17% is repurposed as animal feed and compost.

Table 7. Phosphorus inputs and outputs in the grains, forage and straw to confinement for each growing season during the three cropping years for farm 2

Item	Cropping 2018/19			Cropping 2019/20			Cropping 2020/21			Total
	Summer season	Winter season	Total P	Summer season	Winter season	Total P	Summer season	Winter season	Total P	Three Cropping
	kg/farm			kg/farm			kg/farm			t
Phosphorus input										
Fertilizer	35 919	19 397	55 316	46 450	34 862	81 312	45 548	32 418	77 965	214.6
Compost									4704	4.7
Total crop residue	1029	9950	10 980	6267	10 893	17 160	8090	11 190	19 279	47.4
Maize residue		5724	5724	1829	6587	8416	3048	5789	8837	23.0
Common bean residue		1626	1626	1140	2116	3255	1482	1023	2504	7.4
Soybean residue		2601	2601		2191	2191		4378	4378	9.2
Wheat residue				1647		1647	1434		1434	3.1
Sorghum residue									0	0.0
Oat residue							803		803	0.8
Brachiaria residue							317		317	0.3
Millet residue	1029		1029	1652		1652	1005		1005	3.7
Input soil total	36 949	29 347	66 296	52 718	45 755	98 473	53 637	43 607	97 245	262.0
Input soil 2021/22									4019	4.0
Phosphorus output in grain										
Maize grain	14 466	4623	19 089	16 647	7704	24 351	14 631	1418	16 049	59.5
Common bean grain	5076	3558	8634	6606	4626	11 233	3193	2455	5648	25.5
Soybean grain	8599		8599	7243		7243	14 475		14 475	30.3
Wheat grain		3643	3643		3367	3367		1248	1248	8.3
Oat grain					36	36			0.0	0.04
Sorghum grain								2318	2318	2.3
Total			39 965			46 230			39 738	125.9
Total phosphorus in forage and leftover to confinement										
Maize silage				0		0			470	0.5
Wheat straw[a]		994	994		1006	1006			0	2.0
Total			994			1006			0	2.5

[a] Wheat straw harvest after wheat grain.

(Sanchez, 2019). The amount of P mineralized in both farms (31 kg/ha/year) and subsequently uptake by plants corresponded to nearly 73% for farm 1 and 76% for farm 2 of all P exported to the market (Figs 1 and 2).

Flow of P added to the soil

The annual average fertilization rate of 79.7 kg/ha/year for farm 1 and 70.7 kg/ha/year for farm 2 (Figs 1 and 2 and S1 and S2) is high if the demand for only one crop per year is considered. The P dose recommended for soybean, maize and common bean in this region is 52, 52 and 48 kg/ha, respectively, for soils that have a low nutrient availability (Ribeiro *et al.*, 1999). However, two aspects must be considered. Firstly, the P amount used per year was meant to supply P for two crops per year since the cultivated area is virtually the same for both the summer and winter seasons (Moreira *et al.*, 2023). Secondly, most of the rates for soil P for these two farms are still below the proper rates, according to Ribeiro *et al.* (1999). Thus, one should consider the application of the nutrient to meet the nutritional requirements of the crops, and an additional amount to supply part of the P that is adsorbed to Fe- and Al-(hydr) oxides (Lopes and Guilherme, 2016).

For soils from the Brazilian savanna with low P content, it is recommended to apply an extra P dose (1.3–2.2 kg of P for each 1% increment of clay), regardless of the P-fertilizer rate that is applied (Sousa and Lobato, 2004a; Lopes and Guilherme, 2016). The amount of P normally applied is usually high, and the application is made prior to the beginning of the cultivation of the fields, that is, when an area of degraded pasture with low rates of P is transformed into an area of grain cultivation. The extra application of P above the amount that is extracted by the crops is done with the intention of leaving part of the P in the soil, in order to occupy the P adsorption sites on the surface of Fe and Al oxides and to increase the P available to plants during cultivation (Urrutia *et al.*, 2014; Lopes and Guilherme, 2016; Sanchez, 2019; Volf and Rosolem, 2021).

The average amount of P that was returned to the system as residue was 18.8 kg/ha/year for farm 1 and 16.9 kg/ha/year for farm 2, suggesting that 28.6% of the total P extracted by the crops for farm 1 and 27.6% for farm 2 is returned to the soil. These results are in line with previous studies that showed that from the total amount of P extracted by crops, 28–31% for maize is returned to the soil as crop residue (Silva *et al.*, 2018), 29% for soybean (Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA, 2020), 34–19% for common bean (Silva and Moreira, 2022) and 18% for wheat (Pauletti and Motta, 2019). The amount of P that is returned to the soil is lower than that exported by grains, but it is significant in absolute terms.

Using P from residues, compost or manure can minimize P depletion at is a non-renewable resource (Aznar-Sánchez *et al.*, 2020; Muscat *et al.*, 2021). The amount of P in the residue is usually low ranging from 0.1 to 0.2%, and insufficient to meet crop demand (Sanchez, 2019). However, the available P sources are finite (Heuer *et al.*, 2017) and the reuse of any P-containing residue of by-product is crucial. In fact, this is a relevant circular agriculture premise meant to minimize the depletion of non-renewable resources, encourage regenerative practices, avoid the loss of natural resources and promote the reuse and recycling of by-products (Aznar-Sánchez *et al.*, 2020; Muscat *et al.*, 2021). The demand for P-fertilizers is constantly increasing, reflecting the growing demand for food, feed and fibre that follows the population growth (Fróna *et al.*, 2019; Oberle *et al.*, 2019). Due to the high cost of fertilizers and the fact that phosphate rocks, i.e. a source for P-fertilizers, are a finite natural resource, increasing the use efficiency of P-fertilizers in agricultural systems is critical (Heuer *et al.*, 2017).

The amount of P in the animal manure from farm 1 (1.7 kg/ha/year) and farm 2 (0.9 kg/ha/year) (Figs 1 and 2) were added to the other residues in the compost piles, yielding nearly 1.4 kg/ha/year of P for farm 1 and 1.5 kg/ha/year of P for farm 2 in the organic compost form. This indicates that there are P losses from the manure on farm 1, possibly due to surface runoff during composting, and suggests that the composting process without cover, i.e. bare ground, needs to be improved. In addition, it is important to increase the amount of compost produced, which can be done by increasing the number of animals on a farm.

Flow of P to grains and tubers, animals and market

About 43.7 kg/ha/year of P was exported in the grains and sweet potatoes on farm 1 or 45.0 kg/ha/ year, when also considering the amount exported by the animals (Figs 1 and S1). As for farm 2, around 40.8 kg/ha/year was exported in the grains, and only 0.5 kg/ha/year of P was exported by the animals (Figs 2 and S2). The low amount of P exported by the animals reflected the low number of animals on both farms, i.e. 1 animal/ha for farm 1 and 0.6 animals/ha for farm 2, and that most of the P ingested by animals is excreted in faeces and urine.

Most of the P extracted by the crops was exported in the form of grain that was sold on the market because the vast majority of P uptake by the plants is directed to the grains (Borges *et al.*, 2018; Silva *et al.*, 2018; Pauletti and Motta, 2019; Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA, 2020; Silva and Moreira, 2022), while the remainder of the extracted P was returned to the soil as residues (Tables 6 and 7) or was used for animal feed (Table 5), compost production or stored as forage (Figs 1 and 2).

With respect to the amount of P ingested by the animals (Table S2), 42% for farm 1 and 37% for farm 2 was exported in the live weight of the animal (Table 5) and nearly 60% was excreted by the animals as faeces and urine. The amounts of P excreted per animal varied according to the amount of P ingested in the diet (Vasconcelos *et al.*, 2007; Geisert *et al.*, 2010; Bernier *et al.*, 2014). Usually, the amount of P supplied exceeds the demand of the animals (Vasconcelos *et al.*, 2007). Past studies have reported that the amount of P excreted can range from 11.5 to 24.3 g/day (Geisert *et al.*, 2010) and from 9.7 to 27.9 g/day (Bernier *et al.*, 2014), increasing as P in the diet increases.

Major environmental concerns with the application of animal manure and P-rich waste rely on the contamination and potential eutrophication of water bodies (Vasconcelos *et al.*, 2007; Sanchez, 2019; Basso *et al.*, 2021). However, there is around 100 million ha of degraded pastureland in Brazil (Dias Filho, 2014). The soil in these areas has a low P content and a high P adsorption capacity (Lopes and Guilherme, 2016). It has been estimated that only 1.5% of the total amount of phosphate fertilizers used in Brazil is destined for pasture areas (Withers *et al.*, 2018) although the area under pasture is three times greater than the area used for agriculture. These areas with inadequate soil management, overgrazing, insufficient weed and pest control and lack of fertilization (Feltran-Barbieri and Féres, 2021) have a low carrying capacity, i.e. 1 animal unit/ha, especially due to low biomass production. Consequently, these areas need to be recovered, with an increase in their animal support capacity or even to contribute to an increase in the grain production area, resulting in an increase in yield and thus avoiding deforestation. Thus, integrating agriculture and livestock can be a great opportunity to recover these areas and to contribute to an increase in food production worldwide, with no need to convert native areas into cropland. Furthermore, most soils in tropical regions, especially oxisols, are deep with high a Fe- and Al-(hydr)oxide content (Lopes and Guilherme, 2016; Sanchez, 2019; Volf and Rosolem, 2021), which leads to a high P adsorption in these soils (Urrutia *et al.*, 2014; Lopes and Guilherme, 2016; Heuer *et al.*, 2017), with little possibility of contamination of water bodies by P.

Flow of phosphorus fertilizer recovered and P losses in the soil

The P recovery from both farms was larger than 50%, although it is widely recognized that the recovery of P applied in weathered, acidic soils, rich in Fe- and Al-(hydr)oxides is low (Lopes and Guilherme, 2016; Santos *et al.*, 2016; Heuer *et al.*, 2017; Matos *et al.*, 2017; Nascimento *et al.*, 2018; Vásconez and Pinochet, 2018; Sanchez, 2019; Zavaschi *et al.*, 2020). The recovery of P applied in weathered soils, rich in Fe- and Al-(hydr)oxides is usually low, primarily due to nutrient losses by adsorption into the surface of these colloids (Heuer *et al.*, 2017; Matos *et al.*, 2017; Nascimento *et al.*, 2018; Vásconez and Pinochet, 2018; Zavaschi *et al.*, 2020). Under acidic conditions, the presence of Fe^{2+} and Al^{3+} ions in the soil solution may lead to the formation of precipitates, such as iron and aluminium phosphates, thus enhancing P losses (Urrutia *et al.*, 2014; Lopes and Guilherme, 2016; Sanchez, 2019). Furthermore, the P content of most of these soils is naturally low (Lopes and Guilherme, 2016; Volf and Rosolem, 2021).

The soils in farms 1 and 2 are oxisols, on which most of the applied P can be turned into P forms not readily available to plants, mainly due to the strong bonds of P from fertilizer with the surface of Fe- and Al-(hydr)oxides (Lopes and Guilherme, 2016; Santos *et al.*, 2016; Heuer *et al.*, 2017; Matos *et al.*, 2017). Gonçalves *et al.* (1989) observed that 79–95% of the P applied in Brazilian oxisols turned into non-labile P after 300 days of application. Santos *et al.* (2016) observed that only 26% of the total P that was applied were recovered from an ultisol after 300 days using the Mehlich-1 extractor. Due to the losses of applied P in the soil through adsorption reactions into Fe- and Al-(hydr)oxides and precipitation of the orthophosphate anion with Fe^{2+} and Al^{3+} ions, the use efficiency of P-fertilizers is always less than 40% (Marschner, 2012). Less than 20% of P-fertilizers are usually recovered during the first crop, and less than 36% are recovered during the first two crops (Sanchez, 2019). According to Syers *et al.* (2008), plants use only 10–25% of the P-fertilizer. The P recovery also depends on the amount of P that is applied. After 13 years of application in Brazilian clayey oxisols, 61% of the applied P was recovered when the applied dose was 70 kg/ha of P, decreasing to 35% when the dose was 560 kg/ha of P (Sousa and Lobato, 2004b).

The efficiency of P use in the study farms can also be observed by the high percentage recovered in grains and the body of the animals. In farm 1, 56% (45.0 kg/ha/year of P) of the total P-Fertilizer (79.7 kg/ha/year) applied was exported in grains and animal body. In farm 2, 58% of the amount of P applied as fertilizer was exported in grains and body of the animals. The higher efficiency of P recovery in both farms can be linked to the adoption of circular agricultural practices. In the long term, a reduction in P losses through adsorption in the soils of both farms is expected, as the absence of disturbance of soils cultivated under NT reduces the contact of fertilizer P with soil colloids (Pavinato *et al.*, 2010; Tiecher *et al.*, 2012; Urrutia *et al.*, 2014). An accumulation of SOM over the years is also expected, mainly in the surface layers of the soil (Moreira *et al.*, 2020). This can also reduce P losses through adsorption (Rodrigues *et al.*, 2016; Moreira *et al.*, 2020). When SOM increases, organic radicals in the soil also increase, such as carboxylic groups, which compete with orthophosphate anions for the same adsorption sites (Cessa *et al.*, 2010). Moreira *et al.* (2020) observed that the P content in soil cultivated for 12 years under NT practically doubled compared to cultivated soil that was prepared conventionally. However, during the first three agricultural years of the current study, SOM on both farms did not show a significant increase (Moreira *et al.*, 2023), remaining around 3.2% in 2021. Finally, long-term NT system can reduce soil erosion and runoff, which can also decrease soil nutrient losses including P.

Soil management practices on farms 1 and 2, including cultivation under NT, crop rotation, maize of second season intercropped with grasses and use of cover crops, will contribute over the long term to an increase in SOM rates and to a greater recovery of the amount of P that is applied compared to other studies (Sousa and Lobato, 2004b; Syers *et al.*, 2008; Marschner, 2012, Sanchez, 2019). Nunes *et al.* (2020b) showed that P recovery in oxisol is greater under long-term (21 years) NT compared to intensive tillage, which was linked to the higher accumulation of more labile P forms under NT. In contrast, under intensive tillage, they found that 28% of the applied P was not available to plants. In addition, plants grown under NT exported 21% more P in grains than those under intensive tillage.

Finally, it should be noted that the NT associated with crop rotation, cover crops and maize intercropped with *Brachiaria* is of paramount importance to producing straw to maintain the soil covered throughout the year. This cropping system decreases problems arising from weeds, pests and diseases and increases nutrient (re)cycling (Moreira, 2019), including P. When comparing P use efficiency (>50%) observed on the two farms with literature data obtained from experiments with a linear agricultural practice (Marschner, 2012; Sanchez, 2019) the effect of circular practices on increasing the P recovery is clearly visible. However, it is worth mentioning that this study was conducted on two large commercial farms without any control plots and, thus, no statistical analysis of the data. However, conducting this study under real conditions on commercial farms that adopt circular practice provides a unique opportunity to demonstrate that these practices work. Thus, they will be able to contribute in the future to reducing the use of natural resources and promoting the reuse and recycling of nutrients (Basso *et al.*, 2021, Muscat *et al.*, 2021; Moreira *et al.*, 2023).

Conclusion

The P recovery represented more than 50% on both farms. These values are much higher than those found in the literature. The improved P recovery was due to the use of circular agricultural practices on both farms that included combined livestock and copping systems with crop rotation, maize intercropped with *Brachiaria* and NT soil management. The amount of P applied as fertilizer on farm 1 was 80 kg/ha/year and on farm 2 was 71 kg/ha/year; 56% was exported on farm 1 and 58% on farm 2 in the grains and body of animals. The amount of P that was exported by the animals corresponded to 1.2–2% of the total P exported. This amount was relatively small primarily because the farms still confine a relatively few numbers of animals compared to their large production areas. As most of the P ingested by animals is excreted, an increase in the number of animals on both farms will contribute to an increase in manure production and, consequently, to a greater production of organic compost for the crop production fields.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0021859624000042.

Acknowledgements. The authors express their gratitude to Evandro Ferreira and his partners, the owners of Santa Helena Farm, as well as Wilian Pedro Franco and his partners, the owners of 3W Agronegócio Farm, for providing access to all the farm data. The authors specially acknowledge the farm veterinarian Geraldo Barcelos for supplying the animal diet data and collaborating with data interpretation, and the agronomists Otávio Lopes Vieira Campos and Laura Pereira Reis for providing additional data from farm records. The authors also acknowledge Dr Marcos Inácio Marcondes from Washington State University for sharing beef cattle mineral composition data. The first author acknowledges the fellowship received from the PrInt-Capes Program from Brazil (Process number 88887.587838/2020-00) and expresses high gratitude to Dr Pedro Antonio Sanchez and Dr Gerrit Hoogenboom for hosting him as a visiting scholar at the Global Food Systems Institute at the University of Florida.

Author contributions. S. G. Moreira: resources, formal analysis, methodology, investigation, writing – original draft, funding acquisition, review and editing; G. Hoogenboom: conceptualization, writing – review and editing; visualization; supervision; M. R. Nunes: methodology, validation, writing – review and editing; P. A. Sanchez: methodology, validation, conceptualization.

Competing interest. None.

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