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ENVIRONMENTAL IMPACTS ASSESSMENT OF MAIZE, SOYBEAN, AND WHEAT PRODUCTION IN THE SOUTHWEST OF SÃO PAULO STATE: ALTERNATIVE SCENARIOS FOR THE SUBSTITUTION OF CHEMICAL FERTILIZATION

Gabriela Giusti[1]*, Yovana María Barrera Saavedra[2] & Gustavo Fonseca de Almeida[2]

1 - Federal University of São Carlos, Sorocaba, São Paulo, Brazil

2 - Federal University of São Carlos, Lagoa do Sino campus, Buri, São Paulo, Brazil

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ABSTRACT

Mineral fertilizers are highly impactful in the agricultural sector, and animal manure can be an alternative to mitigate its impacts. The goal of this research was to estimate the potential environmental impacts on the production of soybean, maize, and wheat at the Lagoa do Sino Farm School from the Federal University of Sao Carlos, contemplating the 2016/2017 cropping season and testing the replacement of 100%, 50%, and 30% of chemical fertilization by composted cow manure. Life Cycle Assessment (LCA) was the methodology used. The functional unit was one ton of each crop produced on farm. Impacts were also assessed for one hectare of production for each agricultural product investigated and the system boundary was a cradle-to-farm gate. Impacts were assessed using the CML 2000 world+ method for abiotic depletion, global warming, acidification, and eutrophication. Chemical fertilization was the main hotspot for all crops produced. Soybean showed a potential impact of 1489 MJ, 125 kg CO_2 eq., 0.6 kg SO_2 eq., and 0.4 kg PO_4 eq.; the production of maize 1497 MJ, 197 kg CO_2 eq., 1 kg SO_2 eq., and 0.8 kg PO_4 eq.; and the production of wheat 5863 MJ, 632 kg CO_2 eq., 3.3 kg SO_2 eq., and 2.4 kg PO_4 eq. The 30% substitution scenario was the most efficient observed since there is an increase in fuel consumption if distribution of larger amounts of manure are needed. Enriching the manure and investing in fossil fuel substitution will improve the environmental profile of the crops produced under intensive systems in the Southwest state of Sao Paulo, Brazil.

Palavras-chave:
Produção de cereais
Abordagem sistêmica
Impactos ambientais
Adubo compostado

AVALIAÇÃO DOS IMPACTOS AMBIENTAIS DA PRODUÇÃO DE MILHO, SOJA E TRIGO NO SUDOESTE DO ESTADO DE SÃO PAULO: CENÁRIOS ALTERNATIVOS PARA SUBSTITUIÇÃO DA ADUBAÇÃO QUÍMICA

RESUMO

Os fertilizantes minerais são altamente impactantes no setor agrícola, e o esterco de origem animal pode ser uma alternativa para mitigar seus impactos. O objetivo desta pesquisa foi estimar os potenciais impactos ambientais na produção de soja, milho e trigo da Fazenda Escola Lagoa do Sino da Universidade Federal de São Carlos, contemplando a safra 2016/2017 e testando a substituição de 100%, 50% e 30% de adubação química por um esterco compostado de vacas. A Avaliação do Ciclo de Vida (ACV) foi a metodologia utilizada. A unidade funcional foi de uma tonelada de cada produto pronto para comercialização. Os impactos também foram avaliados para um hectare de produção de cada produto agrícola e as fronteiras do sistema foram do berço da fabricação dos insumos e máquinas até as porteiras da fazenda (crade to farm gate). Os impactos foram avaliados usando o método CML 2000 world+ para exaustão abiótica, aquecimento global, acidificação e eutrofização. A adubação química foi o principal gargalo observado na produção das três lavouras. A soja apresentou impacto potencial de 1489 MJ, 125 kg CO_2 eq., 0,6 kg SO_2 eq. e 0,4 kg PO_4 eq.; a produção de milho 1497 MJ, 197 kg CO_2 eq., 1 kg SO_2 eq. e 0,8 kg PO_4 eq.; e a produção de trigo 5863 MJ, 632 kg CO_2 eq., 3,3 kg SO_2 eq. e 2,4 kg PO_4 eq. O cenário de substituição de 30% foi o mais eficiente na perspectiva ambiental, pois há um aumento considerável no consumo de combustível caso seja necessária a distribuição de maiores quantidades de esterco. Além disso, o enriquecimento do esterco e o investimento na substituição de combustíveis fósseis devem melhorar o perfil ambiental dos sistemas intensivos de produção de grãos no Sudoeste do Estado de São Paulo, Brasil.

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SECTION EDITOR IN CHARGE
André Pereira Rosa

Email (corresponding author)*: gabriela.giusti@hotmail.com.br

INTRODUCTION

Agricultural production in large scale benefits society in several ways: with the production of nutritious food, feed ingredients, liquid and solid biofuels, and economic benefits for various stakeholders (Tsalidis, 2022). However, these intensive production systems require high amounts of inputs (Muñoz *et al.*, 2008), which are responsible for several negative environmental effects. Thus, they are major contributors to pollutant emissions, impacts on water resources due to eutrophication, and land use (Crenna *et al.*, 2019).

According to the EPA (2022), the agricultural sector is responsible for an average of 14% of global greenhouse gas emissions. Enteric fermentation, animal manure treatment, and use of mineral fertilizers account for 32%, 15%, and 7% of these emissions, respectively (FAO, 2019). Seeking to mitigate the effects of climate change, world leaders signed the Glasgow Climate Pact during the 26th United Nations Climate Change Conference (COP-26). The Glasgow Climate Pact recognized the urgency of limiting the global average temperature rise to less than 2 °C, and aimed, among other things, to reduce methane emissions by 30% by 2030, a gas highly emitted in ruminant livestock farming (UN, 2022).

In the world agricultural scenario, maize, wheat, and soybeans are among the five food ingredients with the highest production volume (FAO, 2021). In this perspective, Brazil is the first world producer and exporter of soybeans and occupies the third place in the world ranking for the largest producers and exporters of maize (FAO, 2021). In the case of wheat, even with a lower production volume in the country, the grain stands out as a relevant crop for winter cultivation, especially in the south and southeast regions of the country.

In Brazil, the Midwest region stands out as the leading soybeans and maize producing region, followed by the South region of Brazil. The Southeastern region stands out as the third-largest producer of grains, with the main producing state being Minas Gerais, followed by Sao Paulo (Coêlho, 2018). Concerning wheat production, the Southern region is the major producer in the country, followed by the Southeastern, where São Paulo lead and is followed by Minas Gerais (CONAB, 2018).

However, Brazilian agriculture also stands out for its potential associated with environmental impacts. UN (2021) estimated that from 1990 to 2018, Brazilian agribusiness increased the use of agricultural raw materials by 121%, accounting for 57% of the footprint associated with the usage of industrialized materials, generating impacts in fossil fuel use and mineral depletion. In the same period, Brazilian agribusiness showed an increase of about 70% in greenhouse gas emissions, more than 140% in terms of air pollutants (such as particulate matter, ammonia, and sulfur dioxide), and approximately 2% in impacts associated with land use change (UN, 2021).

On this scenario, there is an urgent need to evaluate and to find ways to mitigate the potential environmental impacts of the agricultural sector. According to Preda (2015), Life Cycle Assessment (LCA), standardized by ISO 14040 and 14044 (ISO, 2006 a, b), is one of the most complete techniques to analyze environmental impacts associated with agriculture and food production, besides requiring a high level of transparency of the procedure performed. The technique is employed by several other researchers interested in the environmental analysis of agricultural and livestock systems. For example, Fantin *et al.* (2017) evaluated the impacts of maize and wheat crops on a farmers' cooperative in Italy. Taki *et al.* (2018) compared wheat production with and without irrigation in Iran. Zortea *et al.* (2018) evaluated the lifecycle sustainability of soybeans production in the Rio Grande do Sul state in Brazil. Despite the differences in cultivars and production sites, the three aforementioned studies identified fertilization as one of the main hotspots of the evaluated systems for resource depletion, acidification, eutrophication, and global warming impacts.

Given the relevant contribution of chemical fertilization activities to the impacts of the agricultural sector, LCA studies have evaluated the environmental viability of replacing mineral fertilizers with manure from animal production systems. For example, Li *et al.* (2020) assessed the mineral fertilizer replacement of 50% with

solid and liquid bovine manure in maize and wheat production in China. The authors observed impact reduction potentials of 18% and 31% for each replacement, respectively. Furthermore, the systems using manure for fertilization showed a 30% higher eco-efficiency than the mineral fertilization system, indicating that benefits can accrue in both the environmental and economic dimensions.

In the same approach, Jiang *et al.* (2021) evaluated replacing 50% of mineral fertilizer with composted swine manure in wheat production in China. The authors observed that manure could elevate global warming, acidification, and eutrophication impacts depending on the dose applied. However, enriching the manure with biochar is an alternative for reducing global warming impacts (Jiang *et al.*, 2021). Du *et al.* (2020) identified that animal manure used as fertilizer could also generate long-term increases in grain yields and benefits for soil life by raising nutrient availability and improving soil pH. However, in developing countries, such as Brazil, a low "recycling" of animal waste is observed (Jiang *et al*., 2021). Since the Brazilian territory is composed of 58% Latosols and clay soil, which is deep, weathered, acidic, and of low natural fertility (EMBRAPA, 2022), the use of animal manure in agricultural production can be a timely research field for the national agricultural sector.

Considering the importance of soybeans, maize, and wheat crops in the country and the efficiency of the LCA technique, this work sought to contribute to the debate on the environmental impacts of the production of these grains, besides seeking mitigation alternatives for the effects associated with the fertilization process of these commercial crops. Thus, the study's goal was to evaluate the conventional cultivation of these crops in the Lagoa do Sino Farm School from the Federal University of Sao Carlos (UFSCar), located in the municipality of Buri, Southwest region of the State of Sao Paulo. Furthermore, it sought to diagnose elements to mitigate the impacts of these commercial crops produced regionally through the alternative production scenarios modeling using animal manure to promote the replacement of mineral fertilizers.

MATERIAL AND METHODS

This research used the LCA technique standardized by ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), contemplating four methodological stages: 1) goal and scope definition; 2) life cycle inventory analysis (LCI); 3) life cycle impact assessment (LCIA); and 4) results interpretation, which contemplates an analysis of hotspots and an analysis of alternative scenarios with mineral fertilizer replaced by cow manure composted after being produced in a dairy compost-barn production system close to the school farm. The compost-barn production system confines cows in a large covered space with ventilation and a lining of sawdust, urine, and manure in a constant composting process (aerobic). This production system aims to ensure animal welfare while producing compost from the cows' waste (Guimarães, 2018). The following sections detail each methodological step used in this study.

Goal and scope definition

The Federal University of São Carlos (UFSCar) inaugurated its fourth university campus in Sao Paulo state in the year of 2011. The Lagoa do Sino campus, which kept the name of the farm donated by the writer Raduan Nassar, started the academic activities in 2014 on a highly productive agricultural farm located in the municipality of Buri-SP, 267 km away from the state capital. The Farm School has 643 hectares, of which 300 hectares are for irrigated crop production (by central pivot systems) and another 100 for non-irrigated production.

The assessment used data from the 2016/2017 cropping seasons to attend the research goals. As a common crop rotation system, soybeans were the main summer crop cultivated, sowed on 384 hectares (52% irrigated) in the first half of October, 2016, and harvested in the second half of February 2017. The farm produced maize in the second season (known as safrinha) on 127 irrigated hectares, and sowing occurred in the second half of February 2017, just after the soybean grains were harvest. The maize harvest occurred in the second half of August 2017. For the winter crop, wheat occupied 184 hectares of the non-irrigated

areas, and the sowing was in the second half of April 2017, and the harvest occurred in the first half of September 2017. After the harvest of the wheat grains, a new cycle began at the Lagoa do Sino Farm School.

All agricultural production was performed under the required technology for an intensive production system, with high consumption of agricultural inputs, fuel and machinery. Based on this context, these LCA study aimed to analyze the potential environmental impacts and the hotspots of the three main crops produced in the 2016/2017 cropping season. The functional unit used in this work was one ton of agricultural products produced. The impacts of the grains production on the basis of one hectare of the agricultural area were also evaluated for complementation. The delimitation of the system boundaries was of the cradle-to-farm gate type, covering input production for the products harvested and stored within the farm gate.

Figure 1 illustrates the boundaries of the evaluated crops.

All crops had the agricultural production steps of soil preparation, planting, agricultural management (chemical control, fertilization, and irrigation), and harvest. Maize and soybean productions were performed in irrigated areas and after harvest, grains went through a drying process before storage, depending on water, electricity, and firewood. In the case of wheat production, there was no irrigation, nor was it necessary to dry the grains before storage in the metallic silos located at the Farm School.

Life cycle inventory analysis

The foreground LCIs of the maize, soybeans, and wheat production systems were drawn up based on interviews with the agricultural technician responsible for the crops production in the Lagoa do Sino Farm School from the Federal University of Sao Carlos (UFSCar). At each activity performed in the field, the technician communicated to the research team, which went to the farm administration to collect information about: the type and quantity of inputs consumed; transportation of inputs to the farm; and machinery used (tractors and agricultural implements), in addition to data on their specifications and fuel consumption (diesel). Equation 1 calculates the agricultural machinery flows, considering the

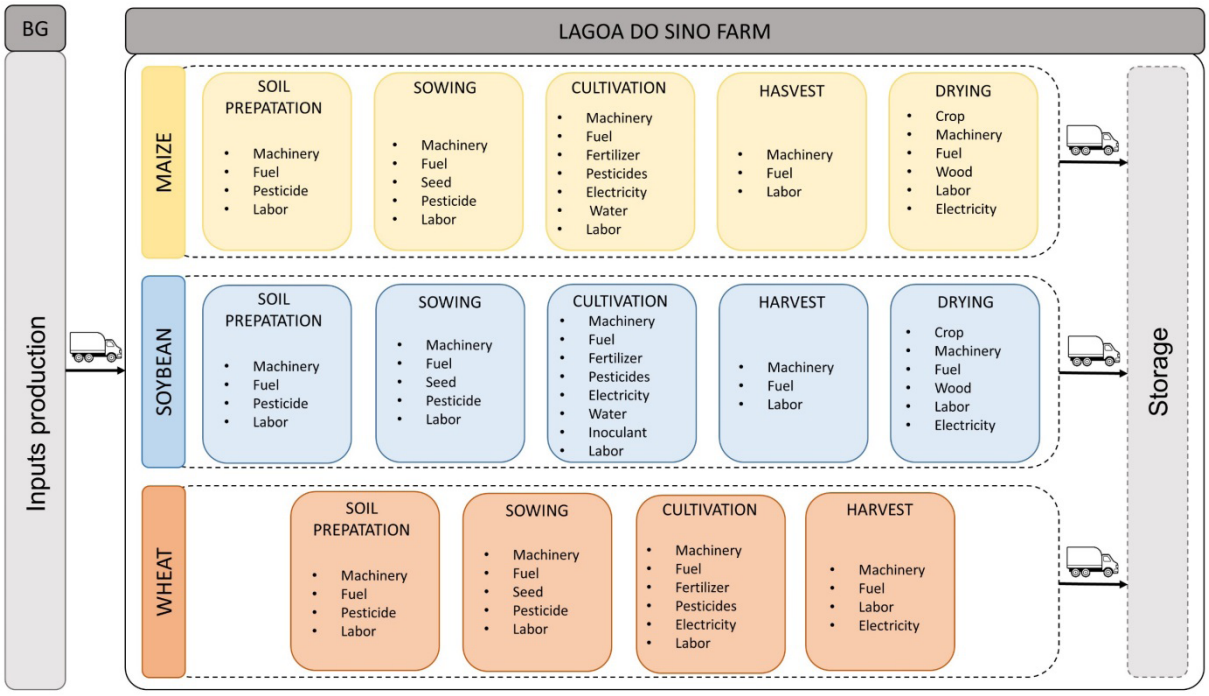

Figure 1. Boundaries of maize, soybean, and wheat production systems produced in the 2016/17 cropping season

weight data of the equipment (in kg), activity speed used on the tractor (h/ha), and equipment lifetime (h). The datasets used in Equation 1 are specified in the supplementary material.

$$\text{Machinery}\left(\frac{\text{kg}}{\text{ha}}\right) = \frac{\text{Machinery weight (kg)} * \text{Velocity}\left(\frac{\text{h}}{\text{ha}}\right)}{\text{Equipment lifetime (h)}} \quad (1)$$

The application of mineral fertilizers occurred in the sowing and in the cultivation stages (cover crop fertilization), generating emissions of pollutants into the air and to the water bodies (IPCC, 2006; Nemecek, 2013). In the harvest process, the production residues were left on the ground to reduce the need for fertilizer use and to provide soil protection (straw mulch). Thus, it was not necessary to allocate part of the impacts to the residues (Boone *et al.*, 2016). However, keeping residues in the soil promotes Carbon Dioxide (CO_2) emissions into the air (Djomo *et al.*, 2015). Therefore, the LCI considered these emissions. In addition to the emissions generated by fertilization and residues left in the ground, the firewood burning for drying maize and the soybeans emitted greenhouse gases into the atmosphere (IPCC, 2006). The LCI methodology was in accordance with the one presented by Giusti et al. (2022) in a comparative LCA study between sweet corn and grain corn produced at Fazenda Lagoa do Sino and marketed in the megacity of Sao Paulo (sweet corn) or exported (grains) though Santos harbor. Thus, as for the environmental output aspects of the production systems, the LCI considered:

(1) The modeling of nitrous oxide emissions to air due to the application of mineral fertilizers considered that 2.75% of the nitrogen applied is emitted as nitrous oxide, according to the emission factor suggested by the GHG Protocol Program (2020);

(2) CO_2 emissions due to agricultural residues kept in the soil were modeled with the equation of Djomo *et al.* (2015) and using the default parameters provided by IPCC (2006);

(3) Phosphate emissions to groundwater, phosphorus, and phosphate to rivers by mineral fertilizers applied to the soil as suggested by Nemecek (2013). The modeling of these emissions considered that, in average, 0.37% of the applied mineral phosphorus was emitted as phosphate to groundwater, 3.6×10^{-11}% as phosphorus to the river, and 0.14% as phosphate to the river;

(4) Nitrous oxide emissions to groundwater are due to the mineral fertilizers' application to the soils. The modeling considered that 30% of the mineral nitrogen applied is emitted as nitrous oxide to groundwater, following Müller (2012);

(5) Carbon dioxide, nitrous oxide, and methane emissions into the air due to the combustion of firewood for maize and soybean drying activities were modeled in the GHG Protocol calculation tool version 2021.01.

It is important to mention that the LCI data for maize production used in this study was adapted from Giusti et al. (2022) to reflect the changes in the scope between both studies, which was from the cradle to the port of Santos in Giusti et al. (2022) and from the cradle to the farm gate in this paper. Thus, the input data and associated emissions were collected from the aforementioned publication, while the transport data and associated emissions are specific to the LCI of this study. Grain yields were 8.68 ton/ha for the production of maize, 4.40 ton/ha for the production of soybeans, and 2.20 ton/ha for the production of wheat. Table 1 consolidated the LCIs for one-ton yields of maize, soybeans, and wheat for the 2016/2017 cropping season of the Lagoa do Sino Farm School from the Federal University of Sao Carlos (UFSCar). The supplementary material provides detailed inventories of agricultural processes for one-ton and one-hectare crop production for the three crops investigated.

The LCIs were modeled in the SimaPro software version 8.5, using the ecoinvent v.3 attributional database to access the background processes. The background processes provided the inventory data upstream of the agricultural cultivation stage in the maize, soybeans, and wheat production chains. After harvesting and drying maize and soybeans, the crops moved on to the transportation, distribution, consumption, and end-of-life stages, but the scope of this research did not cover all those stages.

Table 1. Production inventory of a ton of maize, soybeans, and wheat on the Lagoa do Sino farm for the 2016/2017 agricultural cropping season

Input data				
Inputs	Unit	Maize[1]	Soybeans	Wheat
		Quantity	Quantity	Quantity
Agrochemicals[2]	kg	1.2	0.4	0.4
Seed	kg	13.8	27.3	50.0
Graphite (seed treatment)	kg	8.06×10^{-3}	-	-
Lubricating oil	kg	1.15×10^{-2}	-	-
Fertilizer – Nitrogen	kg	9.6	1.4	7.5
Fertilizer – Phosphorus	kg	6.1	13.6	22.6
Fertilizer – Potassium	kg	6.1	13.6	7.5
Boron	kg	-	-	2.5
Zinc	kg	-	-	4.1
Urea, as nitrogen fertilizer	kg	-	-	38.6
Firewood	m^3	2.07×10^{-2}	1.36×10^{-3}	-
Machinery (implements)	kg	0.6	1.5	2.5
Machinery (tractors)	kg	0.2	0.2	0.2
Diesel	kg	4.1	7.2	10.7
Transport in the farm	t.km	246.2	598.9	354.7
Electricity	kWh	38.6	32.5	4.4
Transport to the farm	t.km	0.1	0.1	0.1
Output data				
Outputs	Unit	Maize[1]	Soybeans	Wheat
		Quantity	Quantity	Quantity
Main product[3]	t	1.00	1.00	1.00
Nitrous Oxide to air (fertilizers)	kg	0.26	0.04	0.67
Carbon Dioxide to air (Residues)	kg	2.33	9.06	68.64
Phosphate to groundwater	kg	0.02	0.05	0.09
Phosphorus to river	kg	2.27×10^{-12}	4.48×10^{-12}	8.95×10^{-12}
Phosphate to river	kg	0.01	0.02	0.03
Nitrate to groundwater	kg	2.88	0.41	7.36
Carbon dioxide to air (drying)	kg	19.26	1.24	0.00
Methane to air (drying)	kg	0.06	4.55×10^{-3}	0.00
Nitrous oxide to air (drying)	kg	1.15×10^{-3}	4.93×10^{-5}	0.00

[1] Adapted from Giusti et al. (2022)

[2] Consider herbicides, insecticides, fungicides, and pesticides

[3] Consider maize with 13.5% of moisture, soybeans with 13% of moisture, and wheat with 13% of moisture

Life cycle impact assessment

The LCIA step was performed on the SimaPro software version 8.5. The evaluated impact categories were global warming (kg CO_2 eq.), abiotic fossil fuel depletion (MJ), acidification (kg SO_2 eq.), and eutrophication (kg PO_4 eq.). The LCIA method used was CML 2000 world+. Mendes et al. (2015) discussed the scarcity of available LCIA methods for the Brazilian context, and CML 2000, considered a global scope, thus, applicable to the Brazilian context.

Interpretation

The interpretation stage assessed hotspots and sensitivity analyses, both foreseen in the ISO 14044 standard (ISO, 2006b). The hotspot analysis defined the critical points of the analyzed systems, i.e., the most impactful processes and

environmental aspects for each production system.

The sensitivity analysis, in turn, was based on the creation and evaluation of alternative production scenarios aiming to improve the understanding of the LCA results and seek directions for environmental improvement of agricultural systems. Thus, the alternative scenarios considered the replacement of mineral fertilizer with composted cow manure generated in a dairy production system with cows managed in a compost-barn system located 15 km from the Lagoa do Sino farm school from the Federal University of Sao Carlos (UFSCar). For this, a simplified LCA of the alternative manure production was developed, as described in the following sections.

LCA of the composted cow manure: goal and scope definition

The dairy production system in the compost-barn was evaluated in the time scope of 2018, when 160 Holstein cows, 147 of which were in lactation, remained in a confined space of 2500 m². The animals' bedding was formed from sawmill waste (sawdust). Twice a day, the bedding was turned over by the use of a tractor with an incorporator, aerating the residues and promoting aerobic composting of the material. An amount of sawdust was inserted weekly as bedding for the animals. At the end of the year, the composted material left the system to be used as a commercial by-product for the dairy farm, serving as a biological fertilizer for crops. The cows were divided into three lots according to daily milking production: (1) primiparous cows at the beginning of lactation line – cows with an average production of 38 liters/animal/day; (2) multiparous cows at the beginning of lactation – an average production of 47 liters/animal/day; and (3) cows at the end of lactation – an average production of 30 liters/animal/day.

The compost-barn intensive system was evaluated exclusively for the animal waste management, considering a cradle-to-farm gate approach. Thus, the scope of the study considered the production of raw materials for the composition and management of the bedding material (sawdust, cattle manure, urine, diesel, and machinery), the transport of inputs to the barn, and greenhouse gas emissions representative of waste management and aerobic composting.

The substitution of mineral fertilizers in the production systems of the Lagoa do Sino Farm School from the Federal University of Sao Carlos (UFSCar) was evaluated in three scenarios, considering the substitution of 100% (scenario 1), 50% (scenario 2), and 30% (scenario 3) of the total amount of mineral fertilizer used by the conventional system (based on nitrogen-phosphorus-potassium corrected values). Thus, the scenario analysis aimed to verify the environmental viability of such substitutions for producing one ton of corn, soybeans, and wheat with the same management, substituting only the values for nitrogen, phosphorus, and potassium supplied by the application of composted manure.

LCA of composted cow manure: life cycle inventory analysis

The foreground inventory of the cow manure management, which outputs alternative compost fertilizer, was developed after interviews with the dairy farm owner. The modeling for the methane and nitrous oxide emissions resulting from the manure management and the aerobic composting process followed the IPCC (2006) tier 1 equation. Table 2 presents the inventory needed to produce one ton of alternative fertilizer.

The production system of the alternative fertilizer is multifunctional, with milk as the main product and the composted manure, the secondary source of income. Based on this, part of the impacts associated with the manure management was allocated to milk production, following an economic allocation procedure based on the producer's gross income. According to the dairy farm owner, the annual production of the alternative fertilizer contributed approximately with 20% of his annual gross income, and milk production made up the other 80%. Thus, 20% of the total impact of manure management was allocated to the alternative manure production.

It is relevant to highlight that the research scope in this study did not cover other environmental aspects of the milk production system, such as animal feed and ingredients used, enteric

Table 2. Inventory of manure management of the dairy system managed in the compost-barn for the year 2018 to produce one ton of the alternative fertilizer

Flow	Unit	Quantity
Inputs		
Sawdust (residues from the wood industry)	m^3	1.15
Cow manure (42.5% of moisture)	t	0.39
Diesel	kg	1.05
Machinery[1]	kg	0.15
Transport of inputs to the farm	t.km	196.59
Outputs		
Alternative fertilizer with 42.5% of moisture*	t	1
Methane	kg	0.105
Nitrous Oxide	kg	0.964

** Main product from waste management*

fermentation, and the use of tractors in usual farm operations. The justification for this consideration is that many LCA studies of milk disregard manure in the system impact allocation since it is generally considered a production waste, not a by-product (Baldini et al., 2017). Thus, this work considers that only 20% of the impacts generated by the manure management were due to the production of composted manure.

Replacement of mineral fertilizers with the alternative fertilizer (composted manure) in the production of crops at Lagoa do Sino Farm School

The replacement of mineral nutrients by the alternative fertilizer was considered at the ratios of 1:2 for nitrogen demand, 1:2 for phosphorus, and 1:1 for potassium, following Ribeiro et al. (1999). To know the availability of organic nitrogen, phosphorus, and potassium in the composition of the alternative fertilizer, two samples of the fertilizer were collected on the dairy farm based on time of composting and sent to the laboratory of soil fertility from Federal University of São Carlos, Araras campus, where the nutrient composition was obtained (Table 3).

Based on the composition of the alternative fertilizer and the replacement ratios of mineral nutrients with organic ones, to replace 1 kg of

Table 3. Composition of the alternative fertilizer composed of bovine manure and sawdust

		Sample	
Parameter	Unit	Composted Cow manure (1 year)	Composted Cow manure (2-5 months)
pH	-	8.4	8.6
Carbon (C)	%	26.6	42.0
Nitrogen (N)	%	1.6	1.9
Phosphorus (P_2O_5)	%	1.4	1.5
Potassium (K)	%	1.7	1.6
Calcium oxide (CaO)	%	3.4	1.8
Magnesium oxide (MgO)	%	1.5	1.0
Sulphate (SO_4)	%	1.3	0.8
Moisture	%	42.5	45.8
Copper (Cu)	ppm	64	47
Iron (Fe)	ppm	23472	13865
Manganese (Mn)	ppm	395	237
Zinc (Zn)	ppm	178	103

mineral nitrogen would require 105 kg of alternative fertilizer; for 1 kg of the mineral phosphorus, 138 kg of alternative fertilizer; and for 1 kg of the mineral potassium, 63 kg of alternative fertilizer.

Scenario 1 (100% substitution of mineral fertilizer) considered two applications of the alternative fertilizer before sowing (planting). Thus, the scenario was modeled considering an initial application of half the total amount of the alternative fertilizer, using a limestone distributor with the adaption to its regulation, coupled to a tractor. The next activity was a harrowing process for incorporating the fertilizer into the soil and, finally, a second application of the alternative fertilizer as coverage fertilization, using the same limestone distributor and tractor. All other cultivation activities were equal in the conventional production system inventory.

For scenario 2 (substitution of 50% of the mineral fertilizer), the total amount of composted manure was considered to be applied before planting, with a limestone distributor attached to the tractor followed by harrowing for incorporation. After this pre-sowing fertilization, the subsequent activities were considered the same as the conventional system inventory, with 50% of the mineral fertilizer applied in the fertilization process during agricultural cultivation management.

Finally, scenario 3 (substitution of 30% of the mineral fertilizer) was modeled similarly to scenario 2, considering the application of the alternative fertilizer before sowing followed by a harrowing for the material incorporation and the subsequent activities were the same to those of the conventional system inventory. Mineral fertilizers were also considered in the fertilization process during crop management. Table 4 presents the consumption of minerals and alternative fertilizers for each proposed scenario.

Crop productivity was altered according to information provided by the dairy farmer, who observed and recorded a 30% increase in corn productivity, 13% in the production of soybeans, and 10% in wheat production when the farmer substituted 30% of the chemical fertilizer for the composted manure. We have also considered the same proportion of productivity increases for the three substitution scenarios investigated in this work, based on the farmer´s empirical knowledge.

The alternative scenarios were modeled in the SimaPro software, and the LCIA step used the CML 2000 world+ method, following the same procedure as the base line scenario (conventional production of the three crops using mineral fertilizers).

RESULTS AND DISCUSSION

The results of this research are presented in two sections. Initially, the results of the potential environmental impacts of the agricultural crops produced at the Lagoa do Sino farm school are presented and discussed, with the analysis of the hotspots for each crop investigated. In the second section, the results of the scenario analysis are presented and discussed.

Table 4. Consumption of mineral fertilizers and composted manure in each alternative scenario for one ton of grains produced

Crop - substitution %	Alternative fertilizer – composted manure (kg)	Nitrogen (kg)	Phosphorous (kg)	Potassium (kg)
Maize (100%)	1012.06	0.00	0.00	0.00
Maize (50%)	506.03	4.81	3.06	3.06
Maize (30%)	303.62	6.73	4.28	4.28
Soybean (100%)	1880.88	0.00	0.00	0.00
Soybean (50%)	940.44	0.68	6.82	6.82
Soybean (30%)	564.26	0.95	9.55	9.55
Wheat (100%)	3114.73	0.00	0.00	0.00
Wheat (50%)	1557.37	12.26	11.29	3.76
Wheat (30%)	934.42	17.17	15.81	5.27

Potential environmental impacts of maize, soybeans, and wheat production

Table 5 presents the potential environmental impacts of maize, soybeans, and wheat produced on the Lagoa do Sino Farm School.

To better understand the environmental impacts of these agricultural systems, Figure 2 illustrates an analysis of the contribution on the total environmental impacts for each category under investigation and highlights fertilization as the main hotspot for the three crops evaluated.

The following items detail the results for each agricultural crop separately.

Potential environmental impacts for the maize production

The maize production of the Lagoa do Sino Farm School for the 2016/17 cropping season presented a high demand for external inputs, receiving the highest volume of mineral fertilizers per hectare of production (189.7 kg) among the three crop production systems evaluated. In addition, maize was harvested with 24% moisture, requiring firewood and electricity to dry the grains before they reached 13% moisture, ideal for storage. This system also presented the highest use of tractors and fossil fuel (diesel) consumption, and electricity (78%) related to the operation of a central pivot

Table 5. Potential environmental impacts for one-ton and one-hectare of maize, soybeans, and wheat production at Lagoa do Sino farm's 2016/2017 season

Impact category	Unit	Maize		Soybean		Wheat	
		Impact/t	Impact/ha	Impact/t	Impact/ha	Impact/t	Impact/ha
Abiotic depletion	MJ	1497.26	12996.22	1489.26	6552.74	5863.74	12900.23
Global warming	kg CO_2 eq.	196.77	1707.96	124.64	548.42	631.72	1389.78
Acidification	kg SO_2 eq.	0.98	8.51	0.63	2.77	3.30	7.26
Eutrophication	kg PO_{4---} eq.	0.78	6.77	0.43	1.89	2.40	5.28

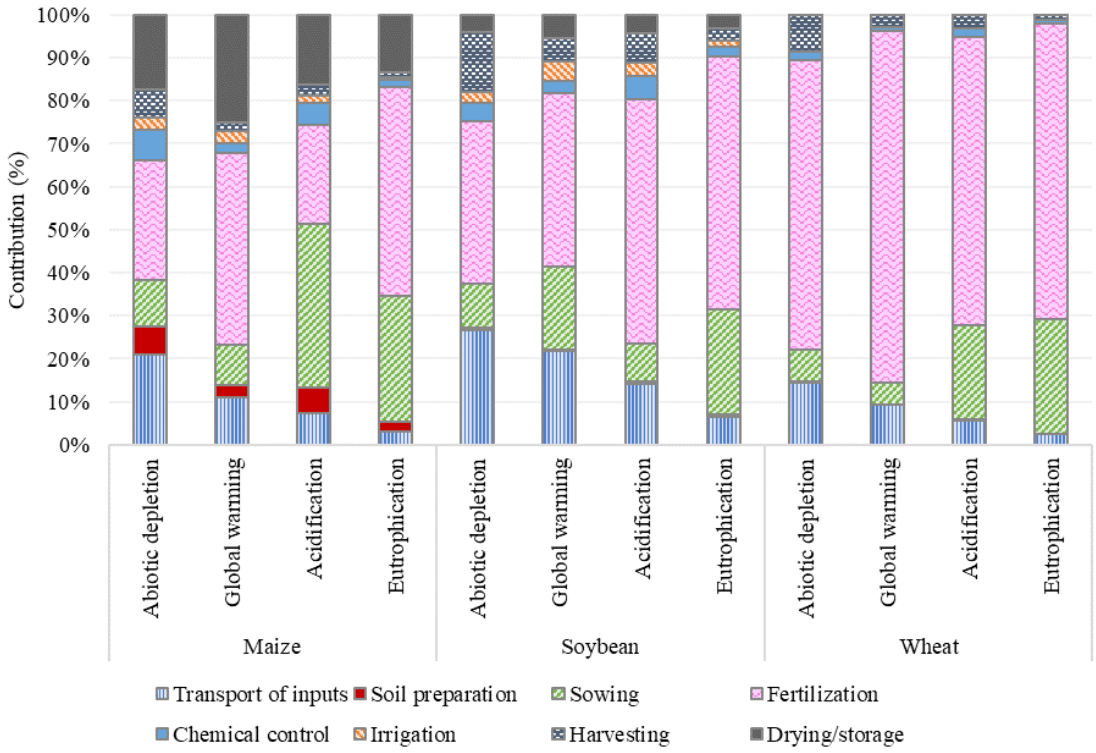

Figure 2. Analysis of the contribution of production processes to the potential environmental impact of maize, soybean, and wheat production in the conventional system at the Lagoa do Sino farm school

for the crop irrigation. However, maize had the highest productivity among the three crops studied, generating a higher dilution of the environmental impacts per unit of production.

The hotspot analysis showed that the fertilization step was the main contributor to environmental impacts in three of the four categories assessed: abiotic depletion (28%), global warming (45%), and eutrophication (49%). In addition, fertilization was the second largest contributor to acidification (23%), just after the sowing/planting stage (38%).

The background systems showed the highest impacts for abiotic depletion, with phosphate and ammonium sulfate yields being the main highlights, contributing 10% and 11% of total system impacts, respectively. Next, the highest contributors were the activities of input transportation to the farm (21% of abiotic depletion impacts) and the drying of the grains (17%). Regarding drying the grains, the impacts occurred mainly due to the production of firewood used for the generation of heat.

For the global warming and eutrophication categories, direct emissions from fertilization presented the highest percentage of impacts on the whole system, at 31% and 38%, respectively. The grain drying stage also showed relevant impacts for the global warming category (25%), with 14% occurring in the background processes (mainly wood and electricity production) and 11% in the emissions of gases from the wood combustion process. For eutrophication, the second most impactful process was sowing/planting, accounting for 29% of the impacts, coming mainly from impacts associated with seed production.

Identifying sowing/planting as the main impact factor of the acidification category also occurred due to impacts associated with seed production, contributing to about 37% of the total impacts. Regarding the fertilization stage, the impacts came from the production of mineral fertilizers, mainly phosphorus (13%).

The identification of fertilization processes as the main hotspot for maize managed in intensive production systems is recurrent in the international literature. Noya *et al*. (2015) observed that the production of mineral fertilizers, notably phosphorus, contributed mostly to abiotic depletion impacts on maize production in Italy. The authors' findings match those of this study and with Fantin *et al*. (2017), who also identified phosphate fertilizer production as a category hotspot.

Fantin *et al*. (2017) further evaluated maize production in Italy in a cradle-to-gate approach, including crop production, transport to the drying shed, grain cleaning and storage, treatment of the cleaning residues, and truck loading. The authors used GaBi 6 software, the ecoinvent 2.2 databases, and the ILCD LCIA method. ILCD uses different impact indicators for abiotic depletion, acidification, and eutrophication. Thus, the results calculated by Fantin *et al*. (2017) are not comparable, for these impact categories, with the results of this study. It is worth noting that Fantin *et al*. (2017) indicate the fertilization process as a hotspot for these categories, in agreement with the findings of this research. For global warming, the authors identified an impact of 450 kg CO_2 eq./t of grain, a value 2.3 times higher than that observed in this study. The variation in results can be explained by the different software used (Silva *et al*., 2019) and differences in production systems boundaries since Fantin *et al*. (2017) included grain processing activities at the cooperative level as part of the process. In addition, inventory data indicated higher consumption of nitrogen (2 times), phosphorus (1.7 times), and diesel (8.5 times).

Li *et al*. (2020) evaluated the production of a maize-wheat cropping rotation system in the northern lowlands of China. The authors used SimaPro v. 8.3.0.0 software, ecoinvent v.3 databases, and the ReCiPe 2016 LCIA method for modeling the potential environmental impacts. Regarding the production of maize, their results indicated a potential impact of 595.2 kg CO_2 eq./t for global warming; 30.7 kg SO_2 eq./t for acidification; 0.034 kg P eq./t for eutrophication; and 96.5 kg oil eq./t for fossil fuel resource depletion. Again, the potential environmental impact obtained by the authors tended to be higher than this work's results. The variation in the LCIA method may account for the observed differences (Cherubini *et al*., 2018) and make the comparison unfeasible when the impact indicator is distinct. Likewise, there were differences in production inventories, as Li *et al*. (2020) indicated about 3.5 times more electricity, mineral fertilizers, and

diesel consumption, and energy costs associated with agricultural machinery than we registered for this study. As an alternative for a more sustainable production system, Li *et al*. (2020) modeled maize production with a partial (50%) replacement of mineral fertilizers, substituted by solid and liquid manure and observed average reductions of 18% and 31% of the analyzed impacts, respectively, for each type of fertilization replacement.

Potential environmental impacts for the soybeans production

Soybean is a cash crop legume that can fix atmospheric nitrogen in the soil through symbiotic processes (Jones, 2019). Due to this biological characteristic, its production demanded a much less nitrogen fertilizer application. During the harvesting, the grains had a moisture content of 16.5%, close to the storage moisture (13%), so the drying process presented less demand for firewood and electricity than the maize drying processes investigated. Consequently, in this study, drying soybeans accounted for lower environmental impacts compared to drying maize grains.

The fertilization process, the main hotspot for the soybeans production, contributed to more than 37% of the impacts for all four categories evaluated. These impacts occurred mainly due to the background process for the production of phosphate fertilizer, which accounted for more than 17% of all impact categories. For global warming and eutrophication, direct emissions due to fertilizer applications were also relevant, with 13.5% and 22.3% contributions to each impact category, respectively.

Input transportation to the Lagoa do Sino Farm School was the second biggest contributor to the impacts of abiotic depletion (26.6%), global warming (21.7%), and acidification (14%) due to consumption of diesel and emissions of pollutants generated by fossil fuel burning. As for eutrophication, the second highest contributor was the grain sowing/planting process, mainly due to impacts associated with the production of the seeds used (23.7%).

Matsuura *et al*. (2017) evaluated the impacts of soybean-sunflower intercropping system in the Brazilian Cerrado and modeled the environmental impacts comparing the system with the monoculture production of soybeans and sunflower individually. The study used SimaPro v. 8.0.5.12 software, the ecoinvent 2.2 databases, and the ReCiPe H midpoint LCIA method. The total system impacts were higher than in this paper: 9510 kg CO_2 eq./t for global warming; 5.44 kg SO_2 eq./t for terrestrial acidification; 0.434 kg P eq./t for eutrophication; and 176 kg oil eq./t for metal depletion. The higher impacts occurred due to the differences in the LCIA methods used and mainly due to the calculation of land-use change emissions performed by Matsuura *et al*. (2017), which were not accounted for in the present study. However, excluding such contributions, the authors highlighted fertilization as the main contributor to the calculated environmental impacts. The intercropping of soybeans and sunflower production in the Brazilian Cerrado proved beneficial. The impacts obtained for the intercropping system were lower than the results for single-crop, monocultural systems.

High variations in total potential impacts for agricultural production systems in LCA studies are recurrently observed since the characteristics of the systems investigated, the study sites, and the methodological decisions of the researchers influenced the results. In this regard, Romeiko *et al*. (2020) evaluated the impacts of soybeans production in the United States. The authors considered the spatiotemporal variability of production systems and used the TRACI method to quantify global warming, eutrophication, and acidification categories. They found variations in impacts of 3%, 300%, and 43%, respectively, according to the different counties (regions) covered in their study. The authors further identified that fertilization activities are the main influencers of impacts for all three categories investigated due to the variations in application amount, leaching, and mineral runoff.

Potential environmental impacts for the wheat production

The lifecycle inventory for the crops (Table 1) showed that wheat production had the lowest demand for inputs per hectare. Moreover, its production did not occur in an irrigated land area and did not need the drying process since the grains

were harvested during winter in Sao Paulo with adequate moisture for storage (13%) after drying naturally in the field. However, wheat productivity was about 50% lower than that of soybeans and 76% lower than that of maize, which stood as one of the main influences for the high potential impact identified due to the non-dilution of impacts associated with productivity, as occurred in the cases of irrigated soybean and maize crops.

The fertilization step contributed over 67% of the impacts for all categories evaluated in the production of wheat. For the global warming and eutrophication categories, direct emissions from the system caused the most potential environmental impacts observed, accounting for about 43% in both categories. For abiotic depletion and acidification, the production and use of urea as a source of nitrogen fertilizer, accounted for most of the impacts.

The second main impact of acidification and eutrophication processes was the sowing stage. These results occurred due to the costs associated with seed production, which contributed more than 20% of the impacts. Input transportation to the farm was the second hotspot for the other two impact categories highlighting the relevance of fossil fuel.

In addition to the emissions from the impacts of maize production from the Italian farmers' cooperative (see section 3.1.1), Fantin *et al*. (2017) also assessed the effects of wheat production. As in this paper, the system occurred in a rainfed area. The authors estimated that over 70% of the total system impacts were due to grain fertilization, mainly by direct emissions. The impacts of acidification (11 mol H+/t), eutrophication (0.061 kg P eq./t), and abiotic depletion (0.0034 kg Sb eq./t) were not compared to this paper because the impact indicators were different. For the global warming category, Fantin *et al*. (2017) calculated an impact of 450 kg CO_2 eq./t, about 40% lower than that presented in the results of this work. The higher productivity of the Italian system (5.8 t/ha) and the methodological differences, such as allocation procedures and the selected LCIA method, justified the observed differences between this paper's results and Fantin *et al*. (2017).

Taki *et al*. (2018) compared the life cycle of irrigated and rainfed wheat production in the Mahyar Plain (Iran). The authors concluded that the irrigated system impacts the environment less than the rainfed due to higher productivity. The authors used SimaPro v. 8.0 software, the ecoinvent 3 and agri-footprint databases, and the CML IA v.3.0.1/ EU 25 method. For the rainfed production system, similar to this research, the authors calculated 0.003 kg Sb eq./t for abiotic depletion, which was not comparable due to the difference in the selected impact indicator. For eutrophication and acidification, the impacts were 3.18 kg PO_4^{3-} eq./t and 11.86 kg SO_2 eq./t, respectively. Both were higher than those found for wheat from the Lagoa do Sino Farm School. On the other hand, for the global warming category (380.16 kg CO_2 eq./t), the impacts were 66% lower than those of this research. Importantly, Taki *et al*. (2018) obtained the system inventory in energy units and used a "farm to harvest" approach, which may have influenced the results obtained. In agreement with this work, the authors highlighted fertilization as a hotspot in all categories evaluated. Seed production also had impacts highlighted on acidification and eutrophication.

Through a comparative LCA, Li *et al*. (2020) concluded that a viable alternative for reducing the impacts of wheat and maize production (see section 3.1.1) is the use of composted animal manure. Thus, the alternative scenarios for this research evaluated these alternatives to fertilization for the cropping production at Lagoa do Sino farm School.

Scenarios analysis: replacing mineral fertilizers by composted manure

Since the fertilization step proved to be the principal impacting process of the production systems investigated, the scenario analysis verified the environmental viability of replacing mineral fertilizer with an alternative fertilizer available locally, a dairy composted manure. Figure 3 presents the comparison between the alternative scenarios and the base scenario of mineral fertilization, traditionally used on the Lagoa do Sino farm School.

The results illustrate that the total replacement of the mineral fertilizers with the alternative source (100% replacement scenarios) increases the impacts of all three crops on the global warming

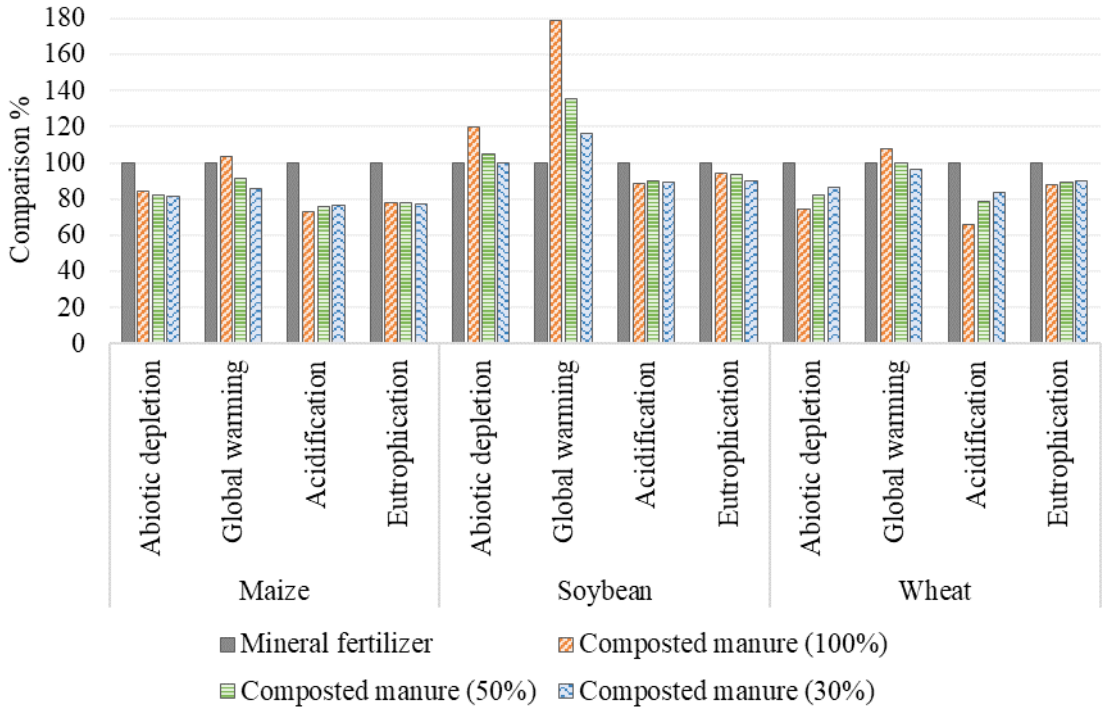

Figure 3. Comparative analysis of the alternative scenarios with the mineral fertilization scenario considering 30%, 50%, and 100% replacement of the mineral fertilizer

category and is not the most environmentally efficient.

The 50% and 30% substitution scenarios were more efficient than the base case for maize production, reducing more than 9% and 14% of impacts in all categories, respectively. For soybeans production, no alternative scenario was efficient in the abiotic depletion and global warming categories, increasing the impacts by an average of 14%. However, the three alternative scenarios could reduce the system's impacts on acidification and eutrophication. For wheat production, the 50% substitution scenario showed no change in the global warming results but reduced the impacts by 14% on average for the other categories evaluated. The 30% scenario was more efficient than the baseline scenario for all categories. With this, the most efficient alternative in environmental terms for the production systems for the three crops studied with data from Lagoa do Sino farm School was the 30% substitution scenario. More specifically, manure use in the production of maize with 50 and 30% of substitution seems more relevant, as well as for wheat production using 30 and 50% of fertilizer substitution, presenting the potential for reducing environmental impacts for most of the impact categories evaluated.

One of the main reasons for the increased environmental impact of global warming and abiotic depletion (in the case of soybeans) is the high quantity of alternative fertilizers needed to replace the mineral fertilizer. It occurred due to the lack of main nutrients in the composted manure, most notably phosphorous and potassium needed for soybeans production (see Table 4). Given the need for a large volume of compost to be applied, another reason worth mentioning is the increased use of machinery and diesel consumption for applying the alternative fertilizer. Fertilization remained as the main environmental hotspot for the three crops investigated and for the three alternative scenarios evaluated. Electric vehicles can change this scenario, benefiting from the increased usage of alternative fertilizers obtained from manure treatment.

Damasceno (2012) interviewed producers of 42 dairy compost-barn systems in the United States. According to the authors, the main benefits of this type of management are: animal comfort; improved hygiene score of the cows; low demand

for system maintenance; proper resting position for the animals; improved condition of hooves and legs; and less use of antibiotics. However, the scope of the environmental LCA approach in this work did not cover these benefits. However, some limitations are also pointed out in the literature, such as the high need for bedding management in the composting shed, with daily revolving and constant replacement of the wood sawdust, and the influence of the climate on the process, the colder and more humid periods being less favorable to aerobic digestion (Brito, 2016). Regarding the bedding material used as fertilizer, Du *et al*. (2020) conducted a literature review seeking to list the main effects caused by the use of manure as fertilizer in agricultural soils. The authors found that, from a long-term perspective, using the alternative fertilizer can improve soil conditions (pH, total nitrogen, available nitrogen, phosphorus, and potassium) soil life and crop yields. They also recorded 17.1%, 14.4%, and 7.9% increases in maize, soybeans, and wheat yields, respectively.

Although, the fertilization replacement should be cautiously done and evaluated for the peculiarities of each system and crop produced. In this sense, it is worth mentioning Jiang *et al.* (2021), who evaluated the life cycle of wheat production using four different fertilization strategies: (1) mineral fertilization; (2) replacement of 50% of the mineral fertilizer by composted swine manure; (3) replacement of 50% of the mineral fertilizer by composted manure with the addition of 5% biochar; and (4) with the addition of 10% biochar. The authors observed increased global warming impacts, freshwater eutrophication, and terrestrial acidification in the replacement scenario with composted manure without adding biochar. The higher energy demand to obtain wheat straw (used in the composting process), diesel, and emissions from the composting process justifies the increase in the investigated impacts. The authors observed better environmental performance for global warming to the production of wheat by inserting biochar as an additive in the alternative compost, but the impacts remained higher for the other categories.

Li *et al*. (2020) also evaluated mineral fertilizer substitution for animal manure. The authors studied the life cycle of maize-wheat rotational system production in the northern lowlands of China, considering three fertilization strategies: mineral fertilizer use; 50% replacement of mineral fertilizer by solid bovine manure; and 50% replacement by liquid bovine manure. The authors did not consider impacts on the production of manure, justifying it as a residue of the dairy production. They concluded that the systems with alternative fertilization are more efficient, having reduced in 25% the impacts for the categories evaluated, including those being worked on in this study. However, it is relevant to mention that Li *et al*. (2020) identify fertilization as the hotspot of production systems for the three scenarios evaluated, agreeing with our findings.

CONCLUSION

- This study assessed the environmental impacts associated with a one-year farming season at Lagoa do Sino farm School from the Federal University of Sao Carlos, thus investigating a rotational and intensive production system for soybeans (summer crop), maize (second crop), and wheat (winter crop) using LCA.
- The research concluded that fertilization is the process with the highest potential for generating impacts on abiotic depletion, global warming, acidification, and eutrophication for the three crops investigated. Scenario analysis showed that replacing mineral fertilizer by composted cows' manure can result in higher impacts if 50% and 100% of nutrient substitution is due to the high amount of alternative fertilizer required and greater use of fossil fuel to apply the manure. In the 30% substitution scenario, the potential impacts were reduced in almost all categories, making it a viable scenario and of possible applicability due to the regional availability of the alternative fertilizer.
- Input substitution promotes a nobler destination for the residues of the wood industry and from the regional animal production, besides encouraging dairy farmers to the beneficial management of compost-barn systems. A scenario in which farmers can have tractors powered by electricity (batteries) can favor

greater substitution volumes by eliminating or even reducing the use of fossil fuels.

- The testing of alternative scenarios with other agricultural residues, such as poultry manure, is suggested as a natural continuation of this work. The search for an additive to the alternative fertilizer to increase its nutrient availability in the agricultural soil, such as biochar (activated charcoal), may also be an opportune field for research for the Brazilian agricultural sector.

AUTHORSHIP CONTRIBUTION STATEMENT

GIUSTI, G.: Formal Analysis, Investigation, Methodology, Project administration, Writing – original draft; **SAAVEDRA, Y.M.B.:** Methodology, Project administration, Supervision, Validation, Writing – review & editing; **ALMEIDA, G.F.:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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