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Soybean and maize cultivation in South America: Environmental comparison of different cropping systems

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ABSTRACT

Maize and soybean are two widely spread crops for food, feed and biofuel production, and in South America there are some of the most important producing countries in the world. This study investigates the environmental impact linked to their agricultural production in a sub-tropical South American context, starting from primary data relating to a cultivated area in eastern Paraguay. To this end, the Life Cycle Assessment approach was adopted in a cradle-to-farm gate perspective, evaluating eight different impact categories. In particular, two widespread intra-annual rotations were compared, both of which consider soybean as a first-season crop, alternating in the second-season with maize or soybean itself. Environmental results were expressed both in a crop-to-crop approach (per t of individual product) and with four different units expressing the land management function (1 ha year^{-1}); the productive function (1 GJ ha^{-1} year^{-1} and 1 t of crude protein ha^{-1} year^{-1}) and finally the financial function (1 USD of gross margin ha^{-1} year^{-1}) of the two different cropping systems. In the cropping system approach, results expressed per hectare of cultivated area and per t of crude protein produced do not see one cropping system performing better than the other consistently over the evaluated impact categories. The soybean-maize rotation, on the other hand, appeared clearly more efficient from an environmental point of view in terms of gross energy and gross margin produced per hectare per year.

The lack of a shared consensus on the most appropriate and comprehensive way to express the results of LCA studies on cropping systems makes difficult the selection of the best system. In particular, there are still on-going limitations and controversies in selecting the most appropriate functional unit for cropping systems LCA.

1. Introduction

The growing demand for feed, food and biofuels is leading to a steady increase in agricultural crop production globally (FAO, 2006). Soybean and maize are two of the most important crops in the world for these purposes. In the last decades, the soybean global harvested area has undergone a great expansion, going from 23.8 million hectares in 1961 to 120.5 in 2019 (FAOSTAT, 2020). South America is a key region in the world market for these commodities, hosting nations such as Brazil, Argentina, Paraguay and Uruguay, which are major producers and exporters worldwide. Since the products derived from soybean and maize are mainly destined for animal feeding, their production plays a fundamental role for the environmental sustainability of the growing world livestock activities (FAO, 2016; GIZ, 2019), which are currently attributed the greatest impact in agriculture (Poore and Nemecek, 2018).

However, the reduction of the environmental load related to feed crops requires an understanding of how this impact arises and how alternative cultivation practices and technical solutions could mitigate these negative burdens. Sustainable cropping systems are characterized by high yield and by an efficient use of the different used production factors (i.e., land, seeds, fertilizers, pesticides) (Lassaletta et al., 2014). Besides the evaluation of the environmental effects related to the cultivation of a single crop, also crop rotations should be evaluated. Rotations are recognized as an effective way to preserve soil fertility and the efficiency of cropping systems while reducing the use of inputs thanks to no pest and weed specialization and a better exploitation of nutrients (Ghaley et al., 2018).

Life cycle assessment (LCA) is an approach widely used to assess the environmental burdens associated with agri-food products or processes, by identifying the consumption of resources and emissions to environmental compartments divided into the different life cycle stages (Finkbeiner, 2014). The most common LCA research on arable crop productions has typically been oriented to the single crop perspective (Noya et al., 2015). However, in recent years the effect that crop

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rotations can have on the environmental performance of agricultural production has aroused increasing interest in the agricultural LCA community (Goglio et al., 2018). The shared purpose is to achieve a more complete understanding and evaluation of agri-environmental systems, being many agricultural operations normally included into complex production schemes that go beyond the single crop. In a given rotation cycle, the previous crop affects the crop that follows because has an effect on the nutrients' turn-over and soil organic and mineral status but also on weed seed bank and pest presence. For example, crop residues remaining on the field or the introduction of green manure crops or catch crops in the crop rotation can have a major impact on the subsequent crop and on the crop rotation as a whole by affecting the soil properties and fertility and, consequently, the potential yield (Jeswani et al., 2018). Neglecting these fluxes and relations between crops and years leads to free-rider situations for crops that consume nutrients left by the preceding crops or leads to soil fertility depletion. LCA studies assessing only one crop have a limited ability to include these effects, thus under- or over-estimating the impacts (Tidåker et al., 2014).

Despite different specific conclusions regarding the impact of the different crops (mainly affected by climate and the cultivation practices), all the above-mentioned studies pointed out that, when different cropping systems are evaluated using the LCA approach more than one functional unit should be considered.

In this context, this study aims to evaluate the environmental performance of two widespread cropping systems in sub-tropical South American by means of a case study developed on Paraguay. On the one hand, the environmental impacts linked to soybean and maize productions are presented separately. Beyond this, a comparison between different intra-annual crop rotations is developed, to compare which is the most environmentally sustainable use of agricultural land in the short term between two widespread alternatives. A methodological reasoning is also presented regarding the selection of the most appropriate functional unit for crop rotations, or in any case verify the influence of its choice.

2. Methods

2.1. Goal and scope

The environmental impact of two alternative intra-annual cropping systems was assessed and compared using the LCA approach. In the following sections the methodology is presented, the framework of which was developed following the ISO reference standards (ISO 14040:2006 and ISO 14044:2006).

In particular, a case study is developed relating to a production area of about 2200 ha in the eastern region of Paraguay (Alto Paraná Department). Thanks to its profitability, the main crop within the year, called first-season crop (or summer crop), is soybean, of which the studied Department is the most productive in the country (FAO, 2018; DGEEC, 2020). This is then alternated within the year with second-season crops, which can be mainly maize or soybean itself in monoculture (see supplementary material for the schematization of the crop calendar). The analyzed farm falls within the share of large (>1000 ha) soybean farms in Paraguay. These are only 3% of the total soybean farms, but they occupy almost half of the soybean area and are responsible for almost half of the total national production (for more details, see supplementary materials) (MAG, 2009). These are farms that provide for high capital inputs and an intense use of machinery, technologies and production materials per unit of land area.

The analyzed double cropping systems are widespread in Paraguay (FAO, 2018), where soybean and maize are respectively the first and second crops occupying the most arable land (DGEEC, 2020), as well as in other areas of South America, particularly in some states of Brazil (Paraná, Mato Grosso and Mato Grosso do Sul; Elobeid et al., 2019). Second-season maize represented about three quarters of the entire Brazilian production in 2020 (USDA, 2020a). This is to underline that methodology and considerations of this study can actually be applied to a larger area than the in-depth one.

The main goal of this LCA study is to compare the environmental performance of two intra-annual cropping systems in a context of a sub-tropical cultivated area. Both the cropping systems produce grain, the first one presents soybean as first-season crop, alternating with second-season maize (Cropping System 1 – CS1) the second-season soybean (Cropping System 2 – CS2). The main environmental hotspots are identified both for single crops (crop-to-crop approach) and through different cropping system approaches, which are also methodologically compared with each other. LCA-based tools represent an excellent opportunity to contribute to the environmental and economic development of the agricultural sector. This work offers an insight of a crop system widely adopted in South America, so it can be useful to support policies, strategies or further research aimed at mitigating climate change, optimizing and saving natural resources and defining a sustainable food production system, also important in terms of food security. At the local Paraguayan scale, where the study is focused, there are only few previous experiences of the use of LCA (i.e., Costantini et al., 2021). Therefore, this work can help to further promote life cycle thinking in the country and in particular for the agricultural sector, which today is the main contributor to GHG emissions in the country (MADES, 2019).

2.1.1. Functional unit

It is well established that the environmental results of LCA studies are expressed with respect to a mathematical unit called functional unit (FU), and that this must be related to the goal and system boundaries of the study. According to ISO standards, the FU should best express the function of the system being analyzed. In a first section of the results, the environmental results are presented referring to the single crop (i.e., second-season maize – SM; second-season soybean – SS; first season soybean – FS). In this section, the FU used was 1 t of grain at 14% of moisture content. Although in some cases multiple FUs have been adopted for LCA studies of single crops (e.g., Bernardi et al., 2018; Tricase et al., 2018), the mass-based FU is the most widely used for agricultural LCA studies as it is accepted that the main function of a single crop (at the farm gate) is to deliver a certain quantity of a certain product. In a second section of the results, environmental performances related to a cropping system that involves two crops in rotation on the same agricultural land in the same year are presented. In this case, expressing results based only on the biomass produced is definitely limiting. The best option to date for transparency and comprehensibility is to express the cropping systems results through multiple FU (Bacenetti et al., 2015; Noya et al., 2017; Zucali et al., 2018; Costa et al., 2020). Therefore, following the framework proposed by Nemecek et al. (2008) and Nemecek et al. (2015), the following aspects were considered:

- the land management function, that is, the impact of cultivating a unit of area for a time unit, in this case one year. Impacts were first expressed in relation to 1 ha $year^{-1}$.
- the productive function, which can be expressed in GJ of produced gross energy per unit area per year. This reflects the productive function of the double cropping system for a fixed unit of area whether crops are intended for animal and/or human nutrition or for biorefinery. As it could be objected that the productive function of soybean, being a legume, is not best expressed by gross energy alone, the crude protein yield per hectare was also considered as an additional functional unit. Therefore, impacts were expressed related to 1 GJ ha^{-1} $year^{-1}$ and 1 t of crude protein ha^{-1} $year^{-1}$.
- the financial function, finally, intends to evaluate the impact from a farmer perspective, for which the main aim of cultivating is represented by the income from agricultural activity. The environmental performance according to this FU improves the more the impacts per gross margin generated are minimized. Impacts were thus expressed related to 1 USD of gross margin ha^{-1} $year^{-1}$.

2.1.2. System boundary

This study focuses on the agricultural production in an attributional "*cradle-to-farm gate*" perspective. The life cycle of each agricultural process has been included within the system boundaries (Fig. 1). More in detail, raw materials extraction (fossil fuels and minerals), manufacture, supply and consumption of productive factors (seeds, fertilizers, pesticides, fuels and agricultural machineries) and emissions to the environment related to field operations (combustion exhaust gases, nitrogen and phosphorous compounds from fertilization and crop residues, and active ingredients from pesticides application) were included.

The downstream processes considered in addition to the field production per se were the transport of the harvested grains to the nearest silo, assumed to be at an average distance of 3 km, and drying. Soybean grain is already harvested at the moisture content suitable for storage, therefore does not require drying. Maize grain, on the other hand, always needs to be dried, which occurs in a dedicated pre-storage area of the silos by means of heat from the burning of eucalyptus woody biomass. This is the most common source of thermal energy for industrial purposes in the country (FAO, 2018). The impact related to manufacture, maintenance and end-of-life of farms infrastructures was excluded. Impacts resulting from further transports and processing, distribution, consumption and all related waste disposal have not been considered.

The organic matter of the soil was assumed in steady state. Accumulation or decline of soil organic carbon are known to occur slowly over the years as a result of cropping systems, and many other agronomic and pedoclimatic variables interfere with these phenomena (Costa et al., 2020). The evaluation of the long-term influence on soil characteristics and the related environmental impacts that crop rotations have is beyond the scope of this work, since it focuses on very short cropping systems (intra-annual). Similarly, the impact possibly linked to land use changes has been excluded from the system boundaries because land use has remained unchanged in recent decades, as has crop management. Furthermore, land use change would not influence the relative comparison between the performances of the two cropping systems, being carried out on the same agricultural land.

Since all the crop-residues are left in the field and return to the soil, it was not necessary to allocate the impact within the single crop as no co-products are generated.

2.2. Inventory analysis

Primary data were collected through interviews with farmers involved in cropping management in the area studied. Documentation regarding the use and costs of material inputs, soil properties, field operations, farm fleet's machinery characteristics and operating parameters and yields relating to the period from 2013 to 2018 was also shared.

The collected data were processed in order to form a distinctive standard production process for each crop, of which the inventory is reported in Table 1. For SM and FS, the observed yields are in line with the national agricultural statistics (DGEEC, 2020; CAPECO, 2020), as well as with those reported for other South American producing countries (FAO, 2016; USDA, 2020a). The marked yield difference between FS and SS is due to a shorter cycle together with non-optimal climatic conditions. For SS, the yield observed in the study area are lower than those reported by FAO (2018) as a national average (2.47 t ha^{-1} in the period 2009–2016). There is no irrigation system, so the crops are completely rain-fed.

As concerns the conversions between different FUs for the cropping system approach, information about the gross energy content of the productions was retrieved from Heuzé et al. (2017a) and Heuzé et al. (2017b) for soybean grain (23.6 MJ kg DM^{-1}) and maize grain (18.7 MJ kg DM^{-1}, reference for Central and South America) respectively.

Table 1
Inventory data for the cultivation of 1 ha of the different crops.

Operations, Inputs & outputs	Unit of measure	First-season soybean (FS)	Second-season maize (SM)	Second-season soybean (SS)
No-till seeding	Number of interventions	1	1	1
Application of plant protection products, by sprayer	Number of interventions	6	4	5
Harvesting	Number of interventions	1	1	1
Transport	t km	9.39	17.7[a]	4.98
Drying	L evaporated water	–	548[b]	–
Seeds	kg	45	30	70
NPK fertilizer (4-30-20)	kg	220	–	–
NPK fertilizer (8-20-10)	kg	–	–	220
NPK fertilizer (10-15-15)	kg	–	220	–
Active ingredients from pesticides, total[c]	kg	3.51	2.34	1.9
Yield	t (DM 86%)	3.15	5.35	1.67
Gross energy yield	GJ	63.93	86.04	33.89
Crude protein yield	t	1.043	0.538	0.553
Gross margin	USD	783.13	496.55	304.93

[a] This transport considers the fresh mass at harvest, at a moisture content of 22%.
[b] Maize grain is dried from a moisture content of 22%–14%.
[c] See supplementary materials for more details.

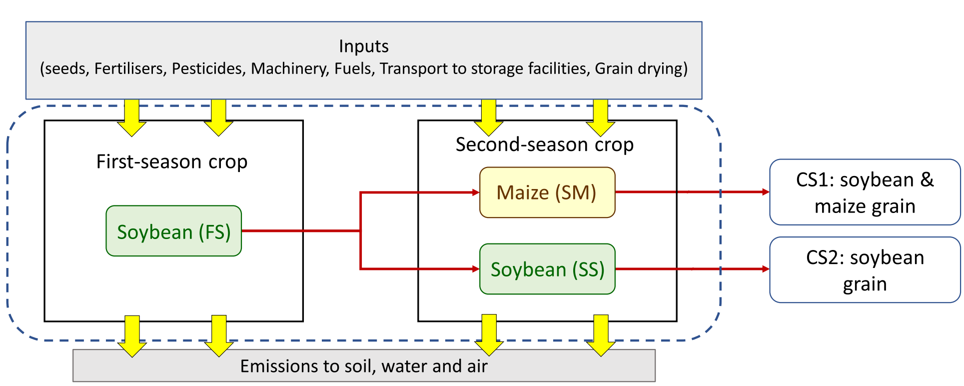

Fig. 1. System boundaries: management of 1 ha in a productive agricultural year for the two alternative cropping systems evaluated.

The gross margin was derived from producer's price commodities minus the direct production costs. Producer's prices were recovered from the FAOSTAT database (FAOSTAT, 2020). These refer to the amount receivable by the producer from the purchaser as output minus any deductible tax, invoiced to the purchaser; excluding any transport charges invoiced separately. Further information can be found in the supplementary material.

Primary data were integrated with secondary data derived from estimation models, retrieved from the literature and concerning in particular the on-field pollutant emissions related to field cultivation. As regards nitrogen (N) compounds emission, the estimate was based on the model proposed by Brentrup et al. (2000). This has been widely used to compute fertilizer-related emissions in agricultural LCA studies in the last decades (Rivera et al., 2017). It is based on a simplified nutrient balance approach that takes into account the main N flows of the soil system for a cultivation year, namely mineral and organic fertilizers application, wet and dry atmospheric deposition as inputs and N content in removed crop portions (products and co-products), leaching and gaseous emissions as outputs. The model was adapted to the conditions of the system under study by also considering within the balance (i) the biological N fixation for soybean and (ii) the N flows associated with crop residues. Beyond these flows, the model assumes a standard steady-state condition of soil nutrients, in which therefore N immobilization and mineralization are in equilibrium, and that the fraction of nutrients lost by erosion is negligible. The latter assumption was considered applicable in this study considering that: the area under examination is a plain with contained field slope; the soil has a predominantly clayey texture; and tillage operations are normally absent since no-till seeding is practiced, as is commonly the case in the country (WWF, 2016), and the soil is never left uncovered. For more details on modeling nitrogen fluxes, see supplementary materials. Phosphate emissions (run-off and leaching) were computed according to Nemecek & Kä;gi (2007), considering fixed emission factors for arable lands and correction factors based on the P input from mineral fertilizers. Phosphorus lost through erosion was excluded due to lack of information. Pesticide products inputs have been inventoried considering the mass of active ingredients they contain (see Table 1), which were also considered to be released entirely into the agricultural soil as outputs, according to Nemecek & Kä;gi (2007).

Background data for manufacture and supply of seeds, fertilizers and pesticides, drying of maize grain, agricultural mechanized processes and transports, and the related manufacture, supply, maintenance and end-of-life disposal of machineries were sourced from the Ecoinvent® database v. 3.6, with allocation at the point of substitution as system model (Weidema et al., 2013; Moreno-Ruiz et al., 2019). The list of processes retrieved from the database is shown in the supplementary material. For field operations, a detailed modeling based on primary data was carried out, therefore the agricultural processes reported in the Ecoinvent® database have been modified considering machinery characteristics (mass, power) and operating parameters (working width and speed, total worked area, etc.) (Lovarelli and Bacenetti, 2017). Based on these parameters, it was estimated the use of a tractor with a power of about 100 kW and a mass of 5.5 t per 300 ha of cultivated land with an effective annual work of 580 h (includes sowing and harvesting operations); and a 220 kW and 14 t combine harvester per 600 ha with an effective annual work of 380 h. The adjusted inventory of the individual field operations is shown in Table 2. The exhaust gas emissions from fuel combustion have been modified by scaling them according to the reported consumption. It is worth emphasizing that the database processes related to the virtual consumption of agricultural machinery include the impacts related to their manufacturing, maintenance (e.g., lubricant oil consumption) and disposal (Nemecek & Kä;gi, 2007).

Table 3
Environmental results per t of grain at 14% moisture (Note: GWP = global warming potential; ODP = ozone depletion; PMPF = fine particulate matter formation; TAP = terrestrial acidification; FEP = freshwater eutrophication; FETP = freshwater ecotoxicity; SOP = mineral resource scarcity, expressed as surplus ore potential; FFP = fossil resource scarcity).

Impact category	Unit of measure	First-season soybean (FS)	Second-season maize (SM)	Second-season soybean (SS)
GWP	kg CO_2 eq	284.4	182.4	590.8
ODP	g CFC-11 eq	3.89	3.43	8.47
PMFP	kg PM2.5 eq	0.51	0.30	0.95
TAP	kg SO_2 eq	1.26	0.84	2.47
FEP	kg P eq	0.13	0.06	0.22
FETP	kg 1,4-DCB eq	14.0	12.8	24.4
SOP	kg Cu eq	3.68	1.57	5.65
FFP	kg oil eq	44.1	26.1	79.8

2.3. Impact assessment

The inventory dataset was characterized by means of the Rivera et al. (2017) Midpoint (H) method, version 1.04/World (Huijbregts et al., 2017), considering 8 impact categories, namely climate change (GWP, expressed as CO_2 eq); ozone depletion (ODP, expressed as g CFC-11 eq); fine particulate matter formation (PMPF, expressed as kg PM2.5 eq); terrestrial acidification (TAP, expressed as kg SO_2 eq); freshwater eutrophication (FEP, expressed as kg P eq); freshwater ecotoxicity (FETP, expressed as kg 1,4-DCB eq); mineral resource scarcity (SOP = surplus ore potential, expressed as kg Cu eq); and fossil resource scarcity (FFP, expressed as kg oil eq). The impact categories have been selected because considered relevant for agricultural activities. Land use was not accounted due to the lack of consensus on how to allocate the use of the land resource between different crops grown on the same land within the same year. The analysis was performed using SimaPro® LCA software v 9.1 (Pré-Sustainability 2020).

3. Results

3.1. Environmental crop-to-crop results

Table 3 shows the environmental results for the evaluated impact

Table 2
Inventory of field operations, adapted to the operating parameters of the studied area starting from the standard field processes of the Ecoinvent® database. Data are expressed in kg ha^{-1} and refer to one intervention.

Field operation	Diesel consumption	Tractor (4-wheel) consumption	Harvester consumption	Agricultural trailer consumption	Other agricultural machinery consumption
No-till seeding	9.6	0.353	–	–	0.699
Chemical weeding, by field-sprayer	1.25	0.140[a]	–	–	–
Combine harvesting, maize[b]	23.38	0.353	1.24	0.44	1.08
Combine harvesting, soybean[b]	23.38	0.353	1.24	0.44	0.52

[a] Self-propelled sprayers have been inventoried as 4-wheel tractors due to the lack of more specific background data.
[b] Harvesting maize and soybean grain requires the simultaneous use of a combine harvester and a chaser bin pulled by a tractor. Fuel consumption refers to the sum of their total consumption per hectare for the operation.

categories for single crops, reported for 1 t of grain at 14% moisture content. In terms of absolute impact per t of product, maize grain achieves the best environmental results compared to soybean for all impact categories. For soybean, the difference between first- and second-season results are remarkable. The latter has greater impacts for all impact categories (from +153.5% for SOP to + 217.7% for ODP). Nevertheless, the main contributors (Fig. 2) are similar between the different crops. The difference between the impact per t of product is primarily due to the different yields. The main differences between the contribution analysis of first and second-season soybean refer to a greater contribution of N_2O from crop residues for first-season soybean in the impact categories concerned (i.e., GWP and ODP), due to the higher yield and, consequently, a greater amount of crop residues returned to soil. First-season soybean is the crop with the higher contribution of N_2O from crop residues (18.4% for GWP and 49.5% for ODP), as well as the only one where N_2O emission from crop residues are higher than the one from fertilization (7.3% for GWP and 19.7% for ODP). This brings out the trade-off between the positive effect for subsequent crops of leaving N-rich crop residues in the field and the potential formation of N_2O related to them. On the other hand, the contribution due to the production and supply of seeds is higher for second-season soybean for all the impact categories because, due to the lower germinability in the second-season sowing period, a higher sowing density per hectare is required (see Table 1).

Fertilizers consumption is the dominant driver of the impact for all impact categories and for all crops. Mechanized operations have a secondary, but not negligible, role compared to fertilizers. The impact category in which these are most prominent is fossil resource scarcity, in which overall they weigh from 38.4% for second-season maize to 40.6% for second-season soybean.

3.2. Environmental cropping system results

Table 4 shows the environmental results for the evaluated impact categories with the cropping system approach, while Fig. 3 shows the relative comparison of the environmental performances between the two cropping systems. In the figure, for each impact category and for each functional unit, the highest result was set equal to 100 and the other proportionally scaled.

The results are influenced by the different FUs selected. When these are expressed per hectare, neither of the two cropping systems stands out with detachment because the results for the different impact categories are conflicting. This is due to the similarity in the management of the 2 s-season crops in terms of field operations and inputs per hectare, and in the similar the arable land management intensity, which is normally the main driver of impact variations when comparing the results per hectare (Tricase et al., 2018). More in detail, CS1 is less impactful for GWP, FEP and SOP, while CS2 for ODP, TAP, FETP, FFP. The two impact categories in which the maximum relative deviation is observed between the two systems are ODP (CS2 13.7% lower), due to the influence of maize grain drying on this, and FETP (CS2 24.7% lower), due to the high impact of atrazine compared to the active ingredients most used for soybean (e.g., glyphosate, 2,4-D).

When the environmental results are expressed in relation to the gross energy produced, the CS2 appears to be the one with the greatest impact, as the CS1 presents lower impacts for all impact categories ranging from −13.4% for FETP up to −41.5% for FEP. This is due to the higher gross energy yield of maize compared to soybean in second-season cropping and ultimately the different dry matter yield.

The results for gross margin are positioned at an intermediate level between those previously presented. The CS2 appears in any case more

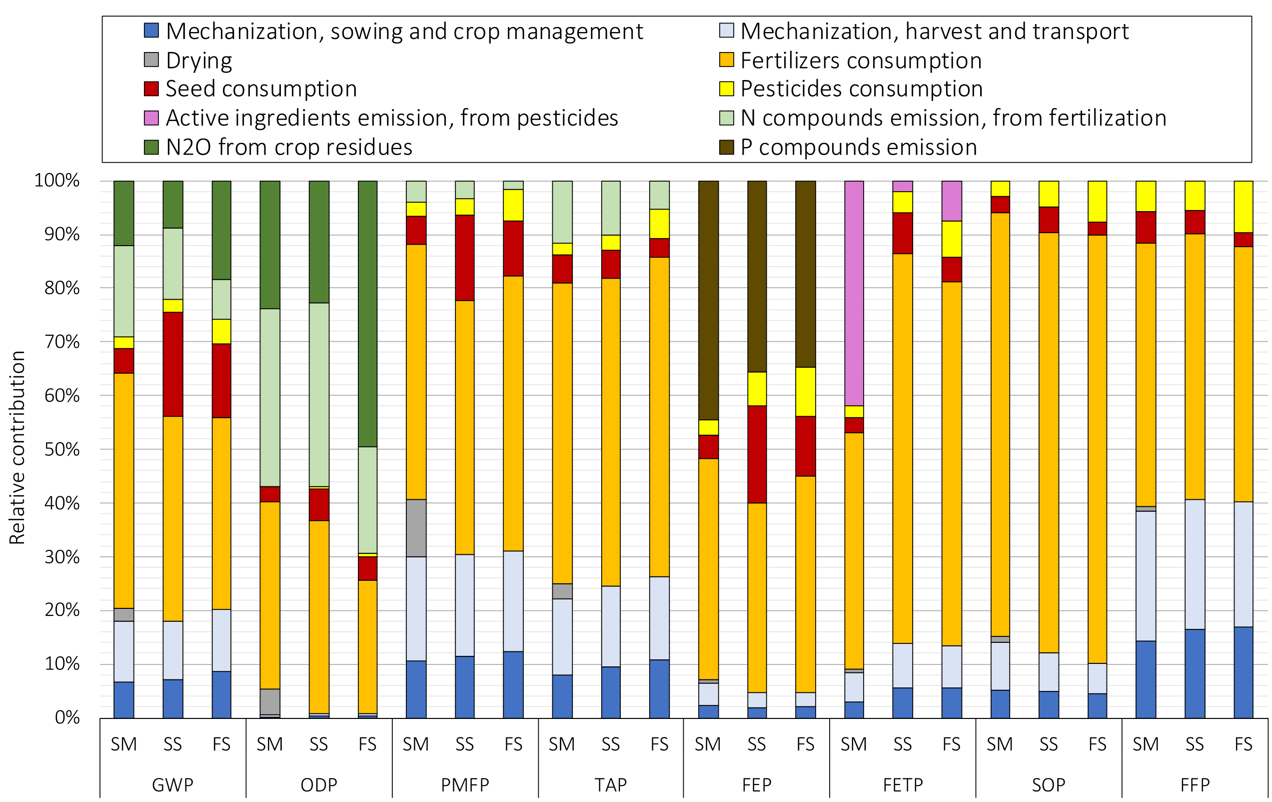

Fig. 2. Crop-to-crop contribution analysis for the evaluated impact categories. (Note: the label *consumption* includes manufacturing, supply and packaging disposal; GWP = global warming potential; ODP = ozone depletion; PMPF = fine particulate matter formation; TAP = terrestrial acidification; FEP = freshwater eutrophication; FETP = freshwater ecotoxicity; SOP = mineral resource scarcity, expressed as surplus ore potential; FFP = fossil resource scarcity).

Table 4
Environmental results according to the cropping system approach, expressed in relation to the different functional units selected.

Impact category	Unit of measure	Land management function (1 ha year^{-1})		Productive function (1 GJ of gross energy · ha^{-1} · year^{-1})		Productive function (1 t of crude protein · ha^{-1} · year^{-1})		Financial function (1 USD of gross margin · ha^{-1} · year^{-1})	
		CS1	CS2	CS1	CS2	CS1	CS2	CS1	CS2
GWP	kg CO_2 eq	1871.4	1882.3	12.5	19.2	1183.3	1179.2	1.46	1.73
ODP	g CFC-11 eq	30.6	26.4	$2.04 \cdot 10^{-1}$	$2.7 \cdot 10^{-1}$	19.3	16.5	$2.39 \cdot 10^{-2}$	$2.43 \cdot 10^{-2}$
PMFP	kg PM2.5 eq	3.18	3.18	$2.12 \cdot 10^{-2}$	$3.25 \cdot 10^{-2}$	2.01	1.99	$2.49 \cdot 10^{-3}$	$2.92 \cdot 10^{-3}$
TAP	kg SO_2 eq	8.48	8.11	$5.66 \cdot 10^{-2}$	$8.29 \cdot 10^{-2}$	5.36	5.08	$6.63 \cdot 10^{-3}$	$7.45 \cdot 10^{-3}$
FEP	kg P eq	$6.98 \cdot 10^{-1}$	$7.78 \cdot 10^{-1}$	$4.65 \cdot 10^{-3}$	$7.96 \cdot 10^{-3}$	0.40	1.41	$5.45 \cdot 10^{-4}$	$7.15 \cdot 10^{-4}$
FETP	kg 1,4-DCB eq	112.6	84.8	$7.51 \cdot 10^{-1}$	$8.67 \cdot 10^{-1}$	71.2	53.1	$8.8 \cdot 10^{-2}$	$7.8 \cdot 10^{-2}$
SOP	kg Cu eq	20.0	21.0	$1.33 \cdot 10^{-1}$	$2.15 \cdot 10^{-1}$	12.6	13.2	$1.56 \cdot 10^{-2}$	$1.93 \cdot 10^{-2}$
FFP	kg oil eq	278.3	272.1	1.86	2.78	176.0	170.5	$2.18 \cdot 10^{-1}$	$2.5 \cdot 10^{-1}$

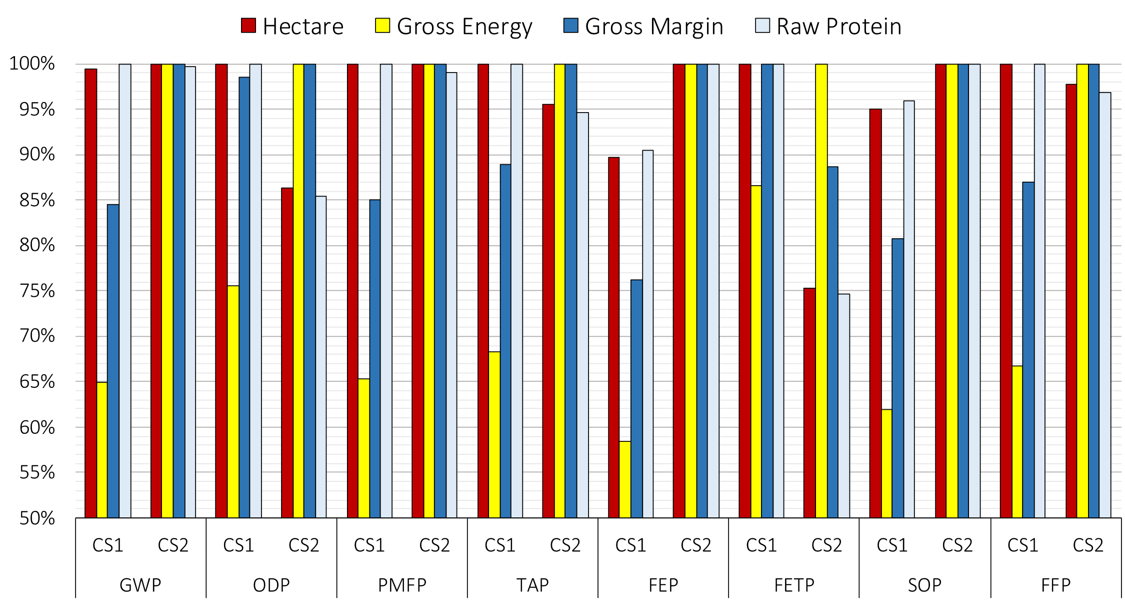

Fig. 3. Relative comparison between the impact of the different cropping systems considered (CS1 & CS2). (Note: GWP = global warming potential; ODP = ozone depletion; PMPF = fine particulate matter formation; TAP = terrestrial acidification; FEP = freshwater eutrophication; FETP = freshwater ecotoxicity; SOP = mineral resource scarcity, expressed as surplus ore potential; FFP = fossil resource scarcity).

impactful for all categories, with the sole exception of FETP, but the gap between the two systems is not as wide as in the case of gross energy, with CS1 having a minor impact ranging from −1.5% for ODP up to −23.8% for FEP.

4. Discussion

Despite several efforts to trace the methodological path in recent years (e.g., by Nemecek et al., 2015 and Goglio et al., 2018), the evaluation of the environmental performance of crop rotations and cropping systems with the LCA approach is still challenging. This depends primarily on the FU selection, which is often not easily identifiable, even for the most basic cropping systems such as those detailed in this study. Using more than one FU allows broad considerations to be made regarding different cropping systems, but requires greater efforts in interpretation and does not facilitate benchmarking or decision-making and could even lead in the worst case to a manipulation of the results according to the subjective interests of those who exhibit/interpret them. For instance, in the case of the present study, CS1 appears more sustainable when considering gross energy production, while the results are conflicting between the different impact categories when taking cultivated hectare or crude protein production as FU.

The gross margin-based FU is intuitive and at the same time also provides information about economic sustainability. However, this is not very robust when comparisons are to be made because it is largely influenced by the business environment in which an LCA study takes place. The price volatility that characterizes the agricultural sector could lead to very different conclusions on the exact same production system in different periods. By a way of example, starting from May 2020, the soybean market experienced a strong and constant rise in prices to reach 475–520 USD t^{-1} in November 2020, the highest ever for many years (USDA, 2020b). Under these conditions, the CS2 would have the largest gross margin which would change the environmental results of the present study under the financial functional unit. Furthermore, direct production costs might show variability depending on the market, managerial choices, agro-climatic conditions, etc.

In both cropping systems an annual negative balance was observed between all nitrogen inputs and outputs. These results may suggest that, with current fertilization rates, each of the two rotations, and especially CS1, could lead to a net mineralization of organic nitrogen and thus to a slow depletion of the soil nitrogen content and/or in a reduction in the productive performance of crops. At the same time, however, fertilization has emerged as a fundamental driver of the environmental impact of crop products, which highlights a trade-off and stresses the importance of the attention that should be paid to plant nutrition in as efficiently and accurately as possible.

5. Conclusions

This study has deepened the environmental impact linked to their intra-annual agricultural production in a sub-tropical South American context, starting from primary data of a cultivated area in eastern Paraguay, with both a crop-to-crop and a cropping system approach. The similarity in the management of cultivation operations and the production factors used determines that: (i) in the crop-to-crop approach, yield is the main driver on the impact per product biomass, which sees the second-season maize with the least impacts, followed by first-season soybean and finally second-season soybean; (ii) in the cropping system approach, results expressed per hectare of cultivated area are similar between the two considered cropping systems (first-season soybean alternating with soybean or maize in second-season). When functional production (gross energy) and financial (gross margin) units were adopted to express the cropping system results, the maize-soybean rotation shows better environmental results than the soybean in monoculture. For gross energy this is explained once again mainly by the higher dry matter yield of this cropping system, while the results of the gross margin also testify to a greater profitability of this rotation in the conditions explored.

However, the achieved results highlighted how the selection of the functional unit can be controversial and can, potentially, affect the study outcomes. Future efforts should be focus on this aspect aiming at the definition of the most appropriate functional unit for cropping systems.

Declaration of competing interest

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2021.100017.

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