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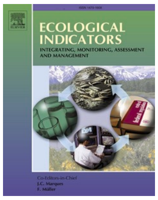

Environmental analysis of crop rotations through the application of the Cereal Unit approach

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ABSTRACT

The sustainability of agricultural practices is a key element for an effective implementation of the UN's Sustainable Development Goals, particularly relating to ending poverty and hunger, responding to climate change and supporting the natural resources. As part of ongoing research and improvement in this field, this study aims to apply Life Cycle Assessment methodology to the agricultural sector, and to discuss and support the use of Cereal Unit (CU) parameter. To overcome the differences that emerge when two or more different crops are compared, the CU can be used as a functional unit (FU) to capture all the functions of the products. This approach avoids the use of economic parameters, providing for more stable comparisons over time, as the price of agricultural products is strongly influenced by market and currency fluctuations. The robustness of this approach was tested by the assessment and comparison of the environmental burdens of two different crop rotations using a CU-based FU. The same systems were also evaluated with a revenue-based FU to assess the pros and cons of the two type of approach. The study considered Argentina, due to the high importance of its agricultural products, which are widely exported in the world. The first crop rotation, called San Justo (SJ), is the one conventionally followed in the region and provides for a low-intensity cultivation, while the other, Evergreen (EG), is the alternative which requires a more intensive exploitation of the soil. The results showed that CU approach allows reliable and stable comparisons and, in this specific case, that the conventional system has a higher environmental load, with land use being the key factor in the assessment.

1. Introduction

Primary sector has a central role in the realization of a sustainable future, firstly because it is an area of significant importance for the provisioning of food and then because it is the oldest activity humans have developed that has impacted and modified the environment directly (Foley et al., 2005) and, at the same time, has been affected by environmental changes (Gruda et al., 2019; Howden et al., 2007).

In the ongoing research in this field, Life Cycle Assessment (LCA) methodology is recognised as an important scientific tool to predict the environmental performances of products and/or processes by considering the impacts of all phases of their life cycle. It, as defined by ISO 14040:2006 and ISO 14044:2018, consists of four phases: (*i*) goal and scope, (*ii*) life cycle inventory (LCI), (*iii*) life cycle impact assessment and (*iv*) interpretation (ISO, 2018; 2006). The agriculture sector plays a significant role in this environmental studies, as evidenced by the numerous LCA analyses that have been carried out on the subject (Boone et al., 2019; Clark and Tilman, 2017; Liang et al., 2019; Martinez et al., 2018; Zhai et al., 2019). The incidence of agricultural studies in LCA research papers has begun to gain more and more ground and now represents about 20% of the total (291 documents out of a total of 1444 relating to the first quarter of 2020) (Scopus website, 2020). However, what emerge from these studies is the difficulty in identifying the appropriate functional unit (FU) to be used. The FU, as defined in ISO standards, quantifies an identified function of the system under study and provides the reference to which the inputs and outputs are related.

Heller et al. in their review (2013) underline the importance of adopting more than one FU when applying the LCA to the agri-food sector as products have different characteristics from each other. This solution allows a study of the system from different points of view and results could consider the different roles that food plays. Other authors reached similar conclusions, combining one FU based on the price of

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products, with one on mass and one on nutritional values (Notarnicola et al., 2017), or with one on mass and one on the hectare of land occupied (Van Der Werf and Salou, 2015). Mass based FUs are quite common in LCA studies, especially when it comes to products (Cano Londoño et al., 2019; Neri et al., 2018; Slorach et al., 2019; Volanti et al., 2019), but in the case of food, function cannot be limited to its amount expressed in mass units, because it should involve nutrient intake. A FU that includes the nutritional quality of foods has been used in several studies, looking at nutritional density (Drewnowski et al., 2015; Smedman et al., 2010), resource consumption related to nutritional quality (Röös et al., 2015) or the impact of the individual product within a diet (Fern et al., 2015; Werner et al., 2014). In particular, when evaluations consider different types of food with different roles (as in diets or crop rotations), an approach that includes a quality-corrected FU is needed (Heller et al., 2013; Schau and Fet, 2008).

Among the various available options, the Cereal Unit (CU) parameter was chosen as one FU for this project, because a study on crop rotations will be carried out and this parameter proved to be the most appropriate in these cases (Goglio et al., 2018; Henryson et al., 2019; Palmieri et al., 2017). Therefore, the aim of this work is to discuss and encourage the use of CU as a criterion of comparison between different crops. Secondly, as a consequence of the analysis of the results on a case study, the project allows to provide suggestions (based on an LCA approach) to farmers in order to minimise the impacts of their agricultural practices. CU, which will be better described below, is a physicochemical and biophysical parameter that considers both the characteristics of crops (amount of fibre, protein, carbohydrates, etc.) and the energy content that can be metabolised for food. Its use in LCA studies considering crop rotations was firstly suggested by Brankatschk and Finkbeiner (2014) and it is considered particularly important in order to capture all the functions of the agricultural products (Rice et al., 2019). Therefore, a comparison between two crop rotations in Argentina using CU as FU is presented. However, to respect the multi-FU indication of previous studies, the same comparison was then carried out with a revenue-based FU, to estimate the differences and discuss the information that both methods could provide.

2. Methodology

LCA methodology was performed in accordance with the mentioned standards, using the SimaPro software (v. 9.0) (PRé Consultants, 1990) to build the models and the Ecoinvent database (v. 3.5) (Ecoinvent, 2016) as the reference for all the background information. ReCiPe H/H Midpoint 2016 (Huijbregts et al., 2016) and Cumulative Energy Demand (CED) (Frischknecht et al., 2007) are the chosen methods to carry out the analysis, since they have already shown their synergic ability to obtain a comprehensive estimation of environmental burdens (Cespi et al., 2016). These methods are used as complementary approaches because CED assesses the direct or indirect resource consumption of the scenarios, while ReCiPe estimates the environmental consequences in different impact categories.

Within the system boundaries of the study the impacts of land use, operation of agricultural machinery, seeds, growth promoters and chemicals (such as fertilisers, herbicides, insecticides and fungicides) per hectare of crop are considered. Since the CU includes the fate of agricultural products (the metabolisable energy depends on the receptor), the study was conducted following a *from-cradle-to-grave* perspective. A full depiction of the system boundaries is shown in Fig. 1.

For the comparison of the crop rotations, two scenarios are modelled on the basis of the same CU production, i.e. the production of each crop multiplied by its CU, and on the revenue of the rotation. Data comes from the company “La Cautiva”, located in the department of San Justo (Santa Fe, Argentina), and can be considered as primary since they are measured, gathered and calculated by the local cooperative of producers. San Justo department’s climate is warm and temperate, classified as Cfa (Humid Subtropical Climate) according to the Köppen-Geiger climatic classification (Kottek et al., 2006). It is characterised by a considerable amount of rainfall (on average 962 mm per year), so there is no need of artificial irrigation. The conventional crop rotation used in this area, for the purposes of the study, is called “Rotación San Justo” (San Justo Rotation, SJ), while the other, called “Rotación Siempre Verde” (Evergreen Rotation, EG), is an alternative one. Both rotations cover a period of six years and apply the *sod-seeding* method, a conservative agronomic technique of soil management that provides for no-tillage in order to maintain a physical fertility comparable to that of natural soil (Cavalchini et al., 2013). The SJ Rotation is a system that provides for a less intensive cultivation, in which only in the first year the soil is exploited in all seasons, from the second year the land is rested in autumn–winter and cultivated in spring-summer. On the other hand, the EG Rotation does not involve fallow periods but requires, in the autumn–winter season of the second and fourth year, the cultivation of rapeseed and ryegrass, with the intent to regenerate the properties of the soil and not to produce goods. They are labelled as “coverage” and their products are not valorised. Table 1 shows the two rotations, assigning each crop to the season and year in which it is planned.

2.1. Functional unit

In order to better understand the results, it is important to investigate in depth the used FUs. As said, the CU parameter considers the fate of the agricultural products, which can be of three types: (*i*) animal feed, (*ii*) human food and (*iii*) industrial use. In all cases, since Argentina is a net exporter of these products (WTO, 2016), not only the local consumption must be considered, but also the use made in importing countries. The international importance of Argentine market is one of the key points of this study. To our knowledge, in fact, this is the first case of application of the CU parameter in Argentina, whose importance is linked to the fact that it exports all over the world. An extensive analysis of the destination and consumption of each product was thus necessary, which is reported in detail in Table S1 in the Supporting Material. In the same table the CU indexes were calculated in accordance with Brankatschk and Finkbeiner (Brankatschk and Finkbeiner, 2015). For use as feed, the metabolisable

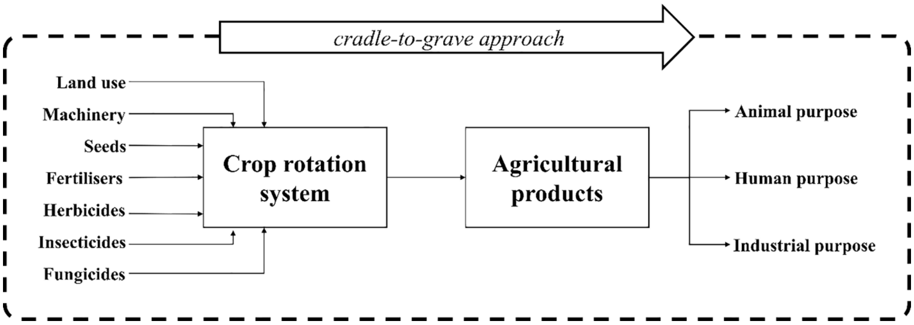

Fig. 1. System boundaries of the study: inputs and outputs of rotations are calculated on a CU-based FU and a revenue-based FU.

Table 1

Schematic representation of San Justo and Evergreen Rotations. (A-W: Autumn-Winter; S-S: Spring-Summer).

Rotation	Season	1st year	2nd year	3rd year	4th year	5th year	6th year
	A-W	Wheat	Fallow	Fallow	Fallow	Fallow	Fallow
	S-S	Soybean	Sunflower & Corn	Soybean	Soybean	Soybean	Soybean
	A-W	Sunflower	Rapeseed (coverage)	Wheat	Ryegrass (coverage)	Rapeseed	Corn
	S-S	Corn	Soybean	Corn	Soybean	Soybean	Mung Bean

energy content of the products, different in each animal and weighted by the percentage of distribution, was considered. For human consumption, the methodology provides for the assignment of a level of production intensity to the crop, which is then divided by the actual production of the crop itself. The CU index for industrial purposes is calculated on the basis of gross energy content of the products. When the index is obtained in energy terms (feed and industrial purposes) it is normalised to the CU by its definition: 1 CU = 12.56 MJ (the metabolisable energy of 1 kg of barley). An example of this calculation process is given in Scheme S1 in the Supporting Material.

The CU factor of each product was then obtained by multiplying the CU indexes of each purpose by their distribution. Finally, the CU factor of each crop is multiplied by its productivity (kg/ha) to define its Cereal Unit, the FU used for comparison. In this context, it is evident that CU is a site-specific parameter, as geographical differences, together with variations in the proportion of feed per animal, as well as food and market differences are relevant. With this in mind, and following the guidelines, the CU indexes obtained in this work are to be considered valid only for the aims of this study with reference to the Argentinian geographic area, even though the same approach could be replicated everywhere.

To carry out the comparison with a revenue-based FU, the cost per kg (in USD$) of all agricultural products were identified. The most recent average annual prices available were considered, in order to limit market fluctuations and because the two rotations can have the same product in two different periods (see the case of sunflower and corn, obtained both in spring-summer and autumn–winter). Single product prices are listed in Table S1 in the Supporting Material. Again, prices are multiplied by the production amount to obtain the revenue that each crop generates, the FU used for this comparison. Table 2 summarises the CU and the revenue obtained from each crop. The two systems will be compared on the basis of the same total CU and total revenue respectively. The full LCI of the crops are given in the Supporting Material (Tables S2 and S3).

3. Results and discussion

As Table 2 shows, the ratio between EG and SJ Rotations is 1.61 when the revenue-based FU is considered (6,117 vs 3,801 USD$), and 1.64 in the case of the CU-based FU (52,989 vs 32,407 CU). Although in this particular case the two rotations will show similar ratios in the comparison results, the use of CU as FU can guarantee a greater stability of results over time as most of the Argentinian agricultural products end up on the international market and their price is strongly influenced by its fluctuations. Fig. 2 shows the price trend of four of the cereals involved in the study during 2019 and as can be seen the variation can be significant (from +61% to +87%.). If a 6-year period is considered (like the time span of rotations) the variations are even greater, from 2014 to 2019 prices increased 5–8 times depending on the product (BCR, 2019). On the other hand, the difficulty in using the CU parameter as FU lies in finding all the information necessary for its definition. It must include both national and international market information, especially in the case of countries where exports represent a large market share, such as Argentina.

CED results, shown in Table 3, indicate that the two scenarios require a similar total amount of resources: 2.5 MJeq./CU and 21.3–21.5 MJeq./$. The demand for fossils is higher for EG Rotation, while the biomass request in SJ Rotation. In both rotations fossil consumption is the main one, responsible for 80–89% of total energy demand. Fossil resources are needed to produce chemical additives (in particular fertilisers as urea and phosphate compounds) and for agricultural machinery, both of which are greater for EG Rotation than for SJ Rotation. However, also CU and revenue are higher in EG Rotation, so the difference in fossil resource demand between scenarios is mitigated, but still slightly higher for EG Rotation. On the other hand, biomass request is mainly due to seeds, which explains the difference of one order of magnitude with the fossil demand. Since the seed difference between the two rotations is lower than other inputs, the FUs normalisation makes the biomass demand for EG Rotation about half that of SJ Rotation.

In order to know which crop is the main responsible for the resource consumption, a contribution analysis was carried out (full results are shown in Table S4 in the Supporting Information). In SJ Rotation the lion’s share is made by wheat, which is responsible for 20% of total resource demand, while in EG Rotation the situation is more evenly distributed with maize, wheat and sunflower accounting for 15%, 13% and 12% of resource consumption respectively. Both rotations have non-productive seasons, but in different ways. In the SJ Rotation the land is left completely fallow, while in coverage periods of EG Rotation it is

Table 2

CU and revenue of each crop. The two rotations are compared on the same total CU and total revenue.

SJ ROTATION			**EG ROTATION**		
Crop	**CU**	**Revenue [$]**	**Crop**	**CU**	**Revenue [$]**
Wheat	8,008	404	Sunflower	2,451	410
Soybean	3,206	470	Corn	6,847	671
Fallow	0	0	Rapeseed (coverage)	0	0
50% Sunflower	1,226	205			
50% Corn	4,184	410	Soybean	3,946	578
Fallow	0	0	Wheat	8,008	404
Soybean	3,946	578	Corn	7,282	714
Fallow	0	0	Ryegrass (coverage)	0	0
Soybean	3,946	578	Soybean	3,946	578
Fallow	0	0	Rapeseed	4,199	569
Soybean	3,946	578	Soybean	3,946	578
Fallow	0	0	Corn	8,368	821
Soybean	3,946	578	Mung bean	3,996	794
TOTAL	**32,407**	**3,801**	**TOTAL**	**52,989**	**6,117**

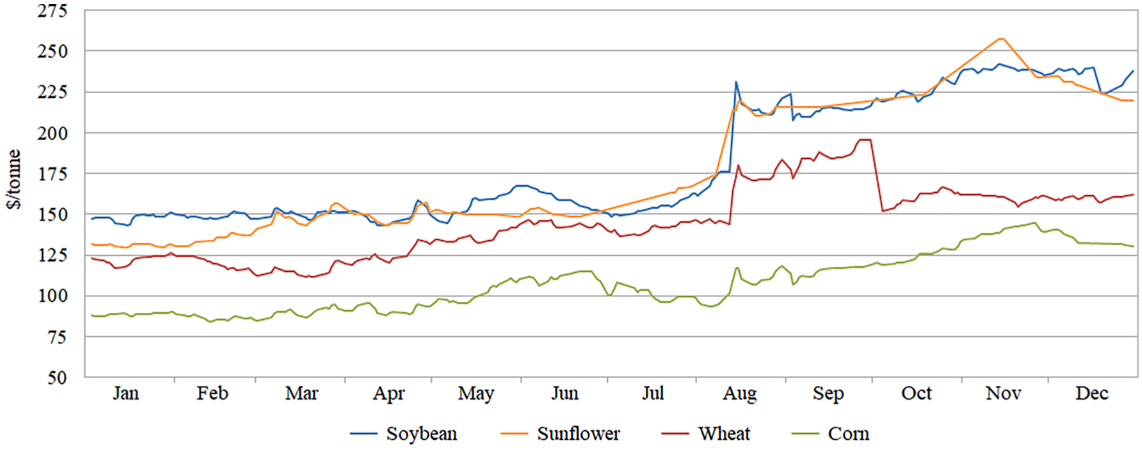

Fig. 2. Trend of cereal prices in 2019 (BCR, 2019).

Table 3
Resource consumption of the scenarios for both FUs. (CED method).

Scenario	Unit	Fossil	Biomass	TOTAL
SJ Rotation	MJeq./CU	2.0	0.5	2.5
EG Rotation	MJeq./CU	2.2	0.3	2.5
SJ Rotation	MJeq./$	17.1	4.2	21.3
EG Rotation	MJeq./$	19.2	2.3	21.5

cultivated to restore the soil quality, but without the harvesting of agricultural products. This difference also emerges in CED results: fallow periods need no resources, while coverage periods contribute for 1% to the resource demand of EG Rotation. Overall, from the point of view of CED method, the two rotations seem to be equivalent, but the resource consumption alone is not enough to describe their environmental performance.

In order to complete the analysis, ReCiPe method was applied, with a hierarchical cultural perspective, at midpoint level to quantify the environmental impacts of the rotations. Table 4 shows the full results of the two rotations for both FUs.

The results show that the largest difference between the two scenarios lies in the impacts attributable to the land use category, where SJ Rotation has an impact 60% higher than EG with both FUs. Since the crops are grown on the identical land area, the difference is due to the FUs. In particular, the ratios between the land use impacts are 1.61 and 1.64 for the CU-based FU and the revenue-based FU respectively, the same ratios identified at the beginning of this section. Stratospheric ozone depletion and marine eutrophication are the other two categories where the difference in scenarios is more pronounced, around 23%, while in almost all other categories the impacts are closer, with differences under ± 10%. Only in water consumption and freshwater eutrophication categories the two scenarios show differences between 10 and 15%. Of the sixteen categories of the method, eight were selected as the most representative of the analysis: global warming (GW), fine particulate matter formation (FPMF), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), land use (LU) and water consumption (WC). Their importance derives from the fact that the method gives them the highest single scores (a way to compare the weight of impacts in different categories) and from now on only these will be considered. From the results of Table 4, SJ Rotation shows higher impacts in GW, FE and ME categories, EG Rotation in TA, HT and WC categories, while in the FPMF the impacts are much similar.

A contribution analysis, Fig. 3, was carried out to identify the cause of impacts in each category.

In GW, FPMF and TA impact categories, fertilisers and agricultural machinery are the inputs that contribute most, ranging from 30% to 55% each. Machinery impact on GW and FPMF is due to the use of fossil fuel for their movement, which directly produces greenhouse gases and atmospheric particulate matter, the fall of these elements to the ground causes impacts on TA. As regards fertilisers (whose share is higher in EG Rotation because they are used in greater quantities) the impacts are mainly derived from the raw materials and electricity of their production chain. Seeds show more incidence in GW category than FPMF and TA, while pesticides contribute 2–5% to the impacts of the categories. In the FE category, the contribution of fertilisers and machinery remains high (30–40% for the first and around 26% for the second), but the

Table 4
Impact assessment of the rotations in terms of ReCiPe 2016 Midpoint H/H.

Impact category	Unit	SJ Rotation	EG Rotation	Unit	SJ Rotation	EG Rotation
Global warming	kg CO_2 eq./CU	1.6E-01	1.5E-01	kg CO_2 eq./$	1.4E+00	1.3E+00
Stratospheric ozone depletion	kg CFC11 eq./CU	2.2E-07	1.7E-07	kg CFC11 eq./$	1.9E-06	1.4E-06
Ionizing radiation	kBq Co-60 eq./CU	4.3E-03	4.2E-03	kBq Co-60 eq./$	3.7E-02	3.7E-02
Ozone formation	kg NOx eq./CU	7.6E-04	7.0E-04	kg NOx eq./$	6.5E-03	6.0E-03
Fine particulate matter formation	kg $PM_{2.5}$ eq./CU	3.8E-04	3.7E-04	kg $PM_{2.5}$ eq./$	3.2E-03	3.2E-03
Terrestrial acidification	kg SO_2 eq./CU	8.4E-04	8.9E-04	kg SO_2 eq./$	7.1E-03	7.7E-03
Freshwater eutrophication	kg P eq./CU	4.9E-05	4.3E-05	kg P eq./$	4.2E-04	3.7E-04
Marine eutrophication	kg N eq./CU	3.9E-05	3.0E-05	kg N eq./$	3.3E-04	2.6E-04
Terrestrial ecotoxicity	kg 1,4-DCB/CU	6.0E-01	6.7E-01	kg 1,4-DCB/$	5.1E+00	5.8E+00
Freshwater ecotoxicity	kg 1,4-DCB/CU	4.4E-03	4.3E-03	kg 1,4-DCB/$	3.7E-02	3.8E-02
Marine ecotoxicity	kg 1,4-DCB/CU	6.0E-03	6.2E-03	kg 1,4-DCB/$	5.1E-02	5.3E-02
Human toxicity	kg 1,4-DCB/CU	4.6E-03	4.4E-03	kg 1,4-DCB/$	3.9E-02	3.8E-02
Land use	$m^2 \cdot a$ crop eq./CU	1.9E+00	1.2E+00	$m^2 \cdot a$ crop eq./$	1.6E+01	1.0E+01
Mineral resource scarcity	kg Cu eq./CU	1.9E-03	2.0E-03	kg Cu eq./$	1.6E-02	1.7E-02
Fossil resource scarcity	kg oil eq./CU	4.4E-02	4.8E-02	kg oil eq./$	3.8E-01	4.2E-01
Water consumption	m^3/CU	4.7E-03	5.4E-03	m^3/$	4.0E-02	4.7E-02

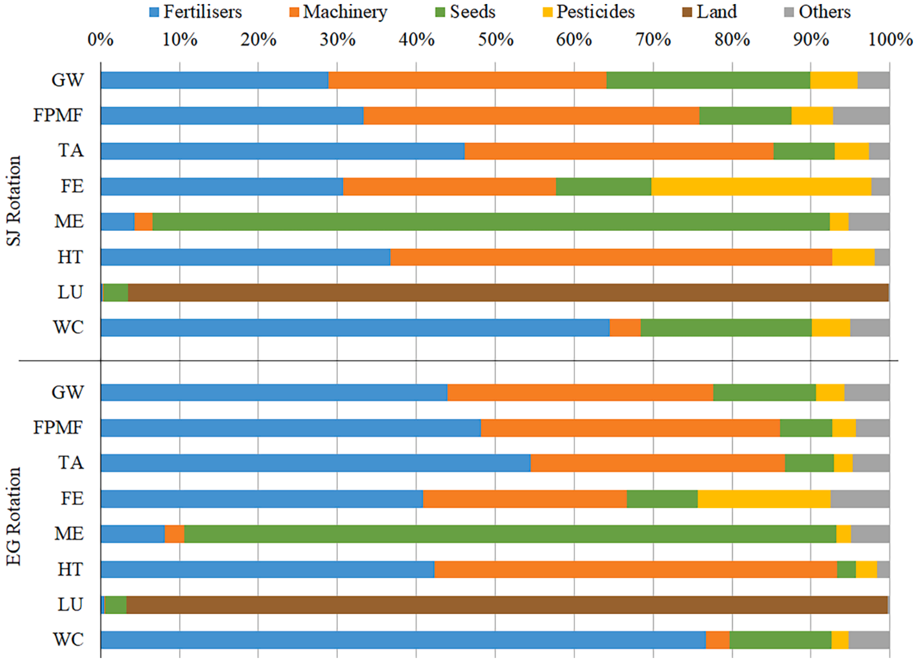

Fig. 3. Contribution analysis of inputs to the impact categories (ReCiPe 2016 Midpoint H/H).

contribution of pesticides increases, accounting for 28% and 17% in SJ and EG Rotation respectively. This is because FE impact category measures kg P eq. and glyphosate (the most important pesticide in both rotations) is a compound containing phosphorus. In the ME category the impact lies for more than 80% in the seeds, caused by the previous crops from which they were obtained. Although pesticides and fertilisers include nitrogenous compounds (the ME category estimates the kg N eq.), they do not bring particular environmental burdens to the category. HT is affected by emissions from agricultural machinery, which covers more than half of the impact category, and by fertilisers, more because of their production than their direct use. LU category, as imaginable, depends almost exclusively on the direct land occupation required by the crops and only a marginal part (about 3%) on that demanded for seed production. Rotations do not involve artificial irrigation, so WC impacts are associated only with the inputs. In this category the contribution of fertilisers is maximum, 64% and 77% in SJ and EG rotations respectively, and comes from the water needed for the production of some precursors (such as ammonia, sulphuric acid and phosphoric acid). On the other hand, seeds affect WC because the Ecoinvent database processes used for their simulation (to ensure the same background for all) include crop irrigation.

Due to their important contribution in 6 out of 8 considered categories, the impacts of fertilisers and machinery have been deepened. The analysis showed that among fertilisers, diammonium phosphate and urea share the responsibility for impacts almost equally, while the machinery that contributes most is the harvesting machine, followed by the sprayer and the sower.

Since the results derive from simulations (both for individual processes and for entire scenarios), an uncertainty analysis was carried out using the Monte Carlo statistical method (Raynolds et al., 1999) to assess their robustness. This method evaluates the frequency with which one scenario has greater values than the other by varying the parameters within their uncertainty range and repeating the calculation of the results for a statistically high number of times. This analysis, reported in Figure S1 in the Supporting Material, shows that in almost all categories the environmental results do not depend on the uncertainty ranges of the parameters, which is an indication of robustness of the results. The only borderline situations are those related to impacts on Marine eutrophication and Freshwater ecotoxicity categories, where the scenario with the highest impact shows it in 68% and 64% of Monte Carlo simulations respectively. In all other categories, the percentage rises above 75% to 100%.

Lastly, another contribution analysis was carried out, this time to identify the responsibilities of the different crops to the ReCiPe impacts.

The results, Fig. 4, indicate that in SJ Rotation the crop with the highest share is wheat, followed by soybean planned immediately afterwards. Soybean in the first year shows a slightly higher contribution than in subsequent years because its productivity is lower (see Table S2) and thus causes an increase in impact, both considering CU-based and revenue-based FU. Corn and sunflower crops show lower contributions because they are grown together during the second year (they are designed on 50% of the land each), but if added together they would contribute the same as wheat. The impacts of the EG Rotation, as its resource consumption in the CED method, are more distributed among its crops. However, in this case the different contribution of corn during the years is not only given by its productivity but also by different inputs of materials (see full LCI of EG Rotation in Table S3). Mung bean shows the lightest contribution to the environmental burden of the rotation and is slightly higher than the coverage periods. In both rotations, contributions from non-productive periods (4–5% each) provide an important information: land occupation is a significant source of impact, whether something is cultivated (EG Rotation) or left completely fallow (SJ Rotation). This confirms the complementarity of the two methods of analysis, the importance of land occupation does not emerge from the CED comparison as it only assesses the resource consumption, where the contribution of fallow periods is zero and that of coverages is very small, about 1%.

Finally, important suggestions for the achievement of the UN's Sustainable Development Goals can be drawn from the results of the analysis. First of all, the critical issues emerged on LU must lead to an increase in agricultural productivity, in order to not lose potential resources in the fight against hunger. This is particularly important in Latin America and is one of the critical points of goal #2 "zero hunger" (UN, 2019). However, the importance of soil quality (goal #15 "life on land", UN, 2019) should not be overlooked, and agricultural practices that go in this direction, such as EG Rotation coverage periods, should be encouraged. Another key point revealed by the results is related to the emissions of agricultural machinery and fertiliser production chain. To

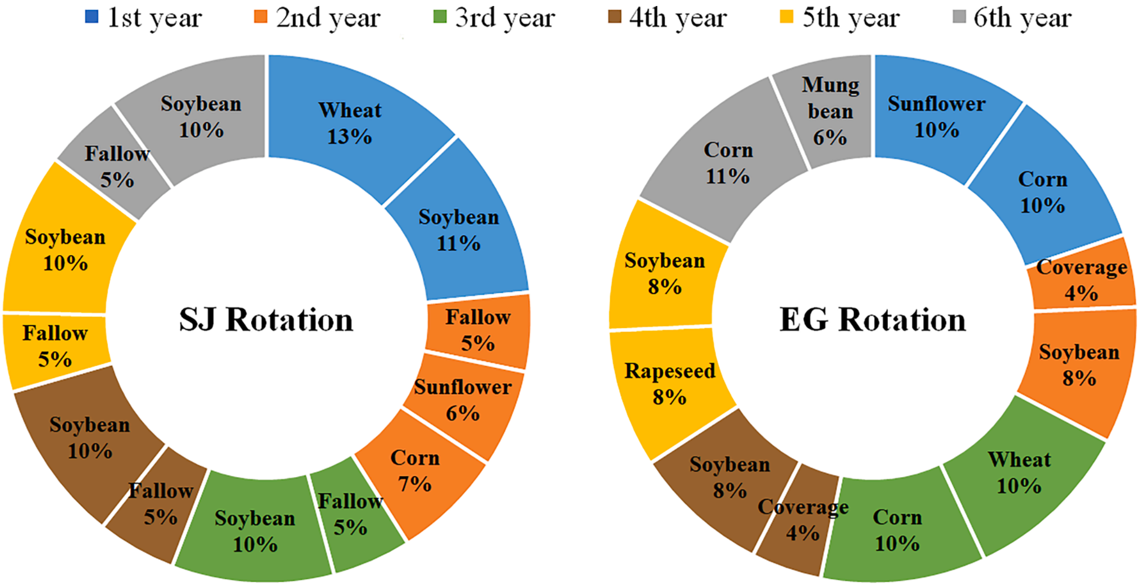

Fig. 4. Contribution analysis of each crop to the impact of the rotation (ReCiPe 2016 Midpoint H/H).

counteract their impact, and thus meet goal #13 “climate action” (UN, 2019), the use of renewable energies should be promoted, but waiting for technological upgrading (which may not depend on the farmer) the suggestion is to use them as consciously as possible. For machinery, this can be done by maximising the efficiency of its use or by replacing machinery work with manual work, unless productivity suffers too much. Furthermore, since fertilisers are essential to maintain high agricultural production, it could be considered to replace them with organic, natural or more eco-sustainable fertilisers.

4. Conclusions

In agricultural practice, the use of crop rotation is an essential strategy that improves nutrient availability, phytosanitary conditions, soil composition and helps to counter biodiversity loss. Assessing the environmental impact of an entire crop rotation is a method able to capture crop-interactions information, not possible in a single crop analysis (Goglio et al., 2018). In this study, based on primary data from the province of Santa Fe in Argentina, a new and alternative crop rotation is compared with the conventional one in the region, characterised by a high export market. The analysis was conducted through the application of the LCA methodology and two different FUs were used, both able to represent all the functions of agricultural products. Using Cereal Unit (CU) production of the rotation as FU allows to summarise in a single parameter the quantity, quality and purpose of each agricultural product, key features of the crops. Alternatively, total crop rotation revenue is often used as a FU that can well approximate all these characteristics. The study showed that the use of a CU-based FU is appropriate for this type of investigation to guarantee stable results over time as it does not depend on price fluctuations of individual agricultural products such as in the case of a revenue-based FU. In addition, compared to the use of energy content, CU is also able to look at the destiny of agricultural products, adding an extra step to the life cycle assessment. In contrast, in order to reliably represent crop rotations, this parameter requires considerable effort to find information on all agricultural products.

The results indicate that from the point of view of resource consumption the alternative crop system (EG Rotation) requires more fossil resources since they are linked to the production of chemicals (pesticides and fertilisers), used more here than in the conventional system (SJ Rotation). However, when the analysis is extended to the impacts, it emerges that the key factor in the environmental assessment is the land use. As already shown in other studies (Jeswani et al., 2015), the importance of the impact on land use is of primary importance and in this category the SJ Rotation is assigned an impact +60% compared to the EG, with both FUs. Since in the other impact categories the differences are not so large, this aspect tips the balance of better environmental performance towards EG Rotation. The critical activities, in environmental terms, that have emerged for both rotation systems are the use of agricultural machinery and fertilisers.

In conclusion, with this project, the use of CU-based FU is encouraged when problems arising from different crop quality have to be overcome, since it could represent the most stable parameter among those which could estimate properly all the functions of the crops.

CRediT authorship contribution statement

M. Volanti: Formal analysis, Writing - original draft, Methodology, Software. **F.O. Savarino:** Conceptualization, Data curation. **F. Passarini:** Conceptualization, Validation, Writing - review & editing. **I. Vassura:** Supervision. **S.A. Grosso:** Conceptualization, Data curation.

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.ecolind.2020.107199.

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